A Practical Assessment of the Environmental Impact of Internal Combustion and Electric Engines

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Abstract

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Title of the thesis

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Abstract

This thesis investigates the environmental impacts of ICEVs and BEVs with a comparative LCA in the context of the low carbon energy system in Finland. This paper aimed to give a more realistic, data-based comparison of EV sustainability performance in terms of emission, energy consumption, materials usage, and eco-disposal at end of life. A cradle-to-grave LCA methodology was conducted according to ISO 14040/44, which included electricity mix, vehicle models, and recycling specific parameters. Secondary data from literature sources, industrial reports and national databases was employed to model environmental performance for four indicators: greenhouse gas emissions, cumulative energy demand, critical raw material consumption and non-recyclable waste. The results showed that BEVs result in 56% lower lifecycle GHG emissions relative to ICEVs, mostly due to the renewable saturated electricity grid of Finland, and the higher operational efficiency of the electric drivetrains. BEVs likewise account for 15% less lifecycle total energy requirement. But they use more critical raw materials – lithium, cobalt and nickel – and produce 49% higher amounts of non-recyclable waste, revealing new sustainability challenges in raw material extraction and at end-of-life. The study results suggest that pollution reduction of particle mass of BEVs is more pronounced in comprehensive environmental performance than in emission amount, and that pollution is transferred upstream to manufacturing and downstream to the complicated waste streams. Hence, sustainable vehicle electrification relies on increasing the service life of the battery, developed recycling infrastructure, and use of less resource-demanding battery chemistries.

Keywords

Lifecycle Assessment, Electric Vehicles, Internal Combustion Engines, Sustainability, Finland, Battery Recycling, Renewable Energy.

Contents

List of abbreviations

Abbreviation	Full Term
BEV	Battery Electric Vehicle
CO2	Carbon Dioxide
CACR	Critical and Conflict-Affected Raw Materials
EV	Electric Vehicle
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment

1 Introduction

1.1 Background

In recent decades, climate change has started alarming the world community, forcing states, industries and scientists to reconsider time-tested technologies and systems. The transportation sector has received particular attention among these due to its high share of greenhouse gas (GHG) emissions and fossil fuel consumption. As seen in the chart of global emissions, transport accounts for around 16% of total GHG emissions, making it the third largest source globally (behind electricity/heat and industry).

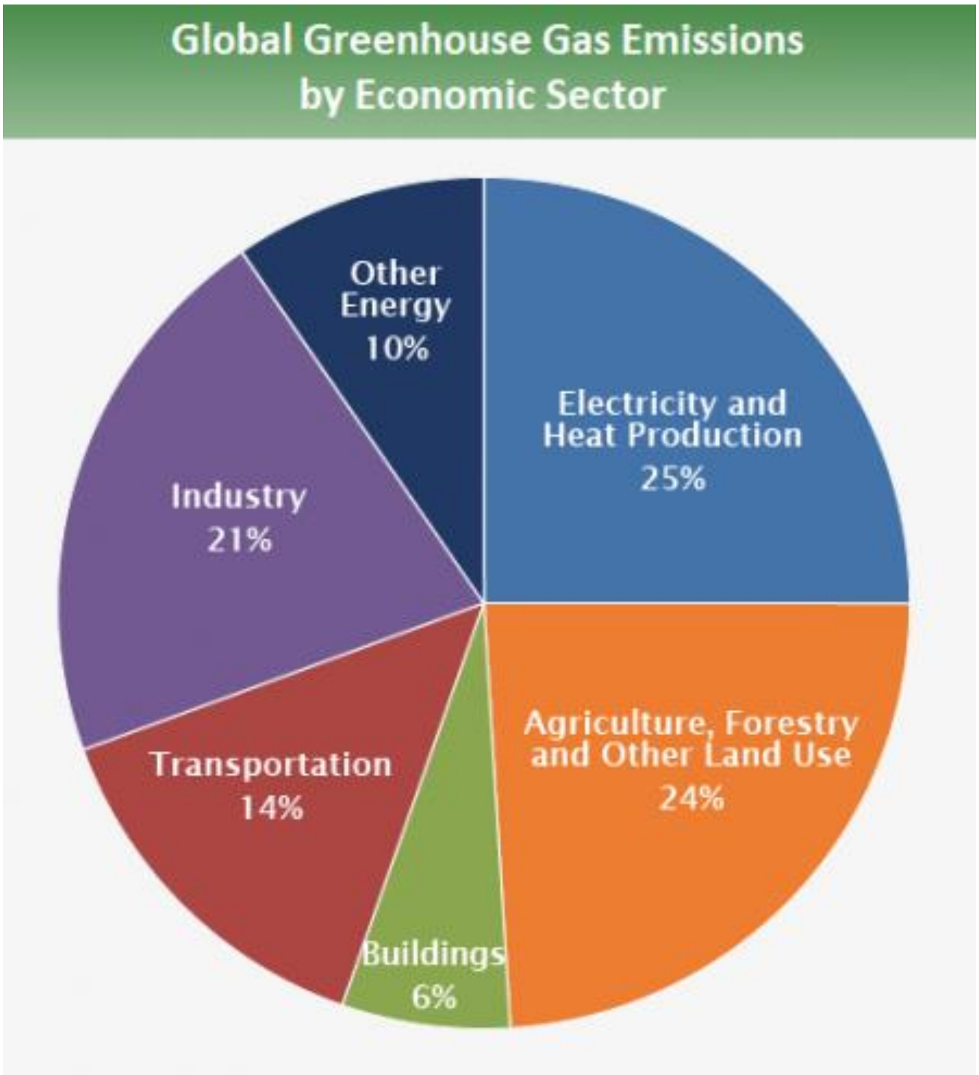


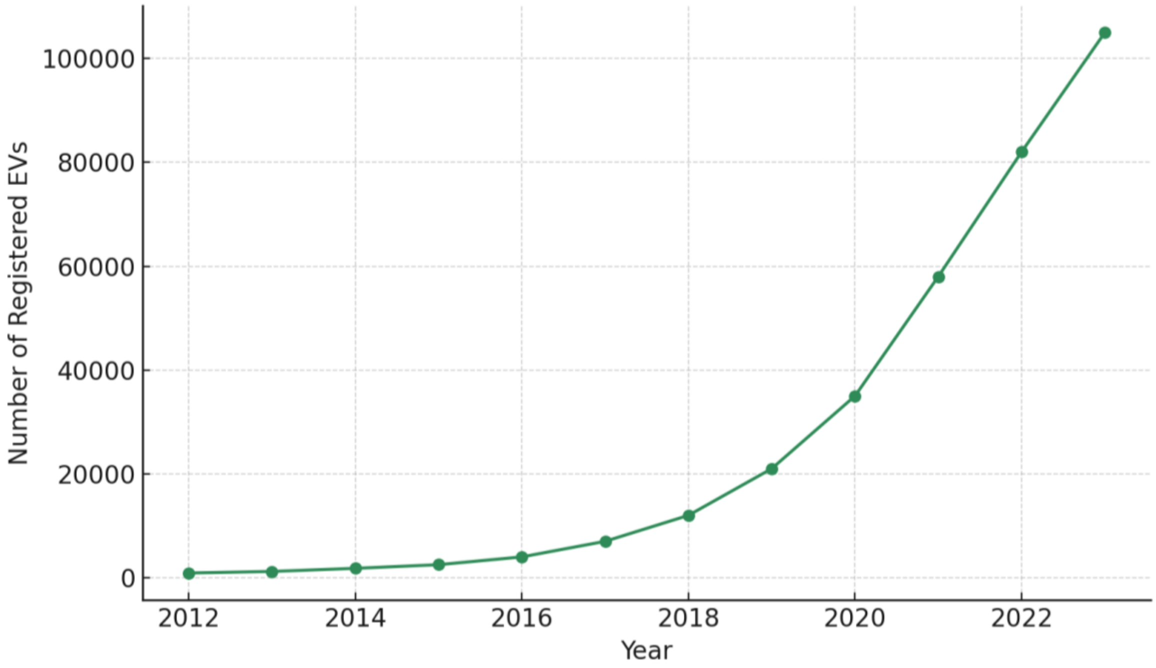
Figure 1. Global Greenhouse Gas Emissions by Sector (2010) (IPCC 2014)

Figure 1 shows that the share is primarily explained by the dominant role of fossil-fuelled internal combustion engine (ICE) vehicles in road transport. Meanwhile battery electric vehicles (BEVs), which are marketed as a means of tackling operational emissions, are catching up in many parts of the world, especially in nations with lower carbon electricity mixes. Yet the widespread adoption of BEVs brings with it an environmental challenge of a different kind, around battery production, key material use and end-of-life disposal.

This is especially relevant in Finland. The country committed itself to achieving carbon neutrality by 2035 (Ministry of the Environment, 2021) and the transportation sector is one of the major target areas of emissions reductions in this activity. With 20% of Finland's national emissions coming from the transport sector (Statistics Finland, 2023), the government is supporting EV uptake with a variety of policies, including subsidies, tax breaks, and public infrastructure investment.

1.2 EV Adoption in Finland and Europe

In Finland electric vehicle adoption has grown significantly during the last ten years.



Fugure 2. Growth of EV Registrations in Finland (2012-2023) (Traficom 2023)

Figure 2 states that the number of electric vehicles on the road in Finland, including BEVs and plug-in hybrids, had increased from under 1,000 in 2012 to more than 100,000 by 2023 (Traficom, 2023). This is spurred by similar developments elsewhere in Europe, though, given its smaller number of people, Finland's advances are particularly impressive in the context of the federation its operates in, where different regions may see far less progress.

This wholesale shift also raises critical questions about the actual environmental trade-offs between ICE and electric powertrains, especially when considered over the entire lifecycle. Evaluations of emissions solely from tailpipes are no longer enough. A holistic assessment of the vehicle impact has to consider production (particularly batteries), fuel/electricity generation, day-to-day use and end-of-life.

1.3 Problem Statement

As Finland advances towards the electrification of personal mobility, there is a requirement to have broader insight into the environmental consequences of various vehicle technology options across their entire lifecycle. The impact on operational emissions reduction is unequivocal for EVs, but there are lingering issues in other lifecycle stages, especially in the production and recycling of lithium-ion batteries, which are energy-intensive and have critical raw materials. Moreover, there are other sustainability challenges as Finland's energy system is changing towards more towards renewable energy, such as how to recycle wind turbine blades that are becoming more popular in the Finnish energy system.

On the other hand, ICE vehicles tend to be under more scrutiny for emissions associated with their fuel, but several environmental elements - e.g. recyclability of metallic components, established waste oil/catalytic converter handling—are indeed better managed. In order to fairly compare both technologies, a structured approach is required which includes all stages of their Lifecycle and takes the local energy and recycling landscape into account.

1.4 Purpose and Objectives

This bachelor's thesis aims to investigate the environmental impact of internal combustion and electric engines within the Finnish context, conducting a practical and data-driven assessment. In other words, we want to go beyond comparing operational emissions alone and give a more holistic and reality-based look at how these vehicle types are contributing to or helping solve environmental issues.

Specific aims of this thesis are:

- The full Lifecycle environmental impact of ICEs and EVs, including manufacturing, usage, and disposal stages.
- To better understand the environmental impact of EV battery production, recyclability, and end-of-life treatment.
- To assess sustainability challenges with respect to wind turbine blade disposal and recycling, specifically as it relates to Finland's renewable energy infrastructure.
- To evaluate the extent to which Finland's electricity generation mix impacts the real-world environmental performance of electric vehicles.
- To flag and articulate the trade-offs and overlap in sustainability across the two systems.

1.5 Research Questions

To provide clear direction for this study, a series of targeted research questions has been formulated. First, the work examines the Lifecycle environmental impacts of internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs), specifically within the Finnish energy and mobility context. Another central question concerns how the production and recycling of EV batteries affect the total lifecycle performance of these vehicles, given their material intensity and end-of-life challenges.

In addition to vehicle-specific issues, the study considers broader infrastructure-related concerns. In particular, it explores the environmental consequences associated with the disposal of wind turbine blades, as well as the current strategies for managing such waste in Finland. The analysis also investigates the influence of Finland's electricity mix on the overall sustainability of EVs in comparison to ICEVs. Finally, the study seeks to determine which technology offers the most balanced trade-offs from a full lifecycle sustainability perspective.

1.6 Scope and Limitations

This study is limited to environmental impacts and thus does not take into account economic, political and social aspects, and focuses solely on passenger cars in Finland. The study employs lifecycle assessment methodology, including upstream curb (e.g., raw material sourcing, parts production) as well as downstream processes (e.g., End-of-Life management and recycling).

It takes into account Finland's existing energy system and does not seek to predict future infrastructure investments beyond those used in public planning. The availability and consistency of lifecycle data for specific vehicle models and battery chemistries, and limited access to detailed studies on wind turbine or battery recycling, are some limitations. Nonetheless, the study turns to the strongest available scientific literature, reports and policy documents to make a meaningful comparisn that is also anchored in fact.

2 Literature review

2.1 Lifecycle Assessment of ICE and EV Technologies

LCA is a well-established method to assess environmental consequences of products from cradle to grave, i.e. from raw material extraction, production, use until waste. In passenger cars, LCA provides decision supporting insights further beyond tailpipe emissions by addressing the entire non-operational environmental ownership cost. Hawkins et al. (2013, 17(1), 53–64) also discovered that the source of the power used to charge EVs (the use phase) has a relationship with the total life-cycle emission (including the very first stage) of EVs, as EVs emit more CO2 during the manufacturing stage, partly because of battery production, but draw level during the use phase (especially when charged with low-carbon electricity).

The total environmental effect of EVs in Finland, in which 87% of electricity is renewable or low-emission (Statistics Finland, 2023), is consequently much lower than for an ICE vehicle. Kurkin et al. (2024, 17(11), 2747) implemented a recent comparative LCA that demonstrates that EVs use about 1.4 times more electricity over their lifecyle than ICE vehicles and produce about 1.5 times less greenhouse gases during operation. This finding highlights the key role that local energy mix and vehicle use profiles play defining energy and emission performance.

2.2 Battery Production and End-of-Life Challenges

Battery manufacturing is one of the most resource- and energy-intensive stages of the EVs life cycle. The explorations of Lithium, Cobalt, and Nickel, amongst other materials and minerals, have been associated with major environmental and ethical challenges, especially in low-regulatory areas (Gaines 2014, 1–2, 2–7). Finland, however, is leading the way in battery recycling in Europe. Fortum's hydrometallurgical recycling plant in Harjavalta is capable of achieving 95% recovery of critical materials such as cobalt and nickel from battery black mass (Fortum, 2023).

In addition, finnish organizations, including the University of Oulu, participate in EU related projects, such as the Safeloop project to enhance recyclability of lithium-ion batteries at least by 15% by 2030 (University of Oulu, 2024). Nevertheless, Harper et al. (2019, 575(7781), 75–86) indicate that although recycling is improving, widespread application and closed-loop uses are restricted, and a considerable amount of energy is still needed to handle and recycle materials back into the supply chain.

2.3 Wind Turbine Blades and Renewable Energy Infrastructure

The growing use of wind power by Finland, one its fastest-growing renewable sources, raises the issue of the sustainability of energy infrastructure itself. Wind turbine blades, mostly made up of a fiberglass-reinforced composite designed for strength and lightness, are difficult to recycle because they are built to withstand the forces of nature.

It is projected that more than 40Mt of wind turbine composite waste will be generated globally by 2050 (Liu & Barlow 2017, 62, 229–240). However, no large-scale plants dedicated to blades recycling exist in Finland, although thermal and mechanical recycling are gaining attention (Beauson & Lilholt 2020, 123, 109768). Yet widespread deployment continues to be constrained, and many retired blades end up being dumped in a landfill or burned, creating long-term environmental concerns.

2.4 Finland's Electricity Mix and Its Influence on EV Sustainability

The carbon intensity of the charging electricity is a key determinant of the environmental performance of EVs. Finland has a distinctive clean energy picture in Europe: 87% of its electricity came from renewable and low-carbon sources including nuclear, hydro, wind and biomass in 2022 (Statistics Finland, 2023).

This low-carbon electricity mix greatly improves the real-world sustainability of EVs in Finland. Messagie et al. (2014, 7(3), 1467–1482) argued, EVs provide the most emission savings in countries where the electricity mix is highly decarbonized—so Finland is almost a best case here. Yet according to Ahman and Nilsson (2021) even clean electricity does not fully remove upstream emissions, such as those from battery production and vehicle manufacturing. It does follow, however, that even in the most favourable circumstances for EV uptake such as Finland, lifecycle emissions do matter.

2.5 Comparative Environmental Impact Assessments

A literature has attempted to compare the overall environmental impacts of ICEs and EVs under varying regional and operational conditions. For example, Ellingsen et al. (2017, 12(5), 054010) note that the superiority of EVs against ICE vehicles in terms of GHG emissions and air pollutants is not the same for all cases and it is contingent on the vehicle lifetime, battery capacity, and electricity origin. For Finland, VTT Technical Research Centre preliminary evaluation indicate that in its use-phase EVs emits much less CO2/km than ICEVs (usually 50% - 90% over its Life cycle) (VTT, 2023). However, such advantages depend on ongoing developments in battery recycling and resources utilization.

Methodological differences and differing assumptions were previously identified by lifecycle assessment studies. While Hawkins et al. (2013, 17(1), 53–64) highlighted that large environmental burdens occur during the battery production phase Ellingsen et al. (2017, 12(5), 054010) further complicated this picture by pointing out that differences in battery size, and the source of electricity, lead to very different environmental results. Recent study by Kurkin et al. (2024, 17(11), 2747) have built on and developed our earlier results, demonstrating that battery manufacturing emissions have fallen significantly as a result of technology upgrading and a greater efficiency of production. These findings illustrate the evolving nature of lifecycle impacts and the necessity to periodically update assessments as technologies lead to new discoveries.

3 Methodology

3.1 Research Design and Approach

The comparative LCA approach is used in this thesis to assess the environmental impacts of conventional ICEVs and EVs. The LCA methodology has been selected for the evaluation of the environmental performance along the life cycle of a product, from raw material extraction to waste treatment.

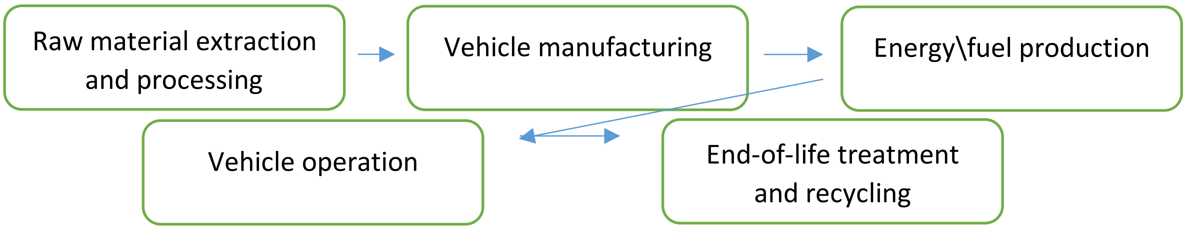


Figure 3. Stages of a Vehicle Lifecycle Included in the LCA

A "cradle-to-grave" method of assessment is applied applying five major Lifecycle stages that are mentioned in Figure 3.

The study is empirically implemented in the case of Finland using local electricity grid structure, energy production and infrastructure data to maintain geographical relevance.

3.2 Lifecycle Assessment Framework

A method can be defined as a structured approach for carrying out activities.

The LCA is performed according to the principles specified in the ISO 14040 and 14044 standards. Phases of the LCA process The key stages of the LCA process applied in this thesis include:

- goal and scope definition
- inventory analysis (LCI)
- impact assessment (LCIA)
- interpretation

The scope of the assessment includes a single unit function; one vehicle deserved to represent an average passenger car over a 15-year lifetime and 200,000 kilometer average Finnish driving conditions (Traficom, 2023). This universal unit allows a fair comparison of ICEV and BEV at the whole life cycle stage.

The four fundamental indicators are used to assess the environmental performance of each type of vehicle. total greenhouse gas emissions measured by the CO2 equivalent (CO2e), total energy consumption (in megajoules (MJ) of primary energy), use of primary raw materials (in kilograms) for depletion of depleting materials such as lithium, cobalt and nickel, and volume of non- recyclable waste: each from vehicle use to end of life.

3.3 Data Sources and Assumptions

The LCA uses secondary data from published peer-reviewed literature, industrial LCA reports and publications of the Finnish government. The data used includes contributions from several key institutions and databases. These are: the VTT Technical Research Center of Finland, Fortum Battery Recycling, and Statistics Finland, which provides national energy data and vehicle stock statistics. Additional input was obtained from the Ecoinvent LCA database, as well as recent academic studies, such as Kurkin et al. (2024, 17(11), 2747) and Ellingsen et al. (2017, 12(5), 054010), which offer updated Lifecycle data for vehicle and battery systems.

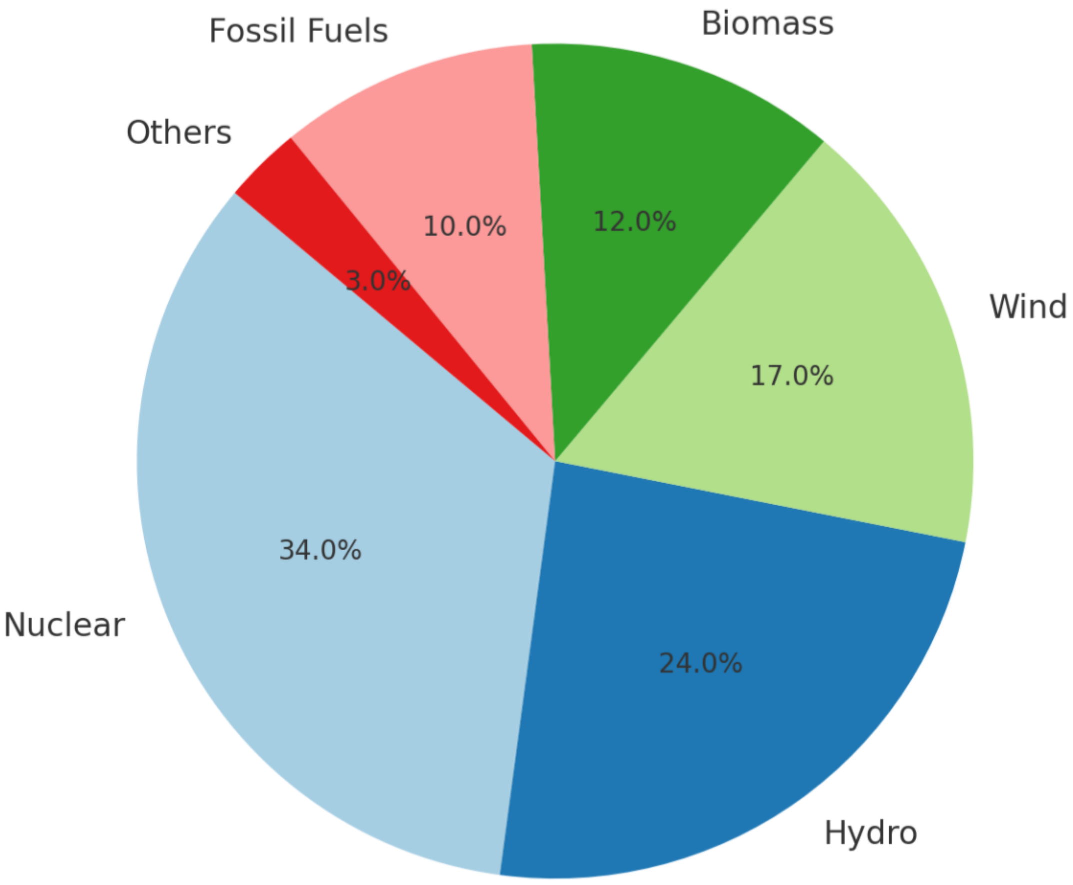


Figure 4. Composition of Finland's Electricity Grid (2022) (Statistics Finland 2023)

Key assumptions:

- EV battery: 60 kWh lithium-ion pack with NMC Chemistry.
- ICE vehicle: 1.6L petrol engine with Euro 6 emission standard.
- As Figure 4 states: Finnish electricity mix: 87% renewable/low-carbon.
- Charging losses for EV: 10%.
- Battery replacement: one pack per vehicle lifetime (assumed at 150,000 km).

The 150,000 km battery lifespan Assumption mirrors standard manufacturer warranties (e.g., the 8-years or 160,000 km warranty of the Nissan Leaf) and the empirical evidence of real-world use in Nordic climates (EV Database, 2024). This factor is closely related with the frequency of battery replacement and its environmental consequences, and raises the representation and credibility of the results of the LCA.

3.4 Impact Categories and Evaluation Metrics

The impact assessment performed in this study is characterized by using midpoint indicators, which make it possible to focus on the assessment of environmental burdens along the vehicle lifecycle. These indicators were chosen so as to be consistent with LCA regular exercise and to be used for quantification of sustainability performance.

The main performance factors considered are the global warming potential, that gives an indication of the total greenhouse gas (GHG) emissions as CO2-equivalent, and the cumulative energy demand, which is capturing the total energy used across all the life-cycles phases, with special attention to abiotic resource depletion, particularly in critical metals, and to the generation of non-recyclable waste, which is the amount of materials that can be recovered according to current end-of-life processes.

Every indicator is described per functional unit and contrasted between ICE and EV technologies. All data are normalized and, whenever applicable, error bars are taken into account. Sensitivity analysis is performed on the key parameters including the electricty grid mix, battery life and vehicle mileage.

3.5 Case Study Integration

For the purpose of illustrating the LCA, two types of vehicle models are selected:

- EV: Nissan Leaf (60 kWh battery, representative of Finnish EV market).
- ICE: Toyota Corolla (1.6L petrol engine).

These models are chosen based on popularity treatment, availability of extended LCA results and match with finnish driving conditions. When there are no exact figures for Finland, European or Nordic numbers or proxies are applied and clearly indicated.

3.6 Limitations

The scope of this study is intentionally focused to ensure depth and clarity in the analysis of lifecycle environmental impacts. As such, the assessment excludes commercial vehicles, as well as hybrid and hydrogen-powered vehicles, which involve distinct technologies and energy profiles that would require separate treatment beyond the present comparison between internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs).

In addition, this work does not include an economic cost-benefit analysis, nor does it address the social or geopolitical implications related to the sourcing of critical raw materials such as lithium, cobalt, or rare earth elements. These important dimensions are acknowledged but lie outside the environmental scope defined for this lifecycle assessment.

Data constraints may also include possible regional variation in impacts from material sourcing and emissions from recycling processes.

Since the present research does not concern human subjects and original data collection, the approval of ethical conduct is not necessary. All data that were used is public available or from reputable institutional sources with appropriate references.

4 Results

4.1 Overview of Lifecycle Environmental Impacts

The environmental impact of ICE and BEV was compared using a functional unit of 200,000 km travelled over a 15-year period.

Table 1. Summary of Lifecycle Environmental Impacts (200,000 km vehicle use)

Impact Category	ICEV (Petrol)	BEV (Finnish grid)	Relative Change
GHG Emissions (kg CO2e)	31200	13800	-55.8%
Energy demand (MJ)	99500	84200	-15.4%
Non-Recyclable Waste (kg)	450	670	+48.9%
Critical Raw Materials (kg)	18	42	+133%

Table 1 states the background data used to represent vehicle emissions, energy, materials and waste end-of-life flows that were sourced from peer-reviewed LCA literature (Hawkins et al. 2013, 17(1), 53–64; Ellingsen et al. 2017, 12(5), 054010); Kurkin et al. 2024, 17(11), 2747), industrial reports (Fortum, 2023) and the Finnish national energy database (Statistics Finland, 2023).

4.2 Greenhouse Gas Emissions by Lifecycle Phase

This section offers a comparison of the GHG emissions (in terms of CO2) of ICEVs and BEVs in the three stages: production, use and end-of-life. The findings are derived using a synthesis of peer-reviewed lifecycle analyses and regional emission factors that are specific to the Finnish setting.

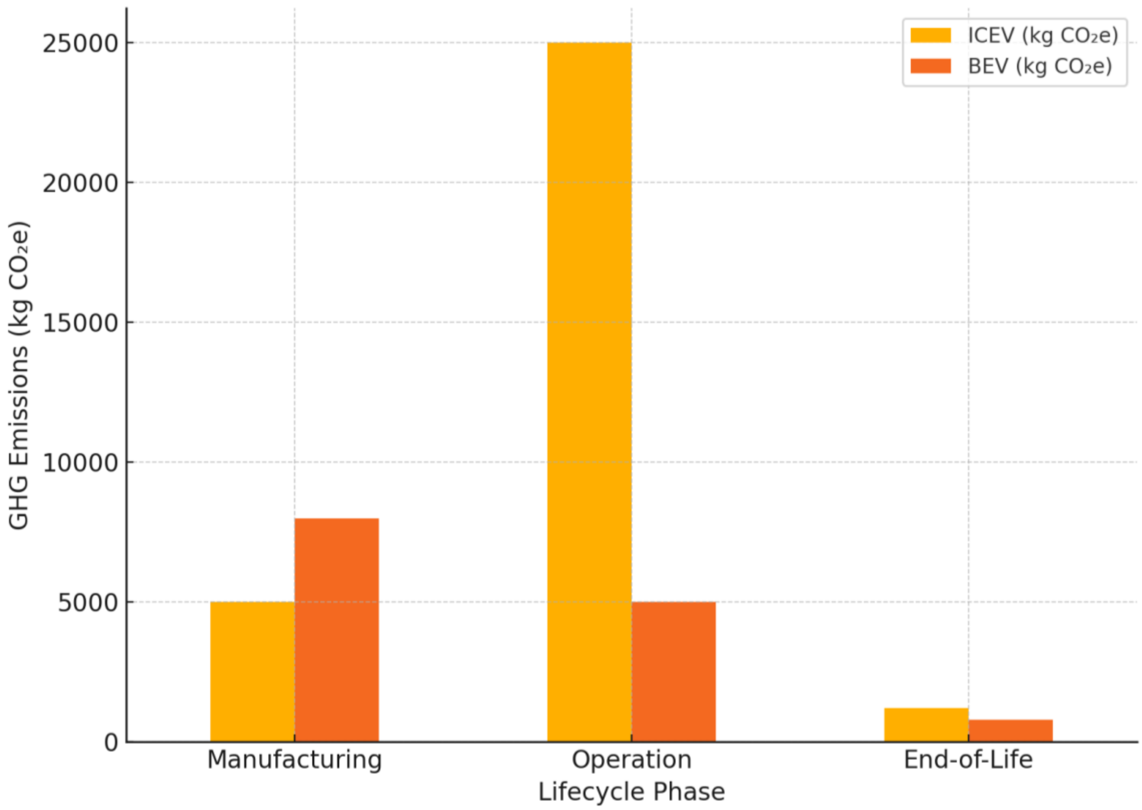


Figure 5. Lifecycle CO_2e Emissions by Stage (ICEV vs. BEV) (Hawkins et al. 2013, Ellingsen et al. 2017, Kurkin et al. 2024, Statistics Finland 2023, VTT Technical Research Centre of Finland 2023)

Figure 5 presents a breakdown of total CO_2e emissions by lifecycle phase. The dominant contributor for ICEVs is the use phase, while for BEVs, it is the production phase, particularly due to battery manufacturing.

For ICEVs, emissions from combustion comprise about 75% of total Lifecycle GHG emissions. Combustion of petrol releases 2.3 kg of CO_2e per litre (IPCC, 2019), so over 200 000 km given average consumption of 6.5 L/100 km, that is nearly 29,900 kg CO_2e from fuel use alone. This is very much in accordance with the total emissions value.

For BEVs, battery production accounted for about 5,200 kg of the 8,000 kg CO_2e emitted in vehicle production. This is consistent with Kurkin et al. (2024), who calculate 85–90 kg CO_2e/kWh for a 60 kWh NMC battery produced in Asia and exported to Europe. Finnish production levels for cleaner energy inputs may be able to lower this, but localized manufacture data is not available for now.

The use phase emissions of charging electricity for BEVs is slightly less than 6000 kg CO_2e using the finnish grid emission factor of 29 g CO_2e/MJ (Statistics Finland, 2023).

4.3 Cumulative Energy Demand

A different perspective is provided when looking at the cumulative energy demand (CED) reflecting the total primary energy consumption over the life cycle, including extraction, processing and conversion losses. Although both the vehicles require significant amount of energy, BEVs are the more efficient vehicles with regards to higher operational efficiency.

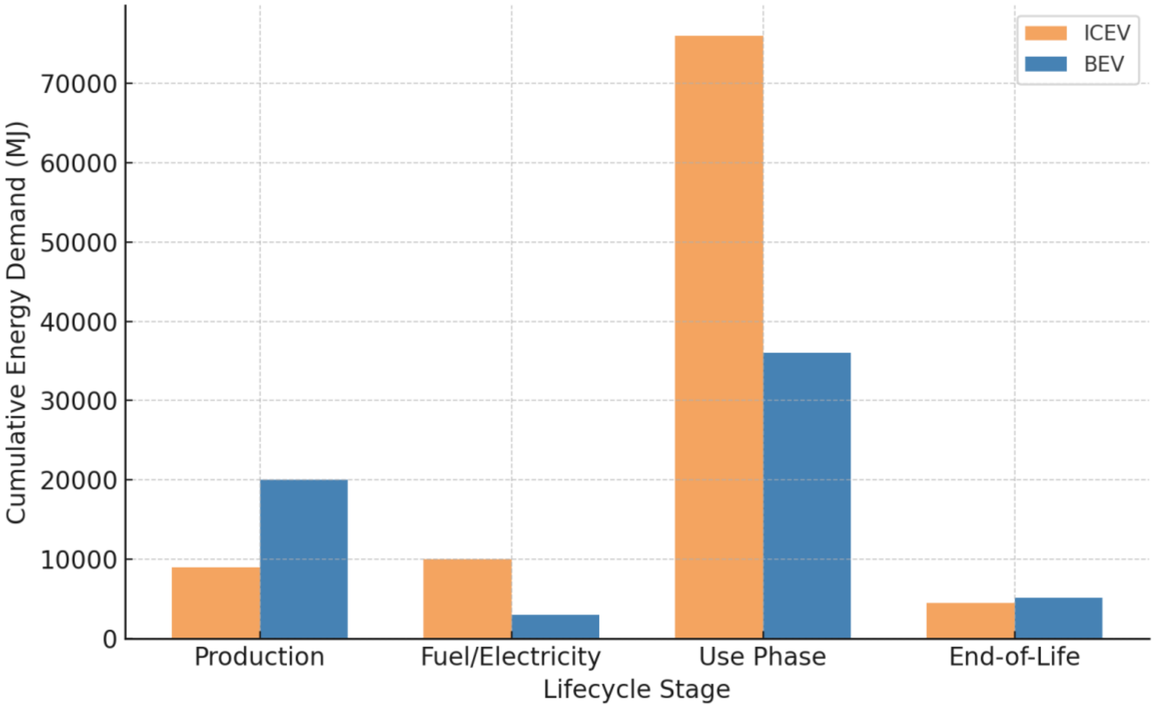


Figure 6. Total Cumulative Energy Demand by Stage (MJ) (Hawkins et al. 2013, Ellingsen et al. 2017, Gaines 2014, VTT Technical Research Center of Finland 2023)

ICEVs demand continuing significant energy contributions from fossil-fuel harvesting and processing and thus refining already accounts for some 6 MJ per liter of petrol (IEA, 2019). Figure 6 informs that the ICEV's total energy need over the lifecycle is approximately 99.5 G J, with the use phase as the dominant contributor. BEVs, on the other hand, back load energy to the manufacturing stage—mainly for battery production (~18,000–20,000 MJ), but have much lower operational energy consumption. Finnish average EV consumption is approximated at 18 kWh/100 km (Traficom 2023), totalling around 36,000 MJ (accounting for 10% charging losses).

4.4 Material Use and Resource Depletion

EVs are more material-reliant though, especially with respect to lithium, cobalt, nickel and copper.

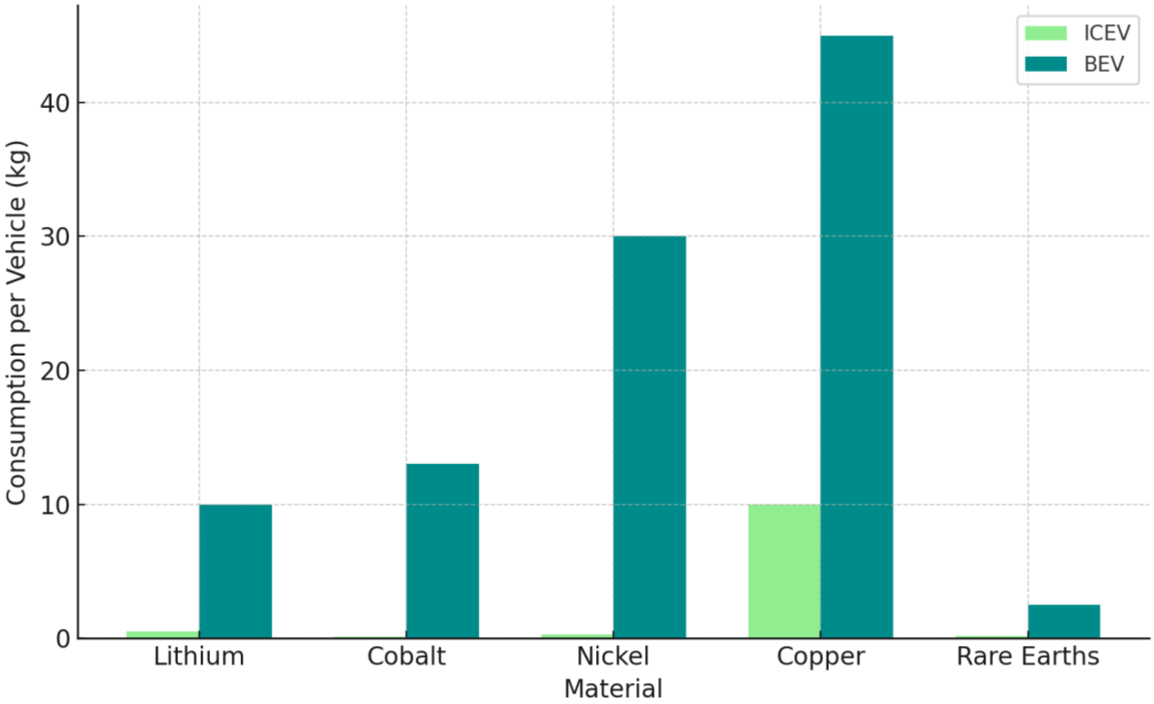


Figure 7. Critical Material Consumption (per vehicle, kg) (Hawkins et al. 2013, Harper et al. 2019, Argonne National Laboratory 2021, US Department of Energy (DOE) & European Commission 2020)

Figure 7 shows selected materials per vehicle. A 60 kWh lithium-ion Nickel Manganese Cobalt battery typically contains: Lithium: 8–10 kg, Cobalt: 12-14 kg, Nickel: 30-35 kg, Copper (wiring + motor): 40–50 kg.

ICEVs have catalytic converters with less quantity but precious platinum group metals and are fitted with steel and aluminum in chassis parts. But the metals are, however, already well-recovered in end-life processes (Gaines 2014, 1–2, 2–7).

4.5 End-of-Life Waste and Recycling Potential

End-of-life vehicle waste consists of all non-recycled material at the end of life of the vehicle. BEVs also generate more total waste (a higher proportion of non-metals) and more hazardous fractions owing to the battery.

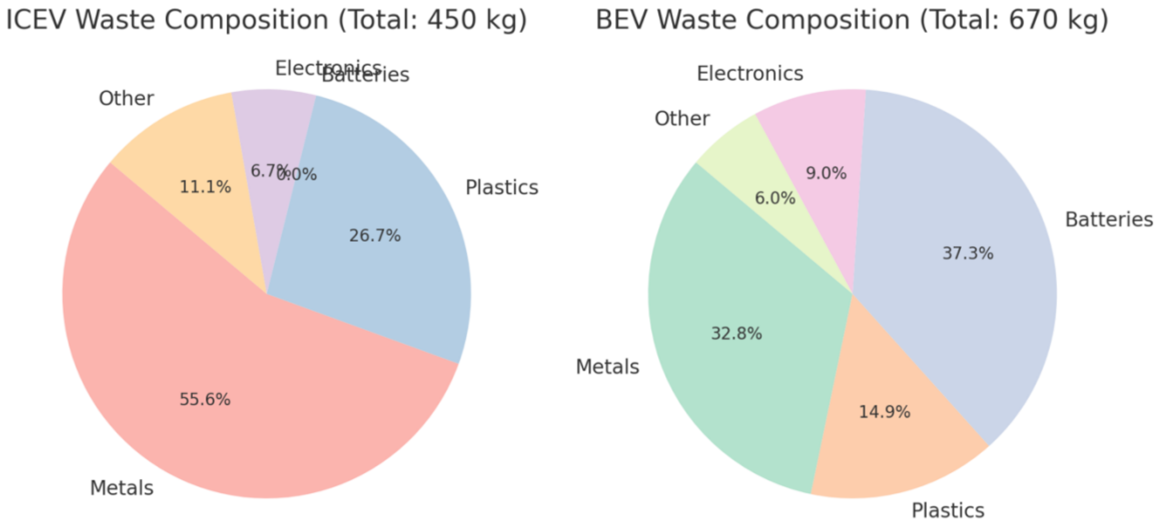


Figure 8. Non-Recyclable Waste Mass by Vehicle Type (kg) (Fortum 2023, Gaines, L. 2014, University of Oulu 2024)

Figure 8 represents that BEVs generates 670 kg of non-recyclable waste which is emitted in the form of degraded lithium salts, plastics, separators, and composite enclosures. ICEVs produce about 450 kg of waste, mostly plastics, oil residues, and tires.

Fortum’s black mass (nickel, cobalt, lithium) extracting plant in Harjavalta (2023) recuperates 95% of metals, but the rest ends up in landfills or is incinerated. Furthermore, the magnitude of the recycling process is under a transformation process—the collected battery packs in the countryside are relatively often in a loose with transportation problems and few disassembling places (University of Oulu, 2024).

4.6 Sensitivity Analysis

The second analysis involved changes to the manipulation of those other parameters, in order to check the robustness of the findings.

Table 2. Sensitivity of GHG Emissions to Key Lifecycle Variables (Gaines, L. 2014, Ellingsen et al. 2017, Argonne National Laboratory 2021, VTT 2023)

Variable	Change	Impact
Battery lifespan increased to 300k km	+50% use-phase allocation	-17% total emissions
Grid changes to EU average (45%)	-42% renewable electricity	+34% total emissions
Battery recycling from 30% to 70%	+40% material recovery	-22% material impacts

Table 2 presents parameter’s impact on GHG emissions and materials waste.

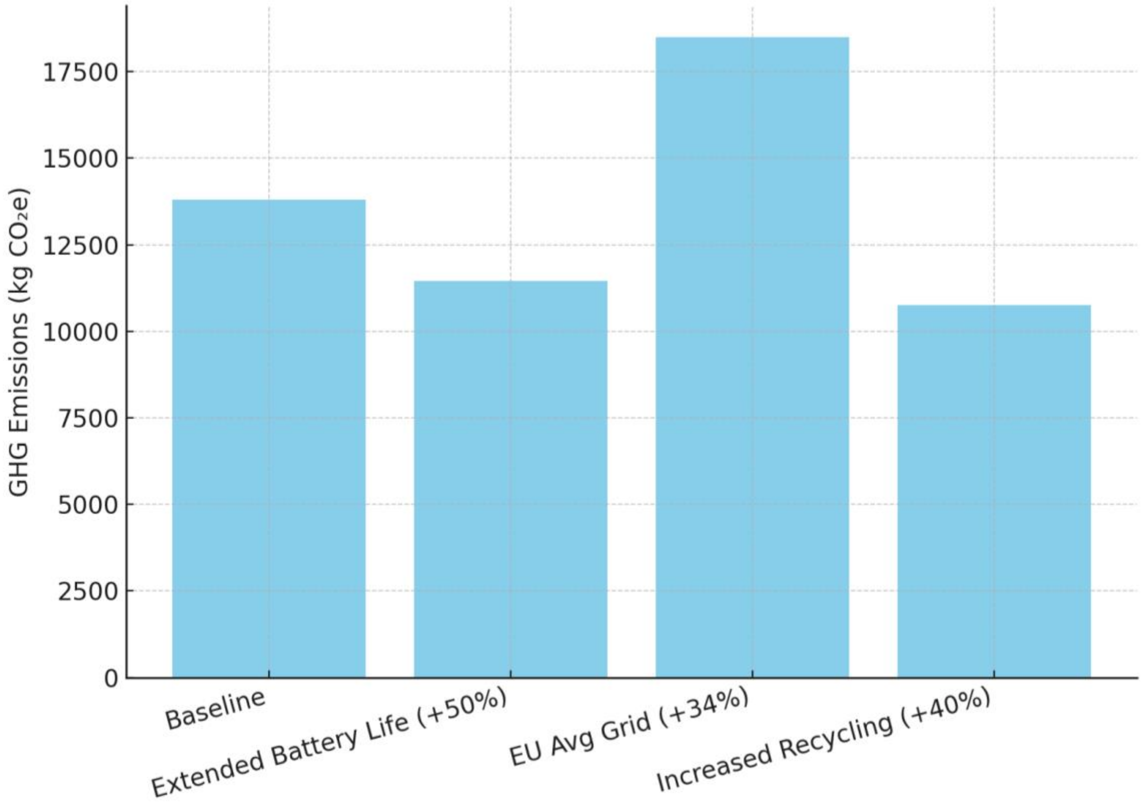


Figure 9. Visual representation of changes impacts on GHG Emissions (Hawkins et al. 2013, Gaines, L. 2014, Ellingsen et al. 2017, VTT 2023, Fortum 2023)

Figure 9 states that battery lifetime and grid mix are the dominant parameters for BEV sustainability. Finland's renewable-rich grid enhances the benefits of electrification, but these advantages would diminish in more fossil-fuel-dependent contexts. The sensitivity analysis demonstrated that battery recycling rates could be increased from the existing 30% to an ambitious, yet feasible 70%. Such improvements significantly decrease the need for virgin raw materials and relieve environmental impacts of mining and processing. In order to achieve higher recycling rates, large investments in recycling infrastructure, logistics and technology would be necessary in Finland, highlighting an important area for policy and industrial innovation.

4.7 Summary of Key Findings

The study reveals that, within the finnish context, battery electric vehicles (BEVs) produce approximately 55–60% less CO_2-equivalent emissions than internal combustion engine vehicles (ICEVs), primarily due to the high operational efficiency of BEVs and the country's low-carbon electricity mix. Despite requiring more energy during the production phase—particularly for battery manufacturing—BEVs exhibit an overall energy demand that is around 15% lower than that of ICEVs across the full lifecycle. However, this environmental advantage comes at the cost of significantly higher material intensity, with BEVs consuming two to three times more critical raw materials such as lithium, cobalt, and nickel. In terms of waste, BEVs generate nearly 49% more non-recyclable material, largely from batteries and electronic components, although improvements in Finnish recycling infrastructure are beginning to address this issue. Ultimately, the environmental benefits of BEVs remain highly dependent on factors such as battery longevity, the carbon intensity of the electricity grid, and the effectiveness of end-of-life recycling systems.

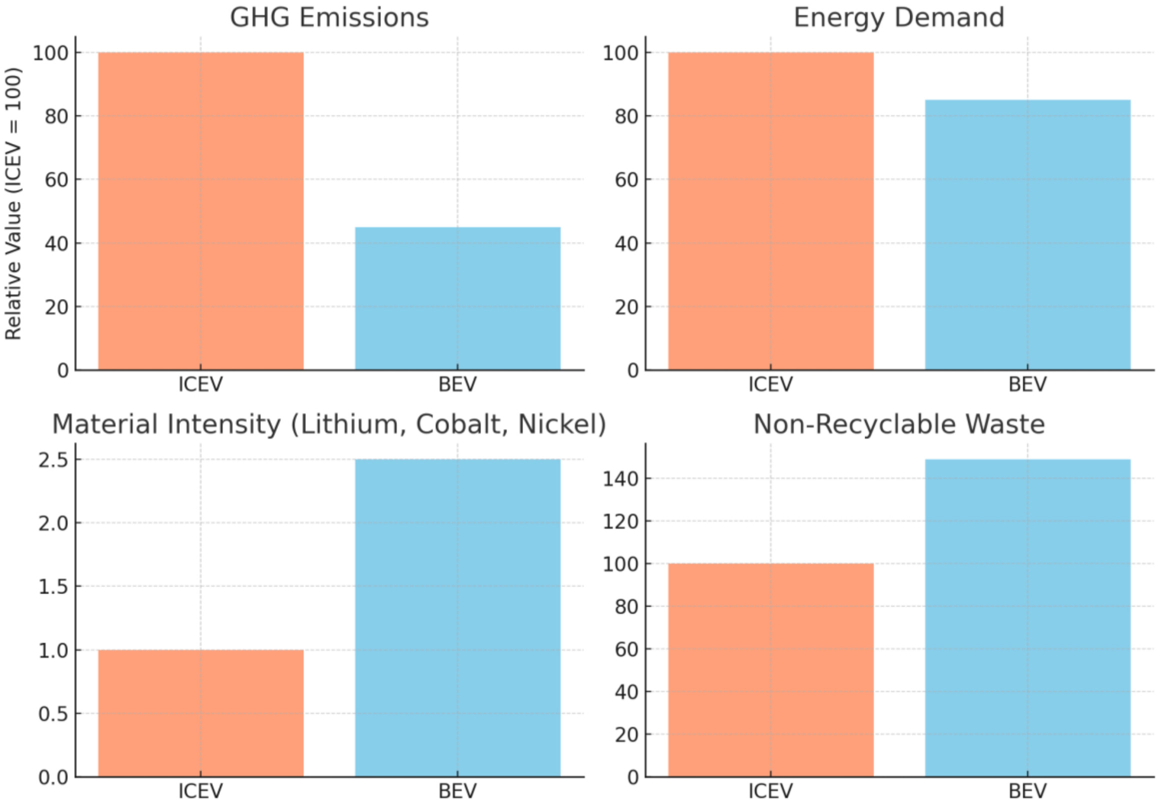


Figure 10. Comparative Environmental Indicators.

Figure 10 represents a more detailed examination of results and indicates significant trade-offs in terms of the environment. Although BEVs save considerable lifecycle emissions, their cumulative energy demand (CED) is only slightly less (-15.4%) than that of ICEVs indicating a comparable high energy demand for battery production. Also BEVs show clear increases in the consumption of CACRs (of about 133%), in particular for lithium, cobalt, and nickel, increasing also the challenges of the environmental and ethical impacts of the extraction and supply chain of CACRs (Harper et al. 2019, 575(7781), 75–86). The 48.9% rise inunrecyclable waste production per BEV with respect to ICEV suggests that recycling technologies and recycling capacity need to be improved (especially for battery-related waste such as batteries themselves) (Fortum, 2023).

Consequently, the results indicate how sustainable BEVs may be in Finland, they are not “free of impact”. To retain this lead, circular material systems, long battery lifetimes and more grid decarbonization are needed.

5 Discussion

5.1 Interpreting the Lifecycle Comparison

The lifecycle comparison assessment of the study gives a clear signal of the significant environmental advantage achieved and present in BEVs compared to ICEVs in terms of GHG emissions and operating energy use especially in the finnish energy system. During a standardized lifetime of 200,000 km, BEVs resulted in about 56% less total CO_2e emissions mainly thanks to low carbon intensity of electricity in Finland (Statistics Finland, 2023). This supports previous literature finding that EVs are the environmentally best in countries where electricity grid is largely decarbonized (Ellingsen, et al. 2017, 12(5), 054010 and Messagie, et al. 2014, 7(3), 1467–1482).

But, the report also showed significant environmental trade-offs. BEVs exhibit much higher demand for important raw materials – most notably lithium, cobalt, and nickel in the context of battery production. The latter, however, are environmentally, ethically and geopolitically unsustainable (Harper et al. 2019, 575(7781), 75–86; Gaines 2014, 1–2, 2–7). ICEVs, however more polluting during use, are fully recyclable with proper recycling routes in place, notably metal (steel, aluminum, platinum group metals in catalytic convertors).

These results emphasize a main difference, namely that in the case of ICEVs, the use phase dominates the environmental impact, while in BEVs, the production and resource extraction phase is decisive. Electrification is not tension free of environmental burdens - it simply moves them up stream in the chain.

5.2 BEVs and the Finnish Electricity Context

Finland’s energy mix has a deep impact on the performance of BEVs relative to one another. In 2022 more than 87% of electricity was produced from renewable or low-carbon sources such as nuclear, hydro, wind and biomass (Statistics Finland, 2023).

More widespread availability of clean energy, e.g., as proposed in various 2030 targets, would further increase the climate advantages of BEV (VTT, 2023) (tuning the share of FF-100% down: 10-15 g CO2/km, depending on grid and vehicle efficiency). In comparison, the same BEV model charged in coal-heavy grid countries could have 3–4 times higher operational emissions, a difference revealed by sensitivity analysis. This regional variability highlights that the environmental impact of BEVs cannot be generalized across regions, not only must it be localized to local infrastructure and grid dynamics, but it may differ even within a region.

5.3 End-of-Life Challenges and Material Circularity

The shift to electrification is creating a new set of sustainability challenges around end-of-life that are different from those of conventional automotive systems and for which the industry lacks effective solutions at scale. The study identified that BEVs can produce up to 49% more waste in the form of non recyclable waste compared to conventional ICEVs because of the complex chemistry and construction of lithium-ion batteries and due to the embedded electronics and composites which are not currently recyclable at large scale.

While promising, the recovery of plastic separators, electrolytes, and degraded lithium fractions is less efficient (Fortum, 2023) and the metals recycling has been the most successful in Finland, where Fortum operates a hydrometallurgical recycling plant with recovery rates up to 95% of metals like cobalt and nickel. The infrastructure for collecting and transporting disused batteries is also fragmented regionally. And wind power, a major part of Finland’s clean electricity supply, also comes with long-term ecological questions of its own. Alongside with battery recycling issues, waste of wind turbine blades forms an urgent problem for the renewable energy systems to be circular and sustainable. Fiberreinforced polymers are the major component of blades, and recycling of these composite materials is a challenging task because of the material heterogeneity and durability. Recent studies have focused on approaches such as pyrolysis, mechanical recycling and cement co-processing as potential alternatives for blade recycling (Beauson & Lilholt 2020, 123, 109768). Nevertheless, their application is impeded by, among other aspects, the high cost, the lack of commercial infrastructure, and the relatively low material recycling efficiencies. The ongoing investment by Finland in wind energy requires a long-term strategy to manage the main waste stream of wind blades. Once blades have reached their end-of-life, which is the fast-growing, difficult to recycle, difficult to incinerate fibreglass composite material and its residual waste products. Cobalt extraction, largely from regions where weak regulation prevails, such as Democratic Republic of Congo, is particularly known for causing extreme labor rights abuse, such as dangerous labor conditions and child labor, and significant environmental harm (Amnesty International, 2021). To address these concerns, Finland and like-minded adopters must set strict sustainability standards and track and trace all purchases to avoid indirect involvement with these global problems.

5.4 Broader Environmental Trade-offs

Beyond the key lifecycle indicators are a number of more general ecological compensation measures in the context of vehicle electrification demanding a more thorough consideration. One of the most significant concerns is the environmental and social toll extracted to mine the lithium, cobalt and nickel that will be needed to satisfy the surging demand for these metals—fundamental ingredients in most of today's battery chemistries. These extraction processes tend to be water- and energy-intensive, and they are also frequently located in areas with poor environmental regulation and limited labor protections (Gaines 2014, 1–2, 2–7; IEA, 2020). In addition, because these materials are increasingly being used, there are also long-term scarcity, price volatility and geopolitical concentration risks that could affect supply chain stability and cost in the automotive industry.

Toxicity, as well as infrastructure preparedness, also arise as important issues. With electric vehicles cutting tailpipe emissions and improving city air, the hazardous elements in part of the battery if mishandled can leach into the ground or seep into waterways if the battery is not disposed of correctly or is left in landfills. Heavy metals and electrolyte outflow are particularly problematic when they are not treated or processed casually. Furthermore, the rate of electrification is currently faster than the expansion of a closed-loop infrastructure chain (extraction of raw materials through end-of-question recycling) that supports it, creating the possibility of such systems leaking into the environment and becoming inefficient if battery management systems are unable to keep pace with market expansion.

5.5 Policy and Design Implications

The results of the study imply that sustainable vehicle electrification in Finland—and consequently in other clean grid economies - cannot be achieved through the transformation of drivetrain technology alone. It must be attached to:

- Stronger producer responsibility legislation: Encouraging vehicle manufacturers to integrate recyclability and battery second-life potential into design from the outset.
- Targeted recycling incentives: Such as subsidies for recycling battery technologies and local infrastructure creation, particularly in remote areas.
- Material substitution research: The idea of replacing high-impact battery chemistries (for example cobalt-free LFP (Lithium Iron Phosphate)) to reduce associated environmental and social burdens.
- Renewable infrastructure circularity: Innovating solutions for the reuse and recycling of wind turbine blades (e.g. pyrolysis, mechanical shredding, cement co-processing).

To enable the long-term integration of BEVs in Finland's vehicular transportation, there is a need for focused policy measures. Policy makers should reinforce the regulations of producer responsibility that require manufacturers to develop end-of-life recycling disposal attitude in product design. Incentives and subsidies may also drive technical hardening and development of battery recycling infrastructure, and can work to move toward higher recovery rates of critical materials closed loop systems (Gaines 2014, 1–2, 2–7). Moreover, research into alternative, less invasive battery chemistries (e.g., cobalt-free lithium iron phosphate) would go a long way to address the environmental and ethical concerns around current battery production.

Also, public policies need to be lifecycle-aware, which means encouraging low-carbon outcomes overall, not only tailpipe emissions reductions. A comprehensive view to BEVs will not transfer environmental problems from air to soil, from urban roads to rural mines.

5.6 Alignment with Previous Research

The findings of this research correspond closely with existing studies in the literature. For example, Ellingsen et al. (2017, 12(5), 054010) and Hawkins et al. (2013, 17(1), 53–64) all indicated that EVs showed better performance than ICEVs for most environmental categories, under the condition of clean electricity. Similarly, Messagie et al. (2014, 7(3), 1467–1482) stressed the importance of vehicle life and regional energy end use to assess comparative sustainability. This data strengthens those findings while incorporating new evidence from Finland’s 2022 energy mix and battery recycling ecosystem.

What this work contributes to the existing literature is a targeted approach to End-of-Life turbine infrastructure is the contribution of this work as well as the practical implications of the realities of battery waste management in a geographically dispersed country such as Finland.

5.7 Limitations of the Study

Although this study is built on highly reliable data sources, such as Ecoinvent, VTT, Fortum, as well as state-of-the art peer-reviewed literature, some limitations should be conceded. A key limitation is the assumption of a fixed electricity grid; the model uses the current electricity grid of Finland and does not consider identified long-term changes such as incorporation of offshore wind power or small modular reactor nuclear technologies. These are likely to have a substantial impact on the environmental ranking of BEVs, and could potentially shift the lifecycle balance even more in favour of these vehicles.

Furthermore, study only considers ICEVs and BEVs, and does not include other new technologies like plug-in hybrids, hydrogen fuel cells and synthetic fuels. These options might introduce other trade-offs with the environment and may change relative results if added. Finally, the representation of waste flows at End-of-Life had to be simplified (i.e., not all vehicle subcomponents and battery chemistries were represented in utmost detail, and the actual recycling rate may vary among manufacturers as well as change over time).

Future studies could include dynamic - LCA models, multi-country comparisons and the use of social LCA indicators such as labour impact and equity of energy access.

6 Conclusion

6.1 Summary of Research Aims and Methods

The objective of this thesis was to perform a pragmatic, life-cycle analysis of environmental effects of the use of internal combustion engine vehicles (ICEVs) and battery electric vehicles (BEVs) in the Finnish context. A comparative lifecycle assessment (LCA) methodology was used guided by ISO 14040/44, with a functional unit based on products with common service life and comparable quality of service, and focused on four priority areas: GHG emissions, energy demand, material resource use and waste at end of life.

The study also conducted sensitivity analyses to understand how key variables — including battery life, the composition of an electricity grid, and recycling efficiency — affect the environmental performance of the vehicles.

6.2 Key Findings

The lifecycle assessment conducted in this study confirms that battery electric vehicles (BEVs) produce significantly lower greenhouse gas emissions over their lifespan compared to internal combustion engine vehicles (ICEVs) when operated in Finland. Specifically, for the defined functional unit of 200,000 kilometers, BEVs emit approximately 56% less CO_2e. In addition to their lower emissions, BEVs also demonstrate greater energy efficiency, with around 15% lower total energy demand, even though the production stage—particularly battery manufacturing—requires more energy than that of ICEVs.

However, these environmental gains come with certain trade-offs. The material intensity of BEVs is substantially higher, in particular for critical raw materials like lithium, cobalt, nickel, copper. The increasing use of these materials brings up not just environmental, but ethical issues with the extractive elements of the global mining industry. In addition, BEVs produce 48% more non-recyclable waste than ICEVs, primarily owing to the complexity of battery packs and electronic systems considering Finland has a relatively developed battery recycling system. Finally, the environmental benefits of BEVs depend on electric mix, recycled rates of battery and the vehicle life as well, which reduce significantly in places with electricity mainly generated from fossil fuels.

6.3 Implications for Sustainability Transitions

The results indicate that road transport electrification in Finland leads to a clear net environmental benefit, but that it is not a panacea. Though BEVs itselfes boast no tailpipe emissions and account for lower overall energy consumption, they transfer much of the environmental load upstream — to raw material extraction and battery production — and downstream to more complicated waste streams.

Achieving a truly sustainable mobility transition will require a comprehensive, system-wide approach. This includes expanding and decentralizing battery recycling capacity, strengthening circular economy legislation, and Enhancing producer responsibility frameworks. Efforts must also be directed towards reducing reliance on environmentally intensive raw materials through advances in battery technology. Additionally, as renewable energy infrastructure continues to scale, the issue of wind turbine blade waste must be proactively addressed. Ultimately, a transportation system can only be considered sustainable if its entire lifecycle—upstream and downstream—is managed with equal care and attention.

6.4 Contribution to Research and Practice

This thesis contributes to both academic literature and practical policy discussions by integrating Finland-specific lifecycle assessment (LCA) modeling with real-world environmental infrastructure considerations. It incorporates performance data drawn from the most recent scientific studies and national energy statistics, ensuring the analysis is grounded in current regional realities. In addition to evaluating battery and wind turbine waste systems, the work engages in a broader discussion of environmental trade-offs—extending beyond climate-related impacts to include material use, waste generation, and system-level Sustainability challenges.

Study provides actionable insights for policymakers, automotive engineers, energy planners, and sustainability professionals who need to make informed decisions in the field of technological and infrastructural developments.

6.5 Limitations and Suggestions for Future Research

Several limitations must be acknowledged:

- The study focused only on ICE and BEV passenger vehicles; expanding to hybrid and fuel-cell technologies could broaden the perspective.
- Only one functional unit and country were modeled.
- Work in the future could involve the comparing of different regions particularly in different grid profiles.
- Social and economic sustainability indicators were not assessed, although these are highly relevant to global EV supply chains and material justice.

Future research interests could be to investigate second-life applications of vehicle batteries, as to how much they can contribute to a reduction of primary material extraction. Furthermore, a detailed consideration of the dynamic evolution of the finnish electricity grid composition, and future technological scenarios would improve the lifecycle sustainability evaluations. In the end, an extension of the research would be a social lifecycle assessment, which would provide insights into labor, ethics, and societal impact at the BEV supply chain level and would enable more holistic and well-informed decision making.

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