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Water Life Cycle Assessment of Cars: a case study of internal combustion engines and battery electric vehicles

Master's thesis in Technology Management and Economics (TEKX08)

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Gothenburg, Sweden 2025
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Abstract

Climate change is intensifying both water shortages and flooding. Stakeholders, investors, and governments are urging companies to implement better water management practices. As the automotive industry shifts toward vehicle electrification, it is essential to understand water consumption throughout the vehicle life cycle. This study reviews water LCA methods, focusing on how they address regional scarcity, measure impacts, and compare data across production stages to support informed decision-making.

This investigation employed a methodology combining systematic literature review with an original water LCA performed via OpenLCA software. Life cycle inventory (LCI) data were secured from a collaborating automotive manufacturer and supplemented with information from the Ecoinvent (versions 3.11 and 3.8) and LCA for Experts databases (for which a temporary educational student licence was employed), published studies, and statistical datasets pertaining to the national-grid electricity mix. The review identified AWARE v1.2 and ReCiPe 2016 Midpoint (H) as the most commonly used freshwater LCA methods. AWARE accounts for water scarcity; ReCiPe does not at the midpoint level. Both methods were applied and compared. The functional unit of this LCA study is defined as provision of a family car capable of driving 200,000 km, with system boundaries covering material production, manufacturing, and use (including maintenance). The geographic scope includes China, the US, UK, Germany, and Sweden. Material production and use phases contributed most to water impacts. Data variability across databases reflects regional water availability, production technologies, and scarcity metrics.

Going forward, more granular and regionally specific data is essential to ensure accurate representation of the life cycle water impact, and meaningful results considering regional water scarcity factors.

Keywords: Water withdrawal, water consumption, water life cycle assessment, internal combustion engine vehicles, battery electric vehicles.

Acknowledgement

We would like to extend our deepest gratitude to Sabrina Altmeyer Mendes and Professor Gregory Peters for their exceptional supervision, valuable guidance, and unwavering encouragement throughout the course of this thesis. Their profound knowledge, critical insight, and continuous support have played a fundamental role in shaping this work, both in substance and direction.

We are also sincerely grateful to the car company supervisor, whose responsiveness and commitment were instrumental in the timely provision of essential data and practical insights. Their collaboration greatly enriched the industrial relevance and applicability of this thesis.

Our appreciation further extends to the Department of Technology Management and Economics at Chalmers University of Technology for providing a stimulating academic environment and access to the necessary resources and facilities. We are thankful to the faculty members and administrative staff for their professionalism and support.

Moreover, we wish to acknowledge our fellow students and colleagues for the engaging discussions, academic camaraderie, and shared experiences that contributed to the depth and quality of this research.

Finally, we are indebted to our families and close friends for their enduring encouragement, patience, and belief in us throughout this academic journey.

Neena Eliza Jose & Prajwal Suresh Patil, Gothenburg, June 2025

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List of abbreviations

BEV	Battery Electric Vehicle
CF	Characterisation Factor
DE	Germany
Eq	Equation
EU 27 + EFT	European Union – 27 countries and European Free Trade Association
EU 28 + EFT	European Union – 28 countries and European Free Trade Association
GLO	Global
ICEV	Internal Combustion Engine Vehicle
LCI	Life Cycle Inventory
LCA	Life Cycle Assessment
LCAfE	Life Cycle Assessment for Experts
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
OEM	Original Equipment Manufacturer
ROW	Rest of the World
UK	United Kingdom
USA	United States of America

1. Introduction

1.1 Background

More than 70% of the earth's surface is water, yet only about 2% of it is drinkable and usable as freshwater (Bras & Fang, 2012). This freshwater is essential for drinking and sanitation, agriculture, energy, industrial use, and conserving ecosystems. Population growth, urbanization, and industrialization are the main factors behind the increased demand for freshwater. Currently, around 3.6 billion people lack adequate water for at least a month in a year, and this figure could reach 4.8 to 5.7 billion by 2050 (Geng et al., 2019). More water sources are being utilized because of this burgeoning population. An acute shortage of water has a significant impact on the health and the quality of life of individuals. This illustrates the need to consider developing a proper water management system with which to devise a strategy for sustainable use of this resource.

Beyond ecological imperatives, corporations are responding to stricter statutory frameworks and investor scrutiny to advance water stewardship. The recently introduced Corporate Sustainability Reporting Directive (CSRD) effectively removes any voluntary oversight, mandating firms to reveal water-related initiatives and attendant risks(European Commission, 2022). Concomitantly, the Carbon Disclosure Project (CDP) has adjusted its scoring methodology, compelling firms to perform documented water governance and robust risk management processes (Carbon Disclosure Project, 2023). The Global Reporting Initiative (GRI) has also updated its water disclosure framework, GRI 303, which now instructs organizations to account for water withdrawals and wastewater exports and imports along the supply chain on a site-specific level (Global Reporting Initiative, 2018). Taken as a constellation, these developments constitute a marked tight on pro forma reporting, with pressing implications for operations located within water-constrained regions.

The Organization for Economic Co-operation and Development (OECD) forecasts that the worldwide appetite for freshwater may surge by as much as 55% by mid-century relative to 2000 levels (Organisation for Economic Co-operation and Development, 2012). Concomitantly, agriculture, the predominant freshwater user, is experiencing a restructuring as its proportionate demand declines relative to the accelerating consumption by industry; this latter expansion is largely prompted by demographic expansion and intensified manufacturing operations.

This change underlines the urgency of implementing sustainable water management strategies, with particular emphasis on the automotive sector. The automotive value chain remains exceptionally vulnerable to resource availability issues, primarily because of its extensive use of metals such as steel, iron, aluminum, and lithium. Concurrently, the sector is undergoing a structural transformation, migrating from

conventional internal combustion engine vehicles to Battery Electric Vehicles. Although widespread BEV deployment has the potential to substantively lower carbon emissions and preserve biodiversity, the production of such vehicles entails a significant water footprint (Kim et al., 2016).

Prospective increases in BEV output, driven by escalating worldwide demand and heightened sustainability mandates, render the prompt and widespread adoption of optimized water management practices imperative(Yang et al., 2023a).

Elevated international climate objectives, coupled with the expansion of battery electric vehicle (BEV) manufacturing, simultaneously heighten the necessity for the adoption of more comprehensive water management approaches within BEV production. Such integrated management, when pursued alongside broader sustainability and efficiency measures, remains essential for safeguarding both industrial and environmental water assets.

1.2. Thesis overview

As highlighted in the previous section, the automotive industry is a significant consumer of freshwater resources, emphasizing the need for comprehensive evaluation and effective management of water use across its entire lifecycle. While numerous studies have extensively addressed environmental impacts such as greenhouse gas emissions and energy consumption, assessments specifically focusing on water usage remain limited, often restricted to manufacturing processes alone. This narrow focus has left crucial aspects of water usage, such as operational activities, indirect water use in supply chains, and vehicle end-of-life management, underexplored and less understood.

Given these knowledge gaps, comprehensive research is essential to broaden the scope of existing assessments, incorporating previously overlooked processes across the full lifecycle of passenger vehicles. Such an inclusive approach is crucial for accurately quantifying water usage and identifying critical stages and processes that significantly affect water impacts. By addressing these gaps, this study aims to provide vital insights for enhancing water sustainability practices within the automotive industry.

1.2.1 Aim

The primary aim of this thesis is to explore opportunities to improve data used for the water life cycle assessment (LCA) within the automotive industry. It seeks to quantify and compare water consumption and the withdrawal across different life cycle stages, evaluate environmental trade-offs, and provide insights into optimizing water

efficiency. Additionally, it aims to identify key levers for improving water efficiency in the supply chain of ICEVs and BEVs.

1.2.2 Research questions

To reach the aim of the thesis, answers have been searched for the following research questions:

1. What are the leading LCA methodologies for life cycle assessment of water use impacts?
2. What are the important stages in the life cycle of ICEVs and BEVs for water use impacts?
3. To what extent do variations in dataset quality influence the accuracy of results in data analysis?

1.2.3 Limitations of the study

Some limitations were encountered while conducting this study:

1. This thesis was based on literature and data from a single car manufacturer. While the aim was to derive generalized insights for ICEVs and BEVs, the results might not have fully represented the variability in impacts across different vehicle models or manufacturers.

2. The thesis relied heavily on generic data sourced from software and databases, with limited availability of regional data for material production, manufacturing, and maintenance stages.

3. Data for the water impacts of electricity supply are only aggregated for certain geographical areas. While these figures served as indicative representations, they did not reflect exact values for entire regions.

4. The end-of-life phase in the life cycle assessment of the car was not considered due to time constraints and limited data availability.

5. Material utilization degree was not treated as a primary factor, as the focus was on identifying closely matched substitutes. Materials such as steel were modelled using closely related alternatives rather than exact matches, due to the use of multiple databases by the car manufacturer. However, data for the vehicle life cycle model was consistently sourced from the Ecoinvent 3.11 database.

6. Time and data constraints significantly affected the study's depth and comprehensiveness. The thesis was completed within a six-month period.

2. Theory

This section introduces the key theoretical foundations of the thesis. It begins by distinguishing between the concepts of water footprint and life cycle assessment (LCA). Following this, it provides an overview of LCA principles, then focuses specifically on water-related life cycle assessment—explaining its terminology and relevance within the automotive industry.

2.1 Quantifying water flows: Water Footprint vs LCA

Two methodologies for assessing water impacts are widely employed: Life Cycle Assessment (LCA) and Water Footprint Assessment (WFA). Although their objectives overlap, each exhibit distinct conceptual and procedural boundaries that merit closer examination.

WFA explicitly categorizes water use according to three volumetric categories: grey water, associated with pollution assimilation; green water, representing uncommitted rainwater; and blue water, encompassing fresh surface and groundwater (Hoekstra et al., 2011). The assessment captures spatial and temporal water availability, reinforcing regional water allocation decisions by processing volumetric accounting alongside annual and site-specific deficits and surpluses (Boulay et al., 2018).

LCA, in contrast, also quantifies water volumes but integrates these data into broader environmental-effect calculations. The methodology, accordingly, interprets water as an indicator with potential consequences for ecosystems and human health rather than as a simple mass balance (Boulay et al., 2018). The AWARE method, for instance, constrains water use assessment to local scarcity and supply relations (Bayart et al., 2010).

2.2 Understanding Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a rigorously structured normative tool employed to quantify the multifaceted environmental consequences pertaining to the entire trajectory of a product, ranging from the extraction of raw materials, through successive phases of fabrication and use, to eventual disposal and resource recovery (International Organization for Standardization, 2006a). The fundamental objective of executing an LCA is to furnish an integrated analysis of the ecological burdens inherent to a product or service, thereby facilitating informed judgments directed toward sustainable development (International Organization for Standardization, 2006c). Figure 1 represents the four interconnected steps of an LCA, which are:

- Goal and Scope Definition: Precisely delineates the extent of the system, articulates the functional unit to which all flows are normalized, and establishes the intended audience and applicability of the study (International Organization for Standardization, 2006a).

- Life Cycle Inventory (LCI) Analysis: Systematically compiles and allocates material, energy, and water inputs, alongside emissions and waste outputs, thereby assembling a balanced material and energy flow account for the defined system (International Organization for Standardization, 2006c).
- Life Cycle Impact Assessment (LCIA): Systematically assigns the quantified inventory flows to environmental-effect categories, converting raw data into comprehensible metrics; the analysis operates either at midpoint (e.g., water-use indicators) or at endpoint (e.g., damage to human health or ecological systems) levels (International Organization for Standardization, 2006a).
- Interpretation: Synthesizes the findings, evaluates the results in light of the defined study goals, and formulates substantiated recommendations to enhance environmental performance (International Organization for Standardization, 2006a).

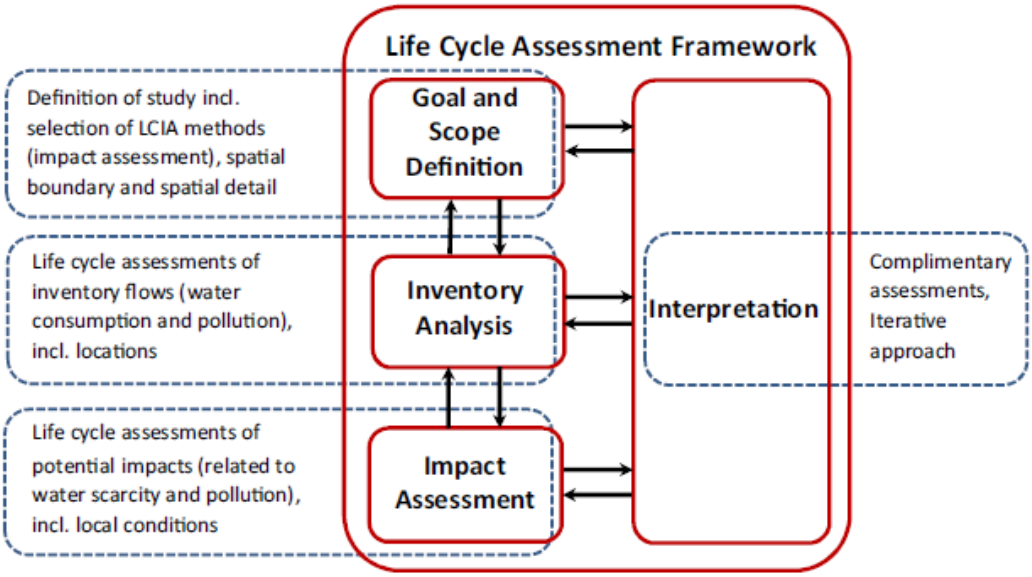

Figure 1: Typical representation of the phases included in the Life Cycle Assessment process

In LCA, the system boundary defines the stages of a product's life cycle that are included in the analysis. Among the most common boundary frameworks are cradle-to-gate and cradle-to-grave, both of which provide distinct insights depending on the study's goals and application.

Cradle-to-Gate

A cradle-to-gate assessment includes all life cycle stages from raw material extraction (cradle) up to the point the product exits the manufacturing facility (gate), ready for distribution. It omits downstream stages such as use, maintenance, and disposal (International Organization for Standardization, 2006a). This boundary condition is particularly suited for analyzing supply chain impacts, comparing material options, or

assessing environmental footprints of intermediate products and components (Curran, 2015).

This approach is often applied in industrial and supplier-level LCAs, where data availability and control over downstream use are limited. For instance, an automotive company may perform a cradle-to-gate analysis to compare the water or carbon footprint of steel versus aluminum used in vehicle bodies.

Cradle-to-Grave

In contrast, a cradle-to-grave LCA spans the full life cycle of a product—from raw material extraction (cradle) to end-of-life disposal or recycling (grave). This comprehensive approach captures impacts during manufacturing, transportation, product use, maintenance, and final disposal or recovery.

Cradle-to-grave assessments are crucial for products where downstream impacts, such as energy use or emissions during the use phase, are substantial. In the context of vehicles, for example, fuel consumption or electricity usage during operation often accounts for a major portion of total environmental impact. Including end-of-life scenarios (e.g., scrapping, recycling, landfilling) further enriches the sustainability analysis.

Utilizing a systematic cause-effect chain modelling approach and quantifying an intermediate effect situated not at the extreme terminal point of the chain, the midpoint indicator within the Life-Cycle Impact Assessment (LCIA) phase translates characterised flows to a potential impact assessment of emissions and resource use. To illustrate, atmospheric releases of carbon dioxide equivalents, which are indicative of potential perturbation to radiative transfer, are routinely employed for quantifying prospective climate change effects. For a more integrated and comprehensive aggregation, endpoint characterisation factors (CFs) reconcile life-cycle inventory (LCI) flows into measurable surrogate variables for defined areas of protection, addressing critical end-point consequences for ecosystems, human health, and resource availability (Sala et al., 2012).

Midpoint and endpoint impact categorization therefore relies on derivation of dedicated characterization factors (CF) detailing linear transformations of inventory flows. The CF effectively translates the flows captured during the inventory phase into interpretable and commensurate environmental consequences (ISO 14044, 2006).

In the domain of water life cycle assessment (LCA), characterization factors take on heightened import owing to the pronounced variability of hydrological impacts across geospatial, temporal, and supply-side parameters. Water-related pressures, in contrast to, for example, radiative-forcing contributions, are intrinsically situated phenomena; their significance is modulated by the particular socio-hydrological context in which extraction or consumption occurs (Boulay et al., 2018). Consequently, the formulation

of water-related characterization factors is routinely augmented by regionally or contextually differentiated parameters, which are designed to capture, among other dimensions, local scarcity indices, hydrological availability metrics, and the sensitivity of affected aquatic and riparian ecosystems.

2.3 Water Life Cycle Assessment (WLCA)

Water Life Cycle Assessment (WLCA) is the application of standard life cycle assessment (LCA) principles to the specific evaluation of water-related impacts over the course of a product's life cycle. Water withdrawal and consumption are systematically measured by WLCA, which takes into account both direct water use and indirect water use related to the production of energy and materials. (Yang et al., 2023a). WLCA thus provides a comprehensive environmental profile of water usage, facilitating the identification of water-intensive processes and enabling targeted interventions for sustainable water management.

2.3.1 WLCA terminologies

In Water Life Cycle Assessment, various terminologies are used to distinguish between different types of water flows considered during an LCA. Understanding these terms is essential for accurate assessment:

- Water withdrawal: “The sum of all water drawn into the boundaries of the undertaking from all sources for any use over the course of the reporting period (European Commission, 2022).
- Water consumption: “The amount of water drawn into the boundaries of the undertaking (or facility) and not discharged back to the water environment or a third party over the course of the reporting period. “Water consumption = water withdrawal – water discharge. Water Consumption is also known as consumptive use of water. Water is consumed due to evaporation or being incorporated into a product. For example, water that is used as an ingredient in a beverage and therefore does not return to the basin is considered consumed”. Water is also considered to be consumed if it is returned to a different catchment or the sea. (European Commission, 2022)
- Water discharge: “The sum of effluents and other water leaving the boundaries of the organization and released to surface water, groundwater, or third parties over the course of the reporting period” (European Commission, 2022).
- Water intensity: “A metric providing the relationship between a volumetric aspect of water and a unit of activity (products, sales, etc.) created” (European Commission, 2022).

Water consumption and withdrawal are both critical aspects of environmental management. Water withdrawal could create a disruption for the ecosystem and biodiversity while the water consumption creates a permanent deletion of water from the water source. (Wada, 2014).

2.3.2 WLCA in the automotive industry

The automotive sector continues to rank among the major freshwater consumers, drawing considerable quantities of water at numerous stages including raw material extraction, primary and sub-component production, vehicle assembly, and throughout the service lifecycle (Kim et al., 2016; Yang et al., 2023a). The nascent shift to battery electric vehicles (BEVs) has intensified scrutiny of water stewardship, as the manufacture of high-density battery cells, alongside the energy required to produce the cells, more than proportionally amasses water demand relative to vehicles powered by internal combustion engines (Noori et al., 2015; Onat et al., 2018).
Past inquiries into the sector's freshwater intensity have narrowly concentrated on the production phase, typically circumscribed to the "cradle-to-gate" boundary, leaving the operational, end-of-life, and out-of-scope supply-chain-related water abstractions largely unexamined (Hoekstra et al., 2011; Semmens & Brasnu, 2013). Consequent investigations now affirm that a circumscribed boundary yields a misleadingly narrow water footprint. Specific findings include:

• Battery and electric powertrain manufacture exhibits water withdrawal and consumption metrics that exceed those encountered in internal combustion vehicle assembly, with the battery pack forming a disproportionate share of the total across life-cycle stages (Wang et al., 2020; Yang et al., 2023a).

• Indirect Water Usage: This water-use footprint, generated primarily through the cooling, extraction, and conversion processes of the electrical supply, is sensitive to the fuel mix supplying the grid, whether primarily intermittent renewables or carbon-intensive coal and gas (Noori et al., 2015; Onat et al., 2018). Hence, a differentiated evaluation of water withdrawal and consumption is mandated to accurately represent the hydrological impact across differing electricity-generation pathways.

• Operational Phase: Modelled lifetime water impacts of light-duty and heavy-duty vehicles previously relegated vehicle maintenance—especially frequent washing in larger, structured fleets—to a secondary importance. Yet empirical studies indicate that the cumulative washing activity, when accounted on a service-mile basis, may contribute water-use fractions that rival impacts from upstream Part manufacture (Kim et al., 2016). The undervaluation of even routine cleaning underscores the necessity for industry models to upscale all indirect and operational-phase water flows to achieve a comprehensive material balance.

Consequently, the battery- and fuel-cell-automotive sectors must adopt a Water Life Cycle Assessment (WLCA) framework encompassing all hydrological flows across the vehicle life-cycle. This entails precise mapping of water consumption in part manufacture, grid electricity generation, routine operational and servicing activities, and end-of-life recycling or landfill processing. By integrating all phases into a unified

model, manufacturers can transparently disclose their net water-use profile, inform prioritization of conservation actions, and credibly communicate progress against global freshwater stewardship goals.

3. Research Methodology

The methodology applied in the study involves tasks aimed at answering the research questions stated in the previous section, 1.2.2 Research Questions.

3.1 Literature review

To answer Research Question 1 — *"What are the leading LCA methodologies for the water impact life cycle assessment?"* — a structured qualitative research approach was adopted, grounded in a comprehensive literature review of scholarly and technical sources. Given the complexity of water use assessment in environmental systems, this methodology aimed to identify and evaluate the most recognized and scientifically robust approaches for quantifying water-related impacts within the LCA framework. This process also laid the groundwork for selecting suitable impact assessment methods for the subsequent modeling of ICEVs and BEVs.

The research was guided by the principles of narrative and comparative review methodology, frequently used in environmental systems analysis to map the evolution of scientific frameworks and evaluate their practical relevance. By focusing on water as an impact category within LCA, the review sought to move beyond inventory-level water accounting and explore how different methodologies frame issues such as water scarcity, consumption, and local stress.

The literature review methodology emphasized a critical review of midpoint and endpoint characterization models — particularly those capable of capturing spatial variability, human health risks, and ecosystem consequences. The review served two roles: (1) to answer the research question directly, and (2) to inform the modeling strategy and method selection used later in the vehicle case study.

3.1.1 Search methodology

The search was conducted using different search engines, including Science Direct, Scopus, Springer, Web of Science, and Google Scholar. Boolean operators and keywords were used, yielding the final database search string presented in Table 1. A From a set of 334 articles 23 articles were identified which gave an idea about different water LCA methods and the way each method evolved from each other. Exclusion criteria included non-English studies, non-relevant studies from thesis point of view like studies on water quality, water contamination, economic impacts,classification of water types, water quality indicators and review articles, which were omitted from the analysis.

Table 1: Literature search string and string result

String Search	Search Result	Excluded	Reason for Exclusion	Included
("life cycle assessment" OR "water footprint" OR "water use impact assessment" OR "vehicle manufacturing water use" OR "freshwater use" OR "globalization of water") AND ("electric vehicles" OR "internal combustion engine vehicles" OR "automotive industry") AND ("scarcity" OR "sustainability")	334	311	The content was excluded because it primarily addressed topics outside the scope of this study, including the economic aspects of water use, polymer contamination, recycled Polylactic Acid , and water use in lithium recycling. It also covered broader themes such as smart city development, water quality indicators, classifications of water types (blue, green, grey), battery management systems, and composite material prototypes	23

The inclusion criteria for the literature search encompassed studies published between the year 2005 and 2024, including reports, journals, standards, conference papers, and textbooks related to life cycle assessment. Studies addressing water LCA, water stress indicators, water consumption, and withdrawal were also considered.

To identify the leading LCA methodologies for assessing water impacts assessment in the vehicle industry, a popularity study was conducted. Therefore, and additional Scopus search was conducted using the keywords “life cycle assessment” AND “vehicles” AND “water”, from where 224 articles were retrieved. Insights from this popularity study guided the selection of methods applied in our water LCA.

3.2 LCA methodology

First, through a literature review, we examined best practices in existing water life cycle assessment (WLCA) methodologies from academic research and standards, addressing Research Question 1. Next, the most suitable methodology was selected based on its ability to measure water consumption, water withdrawal, and water scarcity in alignment with standardized frameworks.

A comparative analysis of existing water life cycle assessment methods was conducted supported by a popularity study. The evaluation criteria included whether the final results are presented as water consumption or water withdrawal (measured in cubic metres), whether regional water scarcity is accounted for, how characterization factors are defined in each method, the availability of each method in OpenLCA, and which midpoint and endpoint indicators are included. The popularity study revealed different water LCA methods in the volumetric and impact assessment categories.

After analysing the leading water LCA methodologies using the criteria as above the research was narrowed down to two methodologies for further analysis. The life cycle assessment was conducted using AWARE 1.2 (Water Use) and ReCiPe 2016 Midpoint (H) (Water Consumption), both of which utilize midpoint indicators.

AWARE 1.2 was selected for its ability to quantify water use in relation to regional water scarcity, as it calculates the remaining available water after accounting for both ecosystem and human needs. ReCiPe 2016 Midpoint (H), on the other hand, was chosen for its capability to assess water consumption without incorporating regional bias.

For performing the research question 2 and to analyze the water intensive stages in the life cycle assessment, data was collected from industry reports, scientific literature, LCA database and a car industry specific data. The functional unit chosen for the LCA is the provision of a family car capable of driving 200,000 km. Two types of LCA are commonly used: attributional and consequential. Attributional LCA describes the environmentally relevant flows within a system, while consequential LCA serves as a decision-support tool to assess the environmental implications of specific decisions (Ekvall & Weidema, 2004). This study adopts an attributional approach. Subsequently after collecting the data, it was analysed, and the research question were answered. Finally, the results of the WLCA of ICE and BEV cars were documented. The analysis results identified the intensive water materials life cycle stage in a car. The project was modelled in Open LCA software by defining the system boundaries across the life cycle stages of a vehicle.

Finally, to answer research question 3, different databases were compared to the literature values to analyze the variation in the data points. Life cycle inventory data was sourced from a car manufacturing company, as well as from the Ecoinvent (3.11 and 3.8) and the LCA for Experts (student educational license) databases, literature

reviews, and statistical sources. Figure 2 shows the step-by-step procedure adapted for completing the thesis through the methodologies.

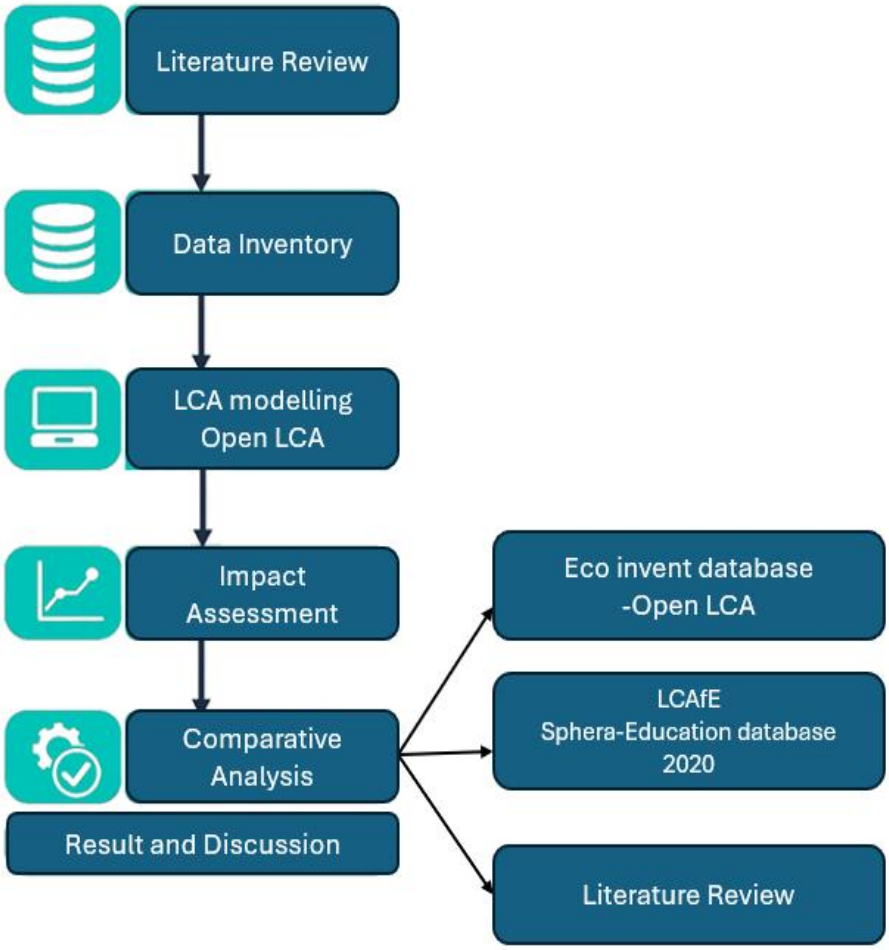

Figure 2: LCA research Process Flowchart

Using comprehensive component-level data and regionally specific water scarcity factors, this LCA aims to assist the authors of this thesis in addressing their research questions and evaluating the overall water consumption and related water stress over the course of a BEV and ICEV life cycle.

The functional unit and the system boundary are included in the life cycle assessment's scope. The provision of a family vehicle with a 200,000 km driving range was selected as the functional unit for the LCA.

As seen in Figure 3, a system boundary was established for average BEV and ICEV with three main life cycle phases: material production, manufacturing, and use phase. Car's system boundary. The vehicle's maintenance is also included in the use phase. Due to data limitations and the insignificant contribution of water use, the end-of-life phase is not included in this analysis.

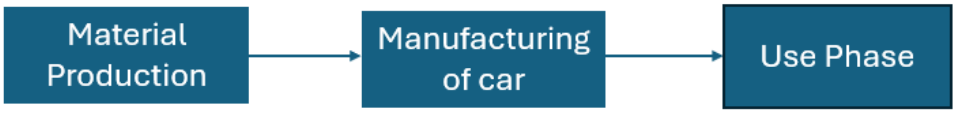

Figure 3: System boundary of the cars

The Life Cycle Inventory (LCI) was developed using a hybrid approach that combines:

- Primary data from the vehicle manufacturer (OEM), including a complete Bill of Materials (BoM) for both vehicle assembly and maintenance scheduling.
- Secondary data from established LCI databases (Ecoinvent v 3.11 and v 3.8, and LCA for Experts (student educational database) to model upstream and downstream water consumption processes.

Each component and material were traced back to its production stage, and relevant unit processes were identified and modelled with regional water intensity and scarcity factors applied wherever possible.

The following section outlines the three main life cycle phases for both BEV and ICEV.

1. Material production

The material production phase was modelled using this BoM (Bill of Materials) provided by the Car OEM and supplemented with data from the Ecoinvent database, forming the foundation for the product system. The BoM includes a comprehensive breakdown of material composition by component—covering structural, mechanical, electrical, and interior elements. This enabled accurate quantification of raw inputs such as steel, aluminium, thermoplastics, copper, glass, and elastomers, each linked to corresponding process datasets in Ecoinvent.

The manufacturing of the BEV required 71 distinct materials, as detailed in the bill of materials (BoM) provided by the automotive manufacturer (Appendix A – Table 9 and Table 10). These materials were classified using the OEM's system and grouped into 11 subcategories based on type and weight contribution Table 11. For the ICEV, 70 materials were categorized into 10 groups using the same classification method, excluding the lithium-ion battery Table 12.

2. Manufacturing

The manufacturing process of the BEV and ICEV requires specific amounts of water and energy, based on data provided by the car manufacturer. Detailed information on water consumption during the manufacturing phase was shared directly by the company, as these figures were available internally. These values were incorporated into the LCA converted results to reflect water consumption accurately. Further details on energy and water consumption are presented in Table 2 below.

Table 2: Specific manufacturing details from car manufacturing company

Specific data for manufacturing phase		
Electricity usage for producing a car	1.678	MWh
Water consumption of a car	1.129	m^3/car

Energy consumption data was collected from six manufacturing plants operated by the car company across China, Sweden, and the United States of America. As most of these facilities run on renewable energy sources, the energy mix used for modelling purposes was assumed to be 50% hydropower and 50% solar power.

3. Use phase

The use phase of BEV is determined based on the primary markets where the vehicle is sold, including China, the USA, Sweden, Germany, and the UK. The average life span of a car is considered to be 15 years or 200 000 km (Hausberger, Lutterbach, & Gschoss, 2024). According to the data provided by the company the vehicle consumes 20.9 kWh of energy per 100 km. Considering a total lifespan of 200 000 km, this results in an overall energy consumption of 41 800 kWh throughout the car's lifetime. The details of the electricity mix in each country are based on the data available from each country. (Germany - Agora Energiewende , n.d.; Swedish energy agency report, 2023; China Energy portal, 2023; UK goverment Energy Statistics, 2023; Institute of energy research, 2023). The details are mentioned in Figure 4 and Appendix A- Table 18

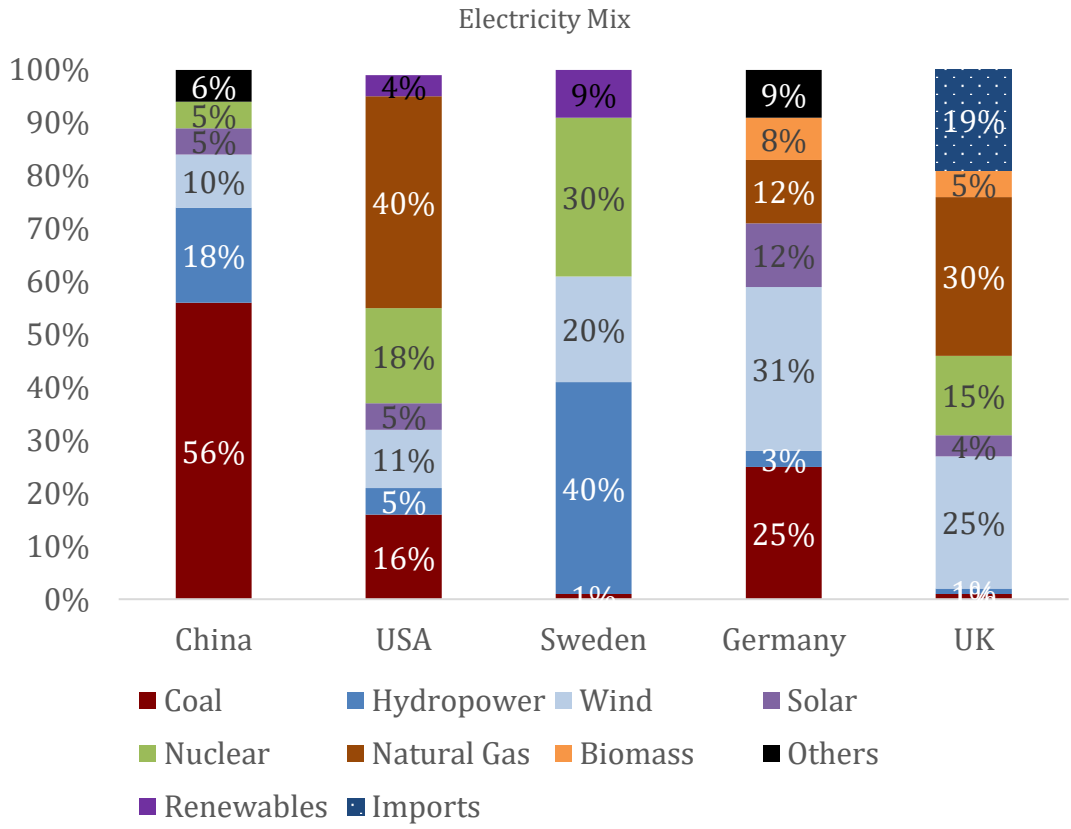

Figure 4: Electricity mix distribution for BEV cars

The use phase was evaluated based on OEM-specified fuel economy figures, modeled over 200,000 km lifetime. Fuel consumption for the ICEV was converted into total liters of gasoline/diesel required and modeled.

a. Maintenance

With regard to the maintenance phase the parts replaced during the lifetime of the BEV during the use phase were obtained from the car manufacturing company and it was modelled in Open LCA as described in Table 3 and Table 4.

Table 3: Parts replaced during the lifetime of BEV

Parts for maintenance for BEV	Quantity
Tyre	16
Wiper blades	39
Brake fluid (litres)	4
12 V batteries	3
Steering joint	1
Link arms	2
Condensers	1
AC fluid	2
Cabin filters	12
Brake pads	20
Brake discs	2
Seatbelt tensioners & idler rollers	2

Maintenance over the vehicle's lifetime was modeled based on a component-specific BoM provided by the OEM for the ICEV, which includes the frequency and quantity of item replacements. Water consumption was calculated for both the production and transport of spare parts and fluids.

Table 4: Parts replaced in ICEV in a lifetime

Parts for maintenance for ICEV	Quantity
Wiper blades	39
Tyres	16
Brake fluid (litres)	4
Brake pads	20
Brake discs	2
12 V batteries	3
Steering joint	1
Link arms	2
Condensers	1
AC fluid	2
Cabin filters	12
Engine oil (litres)	75
Oil filters	15
Automatic transmission oil (litres)	2
Air filters (engine)	3
Fuel filters	1
Spark plugs	12
Camshaft belts	1
Water pump belts	1
Seatbelt tensioners & idler rollers	2
Auxiliary belts	3

After creating a process 3 life cycle phase the product system was modelled in Open LCA with the options described in Table 5 and the environmental impact assessment was performed.

Table 5: Description of Product system modelling:

Options for product system	**Reason**
Auto link processes	To automatically have all upstream processes linked to the reference process.
Prefer default provider	If there are no providers set assigned manually, OpenLCA will consider other default providers to establish connections.
Unit process	To model each phase of the car's life cycle separately and accurately.
Cut-off (No)	As we are considering the material production, manufacturing and use phase. End of life is avoided. We do not consider mass or economic allocation

To address the research question 2, a comprehensive methodological framework was employed that combined quantitative calculations with Life Cycle Assessment (LCA) techniques. The analysis covered both BEV and ICEV, with an emphasis on quantifying water-related impacts across the life cycle. Two widely recognized LCIA methods—ReCiPe 2016 Midpoint (H) and AWARE 1.2 were used to evaluate total water consumption and integrate considerations of regional water scarcity.
A key component of the methodology involved a comparative assessment of 11 material subgroups commonly used in vehicle manufacturing. This comparison focused on calculating water consumption per kilogram of material, enabling the identification and ranking of materials based on their individual water intensity, independent of total weight contribution. This approach provides valuable insight for automotive manufacturers and suppliers seeking to reduce environmental impacts through informed material substitution strategies during the design and production phases.

To address Research Question 3, an in-depth review of relevant databases- Ecoinvent 3.11, Ecoinvent 3.8, Sphera Education license and literature was conducted to explore the variability in reported values. In addition, a sensitivity analysis was performed using the ReCiPe 2016 Midpoint (H) life cycle impact assessment (LCIA) method to evaluate the effect of recycled material content on total water consumption. This analysis focused on BEV manufacturing in China, a key market for the automotive company, and specifically examined the impact of varying recycled content in cast iron and aluminium. Study was carried out to explore how water consumption fluctuates when conventional materials are replaced with reusable alternatives. In this analysis, the overall water usage of China served as the reference point, while the recycled content of aluminium and cast iron was systematically varied. The rationale behind selecting

China as the geographic focus and choosing aluminium and cast iron as the materials lies in the following considerations: China represents a key market for the automotive manufacturer and holds significant potential for the expansion of BEVs. For this analysis, aluminium and cast iron were selected based on the availability of reliable recycled content data within the database. Recycled content information was not consistently available for all materials. Additionally, the respective weights of aluminium and cast iron are documented in relation to the overall weight of an average BEV, allowing for a more accurate assessment of their impact on total water consumption.

4. Results

4.1 Comparative analysis of existing water LCA methods

In most LCA methodologies, midpoint analyses typically focus on water-related indicators such as water consumption, water withdrawal, and water scarcity. Endpoint assessments, on the other hand, are generally used to evaluate the effects of water quality on human health and ecosystems (Kounina et al., 2013). The following leading LCIA methods are widely recognized for assessing water-related impacts, accounting for water consumption, water withdrawal, or both, alongside considerations of water scarcity.

4.1.1. Pfister method (2009)

The Pfister model in life cycle impact assessment on environmental impact of freshwater consumption was developed by Pfister. (Pfister et al., 2009). The water consumption model is based on water stress indices and water scarcity. Water consumption is measured in m^3 (cubic meters) and evaluates the relationship between water withdrawal to availability. This method considers the strong flow regulations as well as the variation in the quantity of water. The following are the main formulas present in the model:

4.1.1.1 Water stress index (WSI):

The WSI is a logistic function of the water withdrawal to availability ratio as shown in Equation 1:

$$WSI = \frac{1}{\left(1+e^{\left(-6.4WTA^{*}*\left(\frac{1}{0.01}-1\right)\right)}\right)} \quad \text{---------- Equation (1)}$$

The Water Stress Index varies from the range between 0.01 to 1, where the high value (one) indicates the most severe water stress area. Water scarcity quantifies at regional

level. Minimal value of 0.01 is set to prevent the zero impact whenever water consumption occurs.

4.1.1.2 Withdrawal to availability ratio:

The WSI is based withdrawal to availability ratio (Equation 2) on a ratio between the sum of freshwater withdrawals (not consumption) for different sectors j (WU) and hydrological availability in the watershed i (WA).

$$\text{Withdrawal to availability (WTA)} = \frac{\sum WU_{ij}}{WA_i} \text{-------Equation (2)}$$

Where, WU_{ij} = Freshwater withdrawals for different sector from i to j and
WA_i = Hydrological availability in watershed i

4.1.1.3 Modified water withdrawal to availability ratio:

This formula in Equation 3 comes into play when the WTA* accounts for the variation in precipitation

$$\text{WTA}^* = \begin{cases} \sqrt{\text{VF}}\ \text{xWTA, for SRF} \\ \text{VFxWTA, for non SRF} \end{cases} \text{----------Equation (3)}$$

VF is the variation factor which differentiates the water storage with strong storage regulation and those without strong water storage regulation. The SRF represents strongly regulated flows. (Pfister et al., 2009)

The Pfister model was integrated to life cycle impact assessment methods like ReCipe 2016 (Huijbregts et al., 2017), IMPACT World+ (Boulay et al., 2014), USEtox. New alternatives for water scarcity like AWARE (Boulay et al., 2018), was also developed on the foundation of (Pfister et al., 2009)work.

4.1.1.4 Variation factor for precipitation

While calculating the precipitation, the entire watershed is divided into grids. Variation factor of a watershed (VF_{ws}) is calculated by mean annual precipitation in grid cell by the formula in Equation 4:

$$\text{VF}_{\text{ws}} = \frac{1}{\sum_1^i \text{Pi}} \text{x} \sum_{i=1}^{n} \text{VFi x} * \text{Pi} \text{----------Equation (4)}$$

where,
VF_i is the variation factor for each grid cell i
P_i is the annual mean precipitation in the grid cell i

The variation factor is calculated based on two types of standard deviation monthly as well as annual precipitation calculated based on the data from the year 1961-1990.

$VF = e\sqrt{\ln(s^*_{month})^2 + \ln(s^*_{year})^2}$ - Equation (5)

Where, s^*_{month} is standard deviation of monthly precipitation
and s^*_{year} is standard deviation of annual precipitation.

The Pfister method has 3 endpoint indicators and they are Human Health- (DALY/m^3 consumed), Ecosystem quality – (PDF.m^2.yr), Resource Depletion – (m^3 deprived /m^3 consumed) (Debarre et al., 2025).

4.1.2 ReCiPe Midpoint H (2016)

The ReCipe model was introduced in 2009 by Mark Huijbregts and Reinout Heijungs in collaboration with National Institute for Public Health and Environment (RIVM)-Pre Consultants, Radboud University and Leiden University. The model was updated in 2016. (Goedkoop et al., n.d.; Huijbregts et al., 2017)

The ReCiPe model calculates the environmental impact in standardized and unified way among different impact categories. It has comprehensive coverage with 17 midpoint indicators and 3 endpoint indicators, and offers global scalability, which allows it to be applied universally rather than being specific to a single location.

The method considers three types of water-related problems: water use, freshwater eutrophication, and freshwater ecotoxicity as midpoint impact categories. It also analyzes three endpoint level : human health damage, resources and ecosystem damage. The characterization factor for water consumed in midpoint is in m^3 (Huijbregts et al., 2017).

It is observed that, to some extent, water consumption is measured in the ReCiPe model. The characterization factor at the midpoint level is ratio of m^3 of water consumed per m^3 of water extracted as mentioned in Equation (6). Water extraction is the water withdrawn from surface and groundwater bodies. The water consumption considers the amount of water the watershed loses on origin.

$$CF_{mid} = \frac{Amount\ of\ water\ consumed\ (m^3)}{Amount\ of\ water\ withdrawn\ (m^3)}$$ ----------Equation (6)

$$CFmid = \begin{cases} 1, & if\ inventory\ is\ in\ m3\ consumed \\ water\ requirement\ ratio, & if\ inventory\ is\ in\ m3\ withdrawn \end{cases}$$--Equation (7)

If the water flow is reported in withdrawn (m^3) then a factor needs to be applied in the water use result or else if the water is reported in consumption (m^3) the midpoint indicator is same as the inventory.

ReCiPe connects the midpoint to endpoint the impact calculations using formulas from (Pfister et al., 2009). The WSI ranges from 0.01-1. The water stress indicators range from high water stress (above 0.8) in areas like Afghanistan (0.89–0.94), Algeria (0.81–0.85), and Azerbaijan (0.91–0.98), to moderate water stress areas with a WSI of 0.4–0.6, such as Myanmar (0.6). Low water stress areas (less than 0.2) include Angola (0.03), Canada (0.1). The formulas adapted in ReCipe Endpoint Calculation for human health are same as the formulas listed in (Pfister et al., 2009) method (Equantios 1 to 5). The endpoint indicators are Human Health - DALYS, Ecosystem quality - species. year, Resource scarcity - USD.

ReCiPe modifies Pfister's method based on the cultural views, different time horizon, uncertain impacts, the way approach have a vision on the nature, society and how well the perspective can be managed.

The Individualistic perspective has cause-effect relations which emphasise short-term effects, consider nature to be robust, and reflects an adaptive management style.

The hierarchist perspective is more tolerant on nature and considers likely effects using a balanced time perspective. It also has a preventive and comprehensive management style with developments within the limits of nature.

In the egalitarian view the precautionary principle is taken into consideration with control and limited management style, by considering all known effects. In this approach all the current and future effects are considered equal. It considers the nature to be vulnerable. (Hofstetter, 1998; De Schryver & others, 2010)

Out of the three perspectives—individualistic, hierarchist, and egalitarian, it is assumed that the hierarchist perspective provides a balanced approach, considering water use, human health, and ecosystem impacts (Huijbregts et al., 2017).

4.1.3 WULCA Aware (2018)

The term WULCA stands for Water Use in Life Cycle Assessment, and AWARE refers to Available Water Remaining. WULCA was founded in 2007 being a part of UNEP-SETAC in the field of Life cycle initiatives. AWARE was a method developed by WULCA in 2017 for assessing the impacts of water scarcity in LCA. This approach primarily considers water consumption and accounts for water scarcity in specific regions. It focuses on determining the quantity of water relative to the available supply in each area, after fulfilling the water demands of ecosystems and human populations. It includes a characterization factor (CF) ranging from 0.1 to 100, which is used to calculate water scarcity. This is a midpoint method specifically applied to water consumption.

Over time, life cycle assessment (LCA) initially relied on the Water Withdrawal-to-Availability (WTA) ratio, typically used in the Pfister model. In this method, water availability was calculated as precipitation minus evapotranspiration, factoring in water quality. Subsequently, the concept of Consumption-to-Availability (CTA) emerged, where water consumption referred to evapotranspiration, water used in products, or water discharged into another sea or basin. The CTA ratio highlighted that water withdrawal, if not returning to the same watershed, might not exacerbate water scarcity, depending on the withdrawal and release points.

The Demand-to-Availability (DTA) approach was then introduced but proved inadequate, as it failed to provide accurate water availability values in units like cubic meters. Finally, the WULCA AWARE method was developed to calculate the midpoint impact score for water consumption, adhering to ISO14046 standards. This score is expressed in cubic meters of world equivalents (m^3 world equivalent).(Boulay et al., 2018)

$$\text{AWARE} = \frac{1}{AMD} = \frac{Area}{Availibility - Demand} \text{(Unit =m}^2\text{.month/m}^3\text{)}\text{---------Equation (8)}$$

Where, AMD is Availability minus demand

Demand is water available after human and ecosystem demand is met

Area is the geographical region/ watershed where the waters-scarcity is considered

$$\text{Characterization factor } (CF_{AWARE}) = \frac{\text{World Average}_{Aware}}{\text{Local Average}_{Aware}}\text{--------Equation (9)}$$

Water Scarcity Calculation = CF_{AWARE}* Water Consumption inventory (m^3)---Equation (10)

An improved version of WULCA AWARE 2.0 will be introduced soon incorporating the updated AWARE factors with more refined and global approach focussing on water scarcity and consumption.

4.1.4 Impact World+ (2019)

Impact World+ is an LCIA method focused on water scarcity with midpoint indicators, and it integrates AWARE method. It was developed in the year 2012 by a group of Canadian researchers and their colleagues. The software was updated in 2019. Computational methods involve calculation of Availability minus demand like in the AWARE method Eq (8) and it considers the presence of regional factors as well

$CF_{IW+i} = CF_{AWARE,\,i} \times f_{regional\ impact}$ ----------Equation (11)

Where, CF_{IW+I} is Impact World + water scarcity characterisation factor
$CF_{AWARE,i\ is}$ Aware scarcity factor for that region
$f_{regional\ impact}$ is the regional impact weighting based on human and ecological water stress. (Impactworld+, n.d.)

Water Scarcity Calculation = CF_{IW+i}* Water Consumption inventory (m^3)---Equation (12)

The result in midpoint level is expressed in m^3 and quantified in the amount of water consumed. Human Health- DALYS, Ecosystem quality - PDF.m^2.yr, Resource scarcity -MJ primary energy or surplus energy are the endpoint indicator (Bulle et al., 2019).

4.1.5 Other water related assessment

This section describes some of the methods that are available in calculating the damage to the water bodies. It includes the water footprint method, Enhanced eco indicator and Ecological scarcity method.

4.1.5.1 Water Footprint

The water footprint assessment method is based on water use and water pollution. It denoted the consumption as well as the degradation of freshwater. They are classified into 3 categories green, blue and grey water. The green component describes about the rainwater consumption, blue component about the surface water and groundwater consumption. The grey water footprint measures the polluted volume of water reaching the water bodies. The grey water pollution also studies about the nutrients, dissolved solids, metals, pesticides. The water footprint method does not consider the non-consumptive portion of water withdrawal (Hoekstra et al., 2011).

4.1.5.2 Enhanced Eco-indicator 99

The method is used to assess the damage to water and to assess the water quality through its endpoint. It is endpoint-oriented method which has 11 main categories and

3 damage areas. The method does not account about the water scarcity and consumption, but it gives impacts of water pollution through aquatic ecotoxicity. The endpoint indicator is human health (DALY) and ecosystem quality (PDF.m^2.yr) Resource depletion (MJ surplus energy) (Dreyer et al., 2003).

4.1.5.3 Ecological scarcity method 2006

The ecological scarcity method incorporates regional water scarcity as a midpoint indicator, quantified using UBP (Umweltbelastungspunkte) or Eco Points. This weighted ecological impact score reflects the severity of water use, with Eco factors ranging from 1 UBP/m^3—indicating minimal environmental burden to values exceeding 1000 UBP/m^3, which represent regions experiencing significant water stress (Hay et al., 2006). The Equation 13 and 14 says about the Ecological scarcity method.

$$\text{Eco Factor} = \frac{\text{Actual use per year}}{\text{Tolerable use per year}} \text{----------Equation (13)}$$

$$\text{Impact} = \text{Inventory flow x Eco Factor----------Equation (14)}$$

4.1.5.4 ReCipe Endpoint E Method:

The ReCiPe Endpoint E is the one of the most precautionary approaches in the LCA method. The E means Egalitarian method it uses a long-time span until 500 years. The method studies all the three damage categories of Human health, Ecosystem quality and resource depletion. It includes more of a cause effect chain. The water quality studies could be studied through this method (Huijbregts et al., 2017)

4.1.5.5 Environmental design of industrial product (EDIP):

It is a LCA method to analyse the water resource depletion and normalised water consumption.

$$\text{Normalised water consumption} = \frac{\text{(Water consumption along lifespan)}}{\text{(product life span)(Global annual per capita water availibility in reference year)}} \text{----Eq (15)}$$

It calculated the results in m^3 of water depletion and it considers water scarcity. (Mir, 2025)

4.1.6 LCI estimation formulae in LCA

This section outlines the details and equations used to estimate LCI data by integrating the parameters directly into the formulas. The data is derived from a literature review of relevant research papers (Bras & Fang, 2017; Yang et al., 2023a).

The first subsection—Cradle-to-Gate Water Footprint via Manual LCA—describes the quantification of water footprint from cradle to gate using manual life cycle calculations. This includes stages such as material production, manufacturing, vehicle assembly, distribution, operation, and end-of-life processes.

The second subsection focuses on the manual calculation of indirect water withdrawal and consumption associated with energy sources.

4.1.6.1 Cradle-to-Gate Water Footprint via Manual LCA (Yang 2023)

While performing the manual calculation, life cycle impact assessment from cradle to gate be quantified with the help of these calculations. In the paper (Yang et al., 2023b) the water withdrawal and water consumption are both reported, and the calculation formulas uniformly noted is represented as "water footprint" (WF). The water withdrawal and water consumption can be reported separately as they have different environmental impacts.

$$WF = \Sigma\, WF_{NCi} + \Sigma_i\, \Sigma j\, WF_{si,j} \text{--Equation (16)}$$

Where WF_{NCi} is the non-combustion water footprint

$WF_{si,j}$ is the WF caused by the energy burning j (L)

a) Production of Materials stage:

$$WF_{NCi} = \Sigma m_k\, WF_{mi,k}$$

$$WF_{Si,j} = \Sigma m_k\, EC_{ji,k}\, EF_j \text{ -- Equation (17)}$$

Where,

M_k is material weight k(t)

$WF_{mi,k}$ is the non burning water footprint related to mass of material k (L/t)

$EC_{ji,k}$ is the consumption of energy j related to material k in the i^{th} stage (MJ/t)

EF_j is the energy water footprint factor of jth item (L/Kj)

b) Manufacturing Parts-Stage:

$$WF_{Si,j} = \Sigma_j EC_{mj}\, EF_j \text{----------Equation (18)}$$

Where,

$EC_{m,j}$ is energy consumption in parts manufacturing (MJ/vehicle)

c) Assembly of Vehicle-Stage

$$WF_{Si,j} = M_V\, \Sigma j\, EC_{a,j}\, EF_j \text{----------Equation (19)}$$

Where, M_V is the vehicle weight (Kg)

$EC_{a,j}$ is energy consumption (MJ/kg)

d) Distribution of Vehicle Stage

$$WF_{Si,j} = D^* M_V * \alpha_{dt}\, EF_j \text{---------Equation (20)}$$

Where, D is the transportation distance (km)

α_{dt} is the coefficient of energy consumption (kJ/kg*km)

e) Operation of Vehicle -stage

$$WF_{Si,j} = VKT^* N * \alpha_{dt}\, EF_j^* \Sigma j\, EC_{u,f}\, EF_f \text{----------Equation (21)}$$

Where, VKT is the annual mileage
N is the service life
F is the fuel type
$EC_{u,f}$ unit of fuel energy consumption (L/km, KWh/km, kg/km)
EF_j is the fuel water footprint factor of jth item (L/Kj)

f) Maintenance of Vehicle-stage

$$WF_{Si,j} = \Sigma_p T_P * WF_p \text{----------Equation (22)}$$

Where, Tp is the number of part replacement
WFp in the part p - water footprint in a placement

g) End of life of Vehicle- stage

$$WF_{Si,j} = (\alpha_m * M_m + \alpha_b * M_b) * \Sigma_j EF_j \text{----------Equation (23)}$$

Where, α_m = consumption of unit energy in end of life (MJ/kg)
α_b = consumption of unit energy in power battery (MJ/kg)
M_m =weight of the body of the vehicle (kg)
M_b = Weight of power battery (kg)

The above equations can be considered for both water consumption and water withdrawal (Yang et al., 2023b). This could be mostly achieved by providing the quantity of water in consumption or withdrawal.

4.1.6.2 Estimating Indirect Water Use from Energy-Based Inputs (Bert Bras 2017)

The studies indicate that direct and indirect water consumption/withdrawal are equally significant due to the presence of electricity, and it could be manually calculated by the following equations:

$$\text{Indirect Withdrawal } (\frac{m3}{year}) = \text{Annual Production } (\frac{vehicles}{year}) * \text{ Electricity Intensity } (\frac{MWh}{vehicle}) * \Sigma \text{ Resource Profile (\%) * Water withdrawal by resource } (\frac{m3}{MWh}) \text{----------Equation(24)}$$

$$\text{Indirect Consumption } (\frac{m3}{year}) = \text{Annual Production } (\frac{vehicles}{year}) * \text{ Electricity Intensity } (\frac{MWh}{vehicle}) * \Sigma \text{ Resource Profile (\%) * Water consumption by resource } (\frac{m3}{MWh}) \text{----------Equation (25)}$$

Where,

- Resource Profile refers to the resource (like solar, wind, nuclear, hydropower energy) from the electricity mix

- Annual Production of vehicles per year
- Electricity intensity is the electricity consumed

4.1.7 Inference

AWARE 1.2 and ReCiPe 2016 Midpoint (H) are among the foremost methodologies in water-related life cycle assessment, recognized for their robust parameters addressing water impacts**.** AWARE 1.2 was chosen in this thesis for its ability to assess water use in the context of regional water scarcity, providing insights based on the remaining water available after meeting both ecosystem and human requirements. In contrast, ReCiPe 2016 Midpoint (H) was selected for its robust evaluation of water consumption on a global scale, offering a standardized measure that does not incorporate regional differentiation.

The leading LCA methodologies were selected and the same is summarized in the as tabulated below in Table 6.

Table 6: Evaluation of leading water LCA methodologies

Researched LCA methods	Final result of the LCA		Consideration of regional water scarcity in mid-point	Midpoint Indicator	Characterization Factor (CF)	Available in Open LCA	Endpoint Indicator
	Water Consumption	Water Withdrawal					
WULCA AWARE Boulay et al (2018)	X		X	Available Water Remaining	(World Average AWARE)/(Local Average AWARE) (0.1-100)	X	No Endpoint
Pfister et al 2009 (Water Scarcity)	X		X	Water stress Index	Water Stress Indicator (WSI) = 0.01-1	X	Human Health- DALYs/m^3 consumed, Ecosystem quality - PDF.m^2.yr,Resource Depletion -m^3 deprived /m^3 consumed
ReCiPe 2016 Midpoint H	X			Water Consumption	CF=1, if water inventory in consumption values and CF as per Equation 7 if inventory in water withdrawal. Only considers water scarcity in endpoint	X	Human Health- DALYs
							Ecosystem quality - species.year, Resource scarcity -USD

Researched LCA methods	Final result of the LCA		Consideration of regional water scarcity in mid-point	Midpoint Indicator	Characterization Factor (CF)	Available in Open LCA	Endpoint Indicator
	Water Consumption	Water Withdrawal					
Ecological scarcity method 2006 (Frischknecht et al. 2006; Frischknecht et al. 2009a)			X	Water Use (UBP)	Eco factor =1 UBP/m³ (low impact) to over 1000 UBP/m³ (highly stressed regions).	X	UBP/Eco Points – Umweltbelastungspunkte- (Weighted ecological impact score)
Enhanced Eco-indicator 99	X			Water Use			Human Health- DALYs*,
							Ecosystem quality - PDF.m^2.yr, Resource scarcity -MJ surplus energy

Researched LCA methods	Final result of the LCA		Consideration of regional water scarcity in mid-point	Midpoint Indicator	Characterization Factor (CF)	Available in Open LCA	Endpoint Indicator
	Water Consumption	Water Withdrawal					
IMPACT World+	X		X	Water Consumption - Aware based	(World Average AWARE)/(Local Average AWARE) (0.1-100)	X	Human Health-DALYs*, Ecosystem quality - PDF.m2.yr, Resource scarcity -MJ primary energy or surplus energy
Water Footprint (Hoekstra A. Y., 2011)				Blue, Green, Grey water footprints		X	No Endpoint

*DALYs - Disability adjusted life years

4.1.8 Popularity study of water LCA methods

A popularity analysis was conducted to identify the most widely adopted water LCA methods. The water related assessments had both volumetric approach (Water consumption) as well as water impact studies (water quality /contamination). Findings indicate a notable increase in the application of water LCA methodologies since 2020. Among the 224 journal articles examined, 21 studies employed the ReCiPe method, with 17 focusing on water consumption and 4 addressing freshwater eutrophication, and freshwater ecotoxicity. This positions ReCiPe as the most frequently utilized water LCA method. In comparison, 11 studies applied the AWARE method, making it the second most popular choice along with the water scarcity factor included. The Figure 5 shows the usage of volumetric based water LCA methods over the years.

The rest of the studies reviewed applied different methods for calculating environmental impacts mostly related to water quality. These studies focussed on other water impacts other than water consumption and scarcity like freshwater ecotoxicity potential, marine ecotoxicity potential, aquatic ecotoxicity, aquatic eutrophication. For example, ReCipe Endpoint E Method was used to assess the effects of water quality, including freshwater eutrophication. Impact World+, UseTox (freshwater ecotoxicity), ILCD (International Reference for Life cycle data) were used for water resource deprivation and freshwater ecotoxicity. Other methods less commonly applied water LCA methods were TRACI (water quality), EDIP (water resource depletion) and Eco Indicator 99-endpoint.

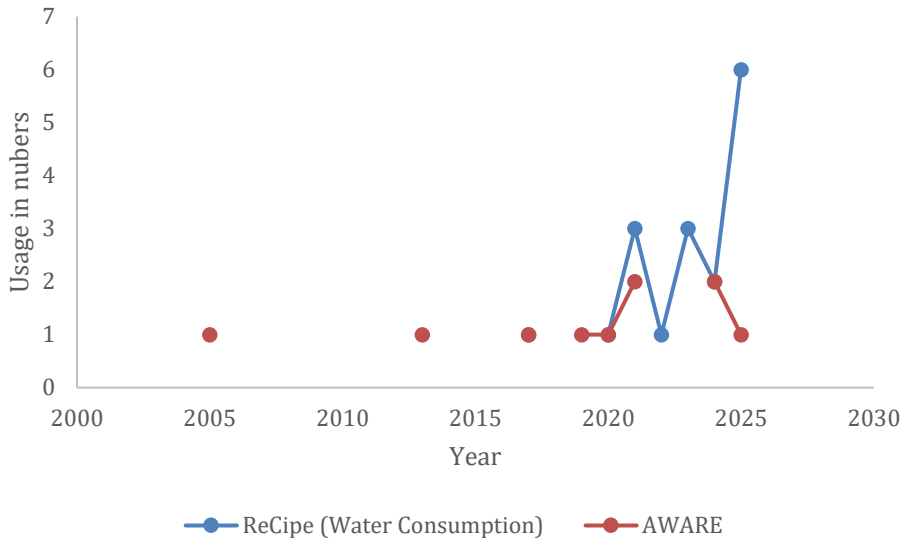

Figure 5: Popularity graph of water LCA methods

4.1.9 Historical relevance

The water impact life cycle assessment has advanced over the last two decades. In 1999 and the early 2000s, the ecological scarcity method, based on Swiss policy and targets, developed a water-based life cycle method. Although it addressed water use, the focus remained on overall use rather than on water consumption or local hydrological conditions. In 2008, the ReCiPe model was introduced, including freshwater ecotoxicity and eutrophication as water-related impacts, but it did not account for freshwater use. In 2009, the Pfister model was introduced, incorporating a consumption-to-availability ratio to represent water scarcity impacts. It marked a shift from withdrawal-based to consumption-based metrics. In 2011, the blue, green, and grey water footprint concept was formulated. This volumetric approach reported total water use, including the blue, green, and grey components of the water footprint. In 2012, the Pfister model was integrated into IMPACT World+, incorporating a water scarcity LCIA framework with endpoint indicators and ecosystem damage. In 2014, the ISO guidance emphasized an impact-oriented water assessment, highlighting the importance of evaluating environmental impacts through scarcity and water deprivation calculations. In 2016, the Pfister model was also integrated into the ReCiPe method, enhancing it with water scarcity impact assessment capabilities. By 2018, the AWARE method was developed to measure marginal water scarcity while accounting for regional differences in available water demand (Mir et al., 2025).

4.1.10 Degree of sophistication

The methods like Eco indicator 99 and Ecological scarcity 2006 had a focus on the volume of water withdrawn without pointing out the consumption volume nor scarcity. Initially LCA used the ratio of water withdrawn to water available where water available is precipitation minus evapotranspiration with water quality. Withdrawal-to-availability (WTA) was used as characterization factors.

As the field evolved, the concept of water consumption came in where water consumed meant evapotranspiration, water used by products, or calculation water being discharged to another sea or basin. Then the Pfister model had the consumption to availability.

Further development came when the CTA - consumption to availability ratio was proposed where water withdrawn but not coming back to same watershed need not worsen water scarcity as it still occur between withdrawal and release points. Meanwhile parallelly the water footprint approach, which is strictly a LCIA assessment method, played a major part in water footprint studies dividing water usage into identification in finding the blue, green and grey water.

The ReCipe 2016 gives an account of the freshwater volume as midpoint indicator and water scarcity is analysed for identifying the damage endpoints. While the ReCipe 2016 doesn’t focus on the water scarcity in the midpoint level and does not give the results

with effect of water scarcity on water consumption. In contrast, the AWARE is one of the most sophisticated method which accounts the available water remaining and the characterisation factors are volume based (Mir et al., 2025).

4.2 Important stages in water LCA for passenger cars (BEV and ICEV)

A comprehensive understanding of critical life cycle stages is very important when considering the water life cycle analysis of cars. According to the data gathered from the literature review the raw material extraction stage (material production stage) for a BEV involves water-intensive processes like mining metals such as lithium and nickel for battery production in electric vehicles (Yang et al., 2023b). For ICEV, a study of three Volkswagen models—Golf, Passat, and Polo—revealed that approximately 95% of total water consumption stems from material production, particularly from iron, steel, aluminum, and various polymers (Berger et al., 2012)

The vehicle manufacturing phase requires substantial amounts of water for activities like painting and fabricating the car's metal body(Yang et al., 2023a). The indirect consumption of water, especially in the production of electricity for manufacturing the materials, has a significant impact on the material manufacturing stage. (Tejada, 2012a). The hydroelectricity increases the water consumption in the total electricity mix. Thus, it is important for the manufacturing companies to reduce the electricity usage in turn to reduce the direct as well as indirect water consumption. In case of manufacturing phase, the indirect water consumption is equal or sometime exceeds the actual direct consumption in automotive manufacturing (Semmens & Brasnu, 2013; Bras & Fang, 2017).

The water consumption is documented to be highest in the use phase of a car where it accounts to 87.5% and followed by the material production and mainly due to extraction of fuel(Bras & Fang, 2012). Energy and fuel production are also water-intensive, especially during the extraction of petroleum products. Producing electric vehicles requires a high amount of electricity to charge the vehicles, and the energy mix plays an important role in water consumption. There is a high usage of indirect water through fuels in both combustion engine cars and electric vehicles.

A calculation was carried out to assess whether car washing during the use phase significantly affects the overall life cycle assessment. Based on the assumptions applied, the resulting estimates for water withdrawal and consumption indicate that the number of car washes can be considered negligible and the details are presented in Appendix A - Table 14.

Regular maintenance activities also involve water for cleaning and parts replacement. The final stage includes recycling and disposal, particularly the recycling of batteries, where water is used effectively (Yang et al., 2023a).

4.3 Water consumption per kilogram of material

To evaluate the water-related impacts of passenger car production, a series of calculations and LCAs were conducted. This section presents the results of those assessments, beginning with an analysis of water consumption per kilogram of material used in both the ICEV and BEV. Leading LCIA methods—ReCiPe 2016 Midpoint (H) and AWARE 1.2—were applied to quantify water consumption and contextualize scarcity impacts.

Figure 6 illustrates the per kilogram comparison of the material used in both ICEVs and BEVs. Among the 11 sub grouped materials natural substances such as cotton and cellulose are the most water-intensive, requiring significant amounts of water for cultivation for the battery electric model. For ICEV natural materials, polymer shows high water consumption. Following these, lithium-ion batteries also demand substantial water consumption in BEVs. The details of the materials with per kg comparison is listed in the Table 13 for BEV and ICEV in appendix A.

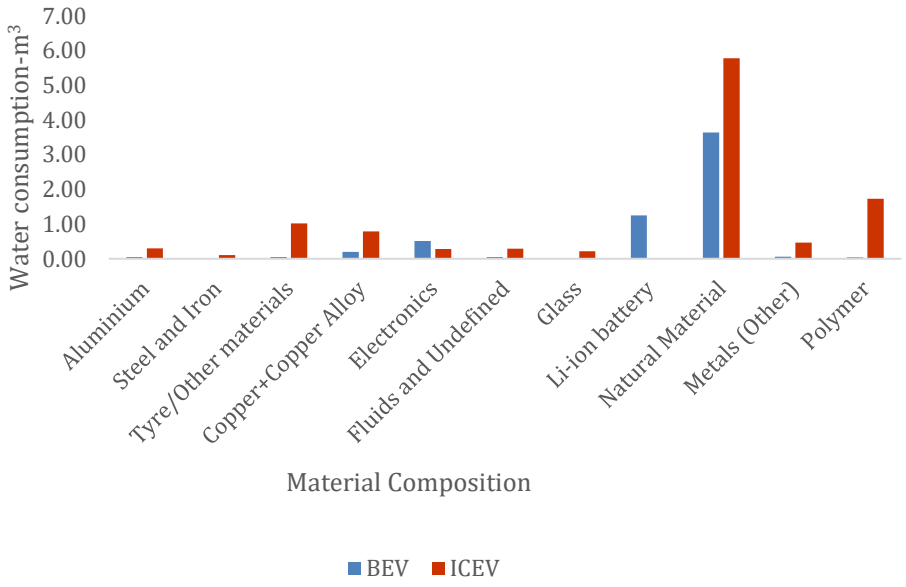

Figure 6: Water consumption of one kilogram of material for both ICEV and BEV car (ReCipe Midpoint H 2016 method)

4.4 Results for water consumption of passenger car

This section presents results the water consumption of an average BEV and ICEV over their life cycles and it evaluates the potential to deprive other users of water, using a regionally sensitive scarcity-weighted score (in m^3 world equivalents). The results are discussed by the life cycle stage and by material category to highlight key contributors and potential opportunities for improvement.

4.4.1 Water consumption for BEV

Water consumption across the three life cycle stages of a BEV was found to be highest in Sweden, with a total of 975 m^3. This elevated figure is primarily due to Sweden's reliance on hydropower, which plays a significant role in its electricity mix. The United States follows with 828 m^3, China with 733 m^3, the United Kingdom with 703 m^3, and Germany with 595 m^3. These values reflect the cumulative water consumption associated with the material production, manufacturing, and use phases of the vehicle life cycle. Details are presented in Appendix-A Table 16 and Figure 7.

Among these stages, the use phase contributes the most to overall water use. This is closely tied to the country's electricity mix, where large-scale hydropower reservoirs result in substantial evaporation losses. These losses are influenced by the size and depth of the reservoirs, as large surface areas tend to increase evaporation, and the evaporated freshwater cannot be replenished. This significantly raises the total water consumption (W. Gerbens-Leenes et al., 2009).

It is important to note that the results are based on the ReCiPe Midpoint H 2016 method, which does not account for regional water scarcity. Therefore, while the model highlights water use impacts, it does not reflect scarcity-related stress. Additionally, vehicle maintenance, which is part of the use phase, is also illustrated separately in Figure 7.

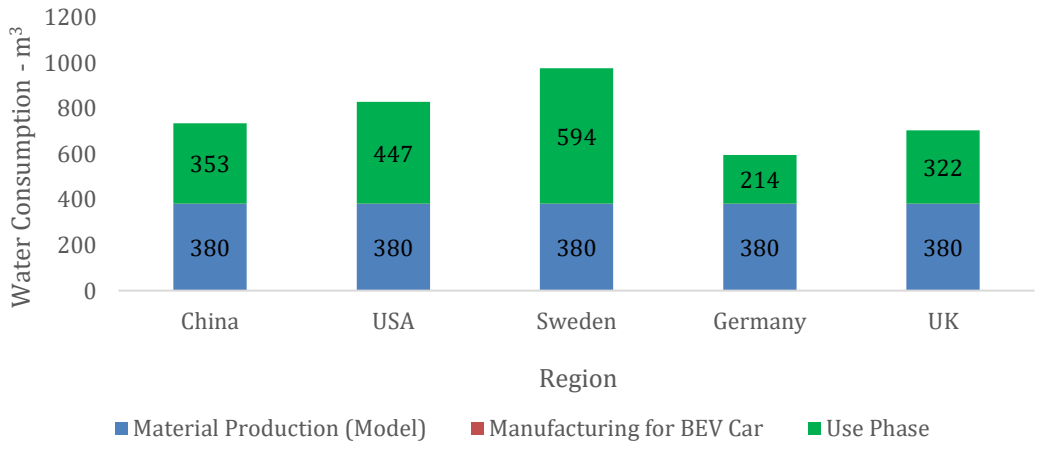

Figure 7: Comparison of total water consumption in the different parts of the world for average BEV car (ReCipe Midpoint H 2016 method)

Water consumption across all three life cycle stages was assessed using AWARE 1.2, a method that accounts for regional water scarcity in its characterization factors. These

factors weigh water use based on local availability and competition, thereby providing a more context-sensitive evaluation of environmental impact.

As a result, countries with higher regional water stress received greater weighting, which significantly influenced the ranking of total water consumption. Under this method, China emerged as the most water-impact-intensive region, with a total water consumption of 44442 m^3 world equivalent, followed by the United Kingdom (20639m^3 world equivalent), the United States (19936 m^3 world equivalent), and Germany (19353 m^3 world equivalent). Sweden, known for its abundant water resources and low water stress, ranked lowest with 18732 m^3 world equivalent.

These figures reflect not just the volume of water withdrawn or evaporated, but also the potential harm associated with using water in areas where it is scarce or highly demanded. The detailed results can be found in Appendix A, Table 17 and are visually represented in Figure 8.

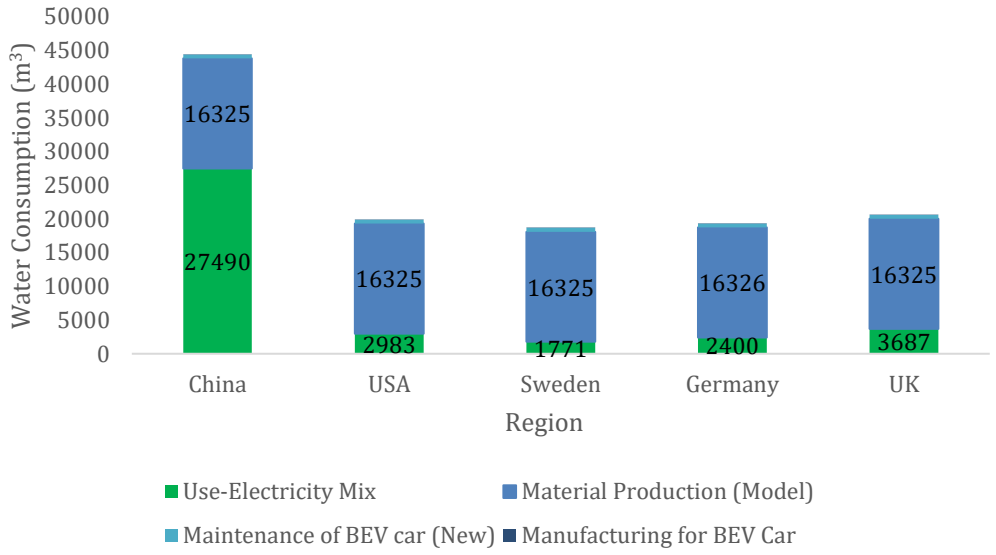

Figure 8: Total water consumption (AWARE 1.2 method with water scarcity factors)

The water consumption of the materials were considered with their respective weight in a BEV and it was found that highest water consumption is in lithium ion battery production followed by aluminium and polymers and the details are listed Table 15 in Appendix A and Figure 9.

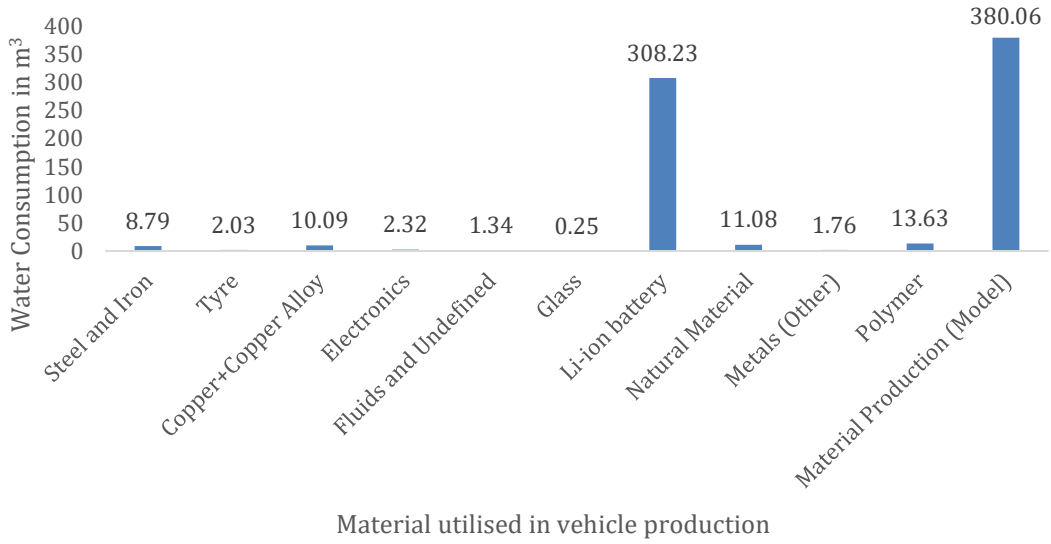

Figure 9: Water consumption pattern of an average BEV based on weight contribution

4.4.2 Water consumption for ICEV

According to the ReCiPe method, the total freshwater consumption impact across all stages of an ICEV is approximately 115 m³. As illustrated Figure 10, the largest contributor is the material production phase, accounting for 48 m³, or 42% of the total. This is followed by the use phase, at 41m³ (36%), and the maintenance phase, at 25 m³ (22%). The manufacturing phase, in contrast, contributes a negligible amount (~1.44×10^{-6} m³), which suggests minimal direct water input during vehicle assembly, though it may also reflect limitations in the granularity of available data.

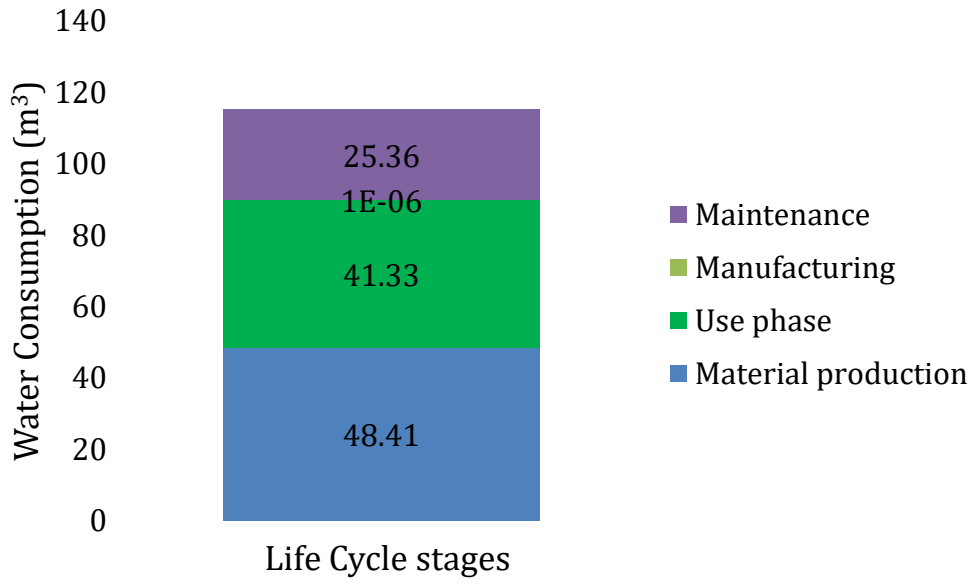

Figure 10: Water consumption of different life cycle phases of ICEV (ReCipe Midpoint H 2016 method)

The high water impact of the material production phase is primarily driven by the inclusion of water-intensive materials such as polymers, aluminium, and steel. These

materials not only require significant amounts of energy during processing but are often produced in regions with water-intensive industrial infrastructure.

Similarly, the use phase contribution stems from fuel extraction, refining, and distribution, especially in petroleum-rich countries where water-intensive oil recovery and refining practices are prevalent. The maintenance phase, though often underestimated, includes repeated replacements of consumables—such as tires, brake fluids, engine oils, and filters—over the 200,000 km lifespan, collectively amounting to a non-trivial water footprint. The manufacturing phase is very negligible compared to other two major phases material production and use phase.

Using the AWARE method, the ICEV's life cycle water impact is quantified as shown in Figure 11 as 4,943.72 m^3 world equivalents, a measure that reflects potential water deprivation due to freshwater consumption in specific regions. AWARE scores emphasize the local water scarcity context and are particularly sensitive to geographic location.
In this analysis, the material production phase again emerges as the most dominant contributor, with an AWARE score of 2,079 m^3 world-eq, constituting 42% of the total. The use phase follows at 1,775 m^3 world-eq (36%), while maintenance contributes 1089m^3 world-eq (22%). As with ReCiPe, manufacturing impacts remain negligible 6.19×10^{-5} m^3 world-eq whole water consumption over a different life cycle stages.

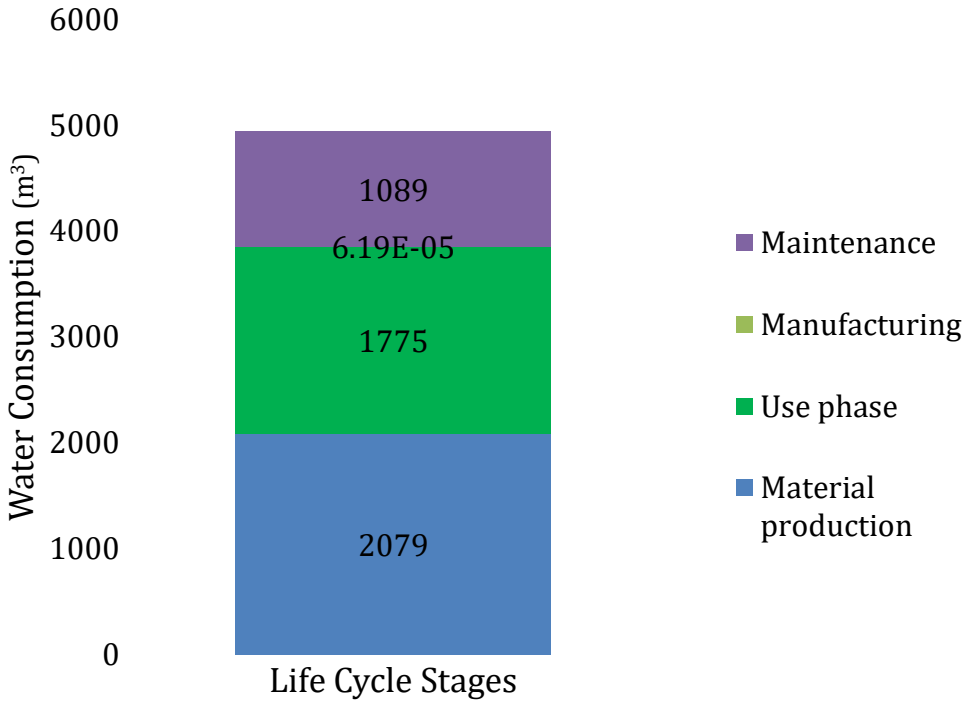

Figure 11: Water Consumption of Different Life Cycle Phases of ICEV (Aware 1.2)

These results reflect that not just how much water is consumed, but where it is consumed, significantly affects the environmental outcome. For example, sourcing

aluminium or petroleum from high water-stress regions such as China, India, or the Middle East increases their AWARE impact despite similar volumetric usage compared to low-stress regions like Sweden or Canada. The total value for the water consumption in the AWARE results are 43 times water consumption results in ReCipe Midpoint H model and this arises due to the fundamental difference between two methods where the regional scarcity characterisation factors are accounted in the AWARE 1.2 LCIA method i.e it provides the impact it makes in the local water stress levels while the recipe calculates the total results in water consumption in absolute terms.

In parallel, a detailed breakdown of water consumption by material group as shown in Figure 12 provides insight into which components within the material production phase drive the most significant impacts

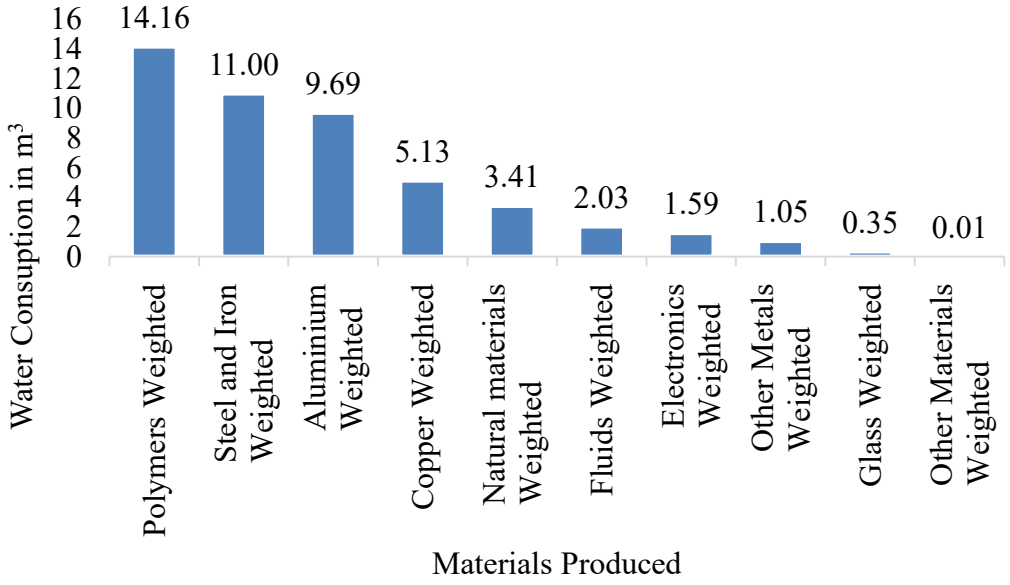

Figure 12: Water consumption for the materials produced for the total aggregated weight for average ICEV

From this, it is evident that polymers are the most water-intensive category, responsible for over 14 m³, despite often being considered lightweight. The prevalence of high-performance polymers and plastic composites in modern vehicle interiors and dashboards, alongside their fossil-derived origins, contributes to their significant water demand.

Steel and iron, while more abundant and often recycled, still contribute 11 m³, and aluminium—frequently used for lightweighting—adds another 10 m³. Notably, even materials used in smaller quantities, such as copper and natural fibres, contribute meaningfully due to high water intensities per kilogram.

4.5 Data set quality variation impact result accuracy

Data variation could affect the quality of the result tremendously. There are many methods in which the data quality could be incomplete or inconsistencies in the data in the environmental results in huge variation in the uncertainty in the whole project (Sheikholeslami & Ebrahimi, 2023). For data quality assessment in LCA, ISO has termed data quality characteristics and there are 10 of them and they are time related, geographical and technological coverage, precision completeness, reproducibility, data source, uncertain information, ability to reproduce and the ability to represent the data (International Organization for Standardization, 2006b). High quality data increases the accuracy of the result and similarly the uncertainty in the data gives the poor results as well (Ciroth & Arvidsson, 2021).

4.5.1 Sensitivity analysis - recycled content - water consumption

The European Commission has imposed strict regulations on reusability, recyclability, and recoverability to improve resource access, achieve environmental targets, and transition toward a circular economy that recovers more valuable materials in a more sustainable manner. The six environmental objectives covered include water protection and the transition to a circular economy. Additionally, the regulations state that their implementation would lead to long-term energy savings during the manufacturing stage and reduce dependency on raw material imports (Urbansky, 2024).

The total water consumption was studied using the Recipe 2016 midpoint H method in China by varying the recycled content and it was found that the cast iron has a negligible impact on the total water consumption, contributing only about 0.01% (or 0.08 m^3) variation across scenarios raising the recycled content from 15 to 30 %. In contrast, aluminium content shows a more noticeable influence. Although the baseline scenario already includes 22% recycled aluminium in 733m^3 of water consumption, increasing the recycled content to 50% results in a 0.95% reduction water consumption over the total life cycle analysed as depicted in Table 7.

These findings highlight that changes in recycled content can meaningfully affect water consumption, particularly in the case of aluminium. Enhancing aluminium recycling emerges as a key strategy for reducing water consumption in BEV manufacturing in China.

Table 7: Total water consumption per average BEV car (m^3) using Ecoinvent 3.11 database (China - BEV)- ReCiPe (2016) – Midpoint H

Baseline -733m^3	Baseline recycled content	Water Consumption-m^3	Percentage change in water consumption	Low recycled content scenario	Water Consumption-m^3	Percentage change in water consumption	High recycled content scenario	Water Consumption -m^3	Percentage change in water consumption
Cast Iron (67kg/ 1974kg)	15%	732.66	0.05%	15%	732.66	0.05%	30%	732.58	0.06%
Aluminium (355kg/ 1974kg)	13%	734	-0.14%	2%	737	-0.55%	50%	726	0.95%

4.5.2 Variation in the data

The water consumption values from Ecoinvent databases (versions 3.8 and 3.11), LCAfE, and various literature sources are shown in Table 8. It highlights that even different versions of the same database can yield significantly different results. Regional differences, data sources, assumptions, and methodological approaches all influence the reported values.

Notably, steel values from the databases generally fall within the broad range reported in the literature, reflecting the variability and complexity in assessing water use across sources. The steel shows a tight cluster between 0.0095-0.0105 m^3 per kg in databases. The literature value of steel has broader range. The broader range possibly might be a result of different production technologies or regional practices. In case of Ecoinvent steel databases it seen that the ROW denotes the area except the RER - average value across the Europe. In case of LCAfE, the steel considered was GLO which indicates average or generalised values across the regions. In case of LCAfE there are specific datasets available for countries like Greece, Hungary, Ireland, India, Italy, Japan Lithuania, Luxembourg, Latvia, Malta, Netherlands, Norway, New Zealand, Poland, Portugal, Romania, Slovenia and Sweden. There is no dataset in LCAfE called as ROW.

In case of aluminium the values vary based on the region across the databases and academic sources provide wide range of information. The results for aluminium have a significant variation. The Ecoinvent database has lower values approximately around 0.045m^3/kg, while LCAfE values ranges from 0.0797 to 0.3049 m^3/Kg, which indicates differences in regions. Possibly, this happens due to the difference in included countries or production process within each dataset. In case of cast iron variation across the database and specific value of water consumption are untraceable in the literature search. While Ecoinvent has consistent values around 0.008m^3/kg while LCAfE reports 0.0002 m^3/kg.

When interpreting the "Rest of World" (ROW) designation, it is important to note that it does not represent the same geographical scope across materials or even across databases. It acts as a residual category, referring to the regions that is not specified in the available national or regional datasets available in the database.

In the case of steel, the Ecoinvent database includes regions such as RER (Rest of Europe) and GLO (Global), so ROW refers to areas excluding these. Conversely, for aluminium, ROW excludes regions like EFTA, EU-27, North America, Africa, Russia, and South America. Therefore, it's essential to verify the geographical scope of ROW before comparing environmental inventory results.

Table 8: Water consumption details of per kilogram materials from different sources

Water consumption (m^3) per kg of material								
	Ecoinvent database-3.11		**Ecoinvent database-3.8**		**LCAfE Sphera-Education database 2020**		**Other sources (e.g. academic paper, industry reports)**	
	Values	**Region**	**Values**	**Region**	**Values**	**Region**	**Values**	**Source**
Steel	0.0104	ROW	0.0105	ROW	0.0095	GLO-World steel	0.002-0.02	(Roy Choudhury, 2017)
Aluminium	0.0436	ROW	0.0465	ROW	0.1205	(EU-28)	0.001-0.137	(Conklin, 1956)
					0.0797	DE		
	0.3002	EU27 + EFT	0.3049	EU27 + EFT	0.1184	EU28+EFT		
Cast Iron	0.0082	ROW	0.0083	ROW	0.0002	DE (automotive open engine)	-	

5. Discussion

5.1 The leading LCA methodology

The evaluation of water consumption, withdrawal and scarcity is crucial in estimating the environmental impacts associated with water use in life cycle assessment. The LCIA methods compared here are Pfister model, ReCiPe H 2016 model, WULCA AWARE model and Impact World+ model, they describe different but interconnected approaches of water consumption and scarcity.

The Pfister model method incorporates several key factors to characterize regional water stress, including the withdrawal-to-availability ratio, hydrological variability, and the availability of storage capacity. These parameters collectively reflect the intensity and vulnerability of water use within a specific region in regional water stress index, withdrawal to availability ratio, hydrological variability, storage capacity. The model is also integrated to ReCipe 2016, IMPACT World+ and has influenced these models. It provides the result in cubic meter of the water consumed in the midpoint level while considering the water withdrawal in the calculation of water withdrawal to availability.

The ReCiPe 2016 framework calculates the characterization factor involving both water withdrawal and water consumption, however the water stress index is calculated towards the endpoint results for analyzing the effect of water stress indicators in the human health and ecosystem damages. ReCipe 2016 explicitly considers the scarcity consideration towards the end point modelling. Midpoint modelling only has globally generalized. Even though it is a balanced approach with global applicability, water scarcity consideration is limited in midpoint level.

The WULCA AWARE method was developed by incorporating the previous concepts and by calculating the Available water remaining (AWARE) after human and ecological demands are met. It means that if the remaining water is scarcer the impact score/characterization factor will be higher. It purely considers the water consumption as the result in cubic metre and focuses strictly on water scarcity with strong regionalized scarcity considerations at midpoint level. There are continuous improvements happening in this field which involves more clarity to the water scarcity measures like AWARE 2.0.

Impact World+ integrates the AWARE method and expands on it with impact pathways of human health and ecosystem services. It gives midpoint results in water consumption however it not only considers the water scarcity but also the presence of regional factors into it.

(Yang et al., 2023a) do not present an LCIA method as such but offer guidance on LCI calculations specifically for cars. Similarly, (Bras & Fang, 2017) provides a method to

determine the role of indirect and direct water consumption/withdrawal through electricity usage.

Based on the goal and scope of the study the LCA practitioner should choose whether the study should indicate the regional stress or absolute quantities in the water consumption results. For LCA practitioners the regional water stress gives an implication about the critical risk that may lead to poor sustainability checks. By modelling the results with LCIA methods with regionalised water scarcity factors. By using these activities, the result could be communicated more transparently as well as effectively.

5.2 Important life cycle phases

It is important to analyze the critical life cycle stages when performing the life cycle assessment of a car. The dominant stages are material production as well as the use stage. Efforts to minimize water consumption should be targeted with the analysis of these hotspots.

5.2.1 Material Production Phase

During the material production stage, natural materials such as cotton exhibited a significant impact on water consumption per kilogram. To improve water efficiency, the use of lightweight and less water-intensive materials—such as flax (Liu et al., 2024) jute (Gonzalez et al., 2023), and modal- a semi synthetic fiber (Lawson et al., 2022) can serve as viable alternatives. These materials could be utilized in interior components like door panels and dashboard hoods, offering a sustainable substitute for cotton.

For BEV, the material production phase results in a water consumption value of 380 m^3 when assessed using the ReCiPe method, whereas the AWARE method estimates a significantly higher impact of 16,325 m^3 world equivalent. Germany and UK shows more material production impact among the total water consumption stages.

In case of ICEV and from the ReCiPe perspective, the material production phase emerges as the largest contributor, accounting for 48m^3, or 41% of the total freshwater consumption. This high impact is predominantly driven by the production of polymers (14m^3), steel (11m^3), and aluminium (10 m^3)—materials that are both widely used in ICEVs and highly are water-intensive due to the energy demand and cooling requirements during their refining and processing. This aligns with earlier findings by (Berger et al., 2012), who reported that material extraction and processing dominate the water footprint in automotive life cycles.

5.2.2 Manufacturing Phase

In case of BEV, the ReCiPe method accounted water consumption as 2 m^3 and for AWARE the water consumption calculated was with 577 m^3 world eq. It accounts to negligible contribution ranging in between 0.1% to 0.3%.

In case of ICEV, while the manufacturing phase contributes only 1.44×10^{-6} m^3 according to the ReCiPe method, the use phase accounts for a significantly share, with 41.33 m^3 or 34.7% of the total water consumption. Although the manufacturing phase contributed 6.19×10^{-5} m^3 world eq. (AWARE)—effectively negligible—this result should be interpreted with caution. The maintenance phase, 1089 m^3 world eq. (20.7%) in AWARE, highlights an often-overlooked aspect of the automotive life cycle.

Water consumption during vehicle assembly operations, such as painting, degreasing, and cooling, is well-documented in industrial case studies (Semmens et al., 2014), but may be underrepresented in global LCI datasets due to data limitations or averaging effects. Further investigation using primary data from manufacturing plants would be valuable for more precise modelling.

5.2.3 Use Phase

In the case of the ReCiPe method applied to BEV, it was observed that Sweden has the highest water consumption. This is primarily due to the significant contribution of hydropower to the country's electricity mix. Large hydropower reservoirs contribute to high evaporation losses, particularly because of their vast surface areas. Since the evaporated freshwater cannot be replenished, this factor plays a major role in total water consumption. Both the size and depth of these reservoirs are critical influences on this outcome. When the surface area is large and the water depth is shallow the evaporation loss of water is higher (P. W. Gerbens-Leenes et al., 2010). On the other hand, this observation was reversed with the AWARE 1.2 results, since water is abundant in Sweden.

A comparison of the water consumption results, based on the AWARE characterization factors, indicates that China ranks highest, while Sweden records the lowest. This contrast may be attributed to factors such as water scarcity in China and greater water availability and the influence of cold climate conditions in Sweden, which are considered in the AWARE assessment in case of BEV cars. The maintenance phase in ICEV is accounted for 25.36 m^3 of water use, representing 21.3% of the total impact according to the ReCiPe method. While individual items such as filters, brake pads, and engine oil may not appear impactful in isolation, their cumulative water demand over the vehicle lifespan is substantial. These results underscore the importance of adopting lifetime-based impact thinking and possibly extending maintenance intervals or using low-impact materials in consumables to reduce their burden.

Under the AWARE methodology, which contextualizes water use within local scarcity factors, the material production phase for ICEV contributes an even greater 2079 m³ world equivalents, or 39.5% of the ICEV's total water scarcity impact. This reinforces the importance of geographic sourcing in material-related decision-making. For instance, sourcing aluminium from water-stressed regions in China or the Middle East amplifies the scarcity footprint significantly compared to sourcing from hydrologically stable areas such as Scandinavia or Canada.

The use phase of ICEV contributes 1775 m³ world eq. (33.8%) in AWARE. These values largely stem from the fossil fuel lifecycle, including crude oil extraction, refining, and combustion. Many of these upstream processes occur in arid regions with high water stress, resulting in elevated AWARE scores despite relatively moderate volumetric water use. This emphasizes the importance of fuel source decarbonization and diversification—for instance, by shifting toward lower-water-intensity energy carriers or integrating more water-efficient refining technologies, as suggested by (Boulay et al., 2018; Onat et al., 2018)

An evaluation of water use associated with routine car washing during the use phase revealed that its contribution to the overall life cycle water consumption is minimal. Based on the assumptions presented in Appendix A – Table 14 , a vehicle washed once per month over a 15-year lifespan results in approximately 1.35 m³ of total water consumption. When compared to the vehicle's total life cycle water footprint of 680 m³, this represents merely 0.19% of the total. Given this negligible share, the car washing can be neglected from the scope of the study.

The combined results from the ReCiPe 2016 and AWARE 1.2 methods consistently underscore the dominance of the Use Phase and Material Production Phase as the primary contributors to the water footprint of ICEVs. This pattern is not only evident in volumetric terms but is further magnified when regional water scarcity is taken into account, confirming insights from prior LCA studies in the transport sector (Pfister et al., 2009; Kim et al., 2016).

An important insight from the material category analysis is that non-metallic components such as polymers and natural fibers can carry surprisingly high water footprints, particularly when biobased sources are used inefficiently. For example, cotton and cellulose-based materials, while often marketed as eco-friendly, can demand upwards of 3.5 m³ for relatively small weight fractions in the vehicle. This opens up opportunities for alternative material exploration, such as switching to modal, jute, or bast fibre composites, which have demonstrated both mechanical viability and lower water impacts in recent research (Gonzalez et al., 2023; Liu et al., 2024).

5.3 Data variation and accuracy

Data variation arises from differences in databases, regional contexts, data collection methods, system boundaries, and modelling assumptions. These discrepancies can significantly influence result interpretation, particularly for water-intensive materials like aluminium, which is highly sensitive to recycled content. Therefore, choosing the most appropriate and up-to-date data source, one that includes relevant geographical and technical details, such as specific processes is crucial for ensuring accurate and meaningful outcomes. Table 8 also shows that across the database there are some similarities as well, but it is necessary to confirm the geographical area before drawing conclusion from the comparative dataset. The transparency and robustness in environmental reporting should be given attention. Overall, the study shows the variability and complexity in assessing the datasets from different processes involved in producing each material, data sources and regions.

6. Conclusion

Understanding water consumption, withdrawal, and scarcity is crucial for assessing environmental impacts. The water LCA methods analyzed—Pfister method (2009), ReCiPe Midpoint H (2016), WULCA AWARE (2018), and Impact World+ (2019)—offer distinct but interconnected approaches for evaluating water use and scarcity. These LCA methods looks into water consumption instead of water withdrawal. For analysing the risk associated with water, planning the future availability of water and for implementing better policy and management for government it is important to distinguishing water withdrawal and water consumption capacities. Among them, WULCA AWARE is the current life cycle impact assessment method for water scarcity and is set to advance with the upcoming WULCA AWARE 2.0 model. The Pfister model has contributed to the development of newer models like ReCiPe 2016. The ReCiPe Method 2016 doesnot consider scarcity factors in the midpoint level however uses the scarcity contribution for calculating the endpoint indicators in human health, ecosystem quality and resource scarcity.

Material production and the use phase are the most dominant life cycle stages in a car's water consumption, serving as critical areas for minimizing water consumption. In both BEV and ICEV cars, the material production and use phases account for more than 70% of the water consumption. Identification of critical stages can enable us to minimise the water consumption and to improve the water efficiency across the life stages of the car. The selection of material also plays a prominent role, for example, using recycled content or alternative materials with lower water use like modal in textiles shows a significant impact in the water consumption figures. Even alternative material selection modal, jute, or fibre composites instead of cellulose and cotton could also reduce the consumption. Additionally, the source of electricity also makes a significant impact. Hydropower is considered to have a high impact on water consumption compared to other electricity sources due to the water losses from evaporation in water reservoirs.

Ultimately, data quality, regional data variability, and the selection of the water LCA method play a crucial role on the data accuracy of results. Variations in data accuracy arise due to differences in databases, regional contexts, data collection methods, system boundaries, and modelling assumptions. These uncertainties highlight the importance of monitoring environmental trade-offs in both water-scarce and water-abundant countries, particularly in relation to aquatic ecosystem health. At the same time, ongoing advancements in water scarcity models offer valuable opportunities to improve strategies for more efficient and sustainable water resource management.

7. Future recommendations

Most of the life cycle assessment studies are primarily focused on carbon dioxide emissions and models. However, there is requirement of better water life cycle impact assessment in the industry. Enhanced regionalized data including finer detailing of water scarcity characterization factors is desirable. Developing a unified framework for regional water scarcity tools would enhance the comparability and consistency of water LCA.

Updating and enhancing the life cycle inventory databases would also be a valuable focus. Water intensive industries and processes—such as textiles, metallurgy and mineral extraction (e.g. lithium), and agriculture—should be better represented in LCA databases. Additionally, including detailed information on recycled content would improve the accuracy of the assessments.

Further research should focus on sustainable alternative materials and on developing effective material substitution strategies. In addition, adopting standardized models across water LCA tools, along with clearer guidelines for interpretating midpoint and endpoint results, would strengthen the comparability of assessments.

Finally, raising awareness among different stakeholders through guidelines, training materials, and improved public access to data would enable more accurate evaluations and informed critiques of products within water life cycle assessment.

8. Bibliography

Bayart, J.-B., Bulle, C., Deschênes, L., Margni, M., Pfister, S., Vince, F., & Koehler, A. (2010). A framework for assessing off-stream freshwater use in LCA. *The International Journal of Life Cycle Assessment*, *15*(5), 439–453. https://doi.org/10.1007/s11367-010-0172-7

Berger, M., Warsen, J., Krinke, S., Bach, V., & Finkbeiner, M. (2012). Water footprint of European cars: Potential impacts of water consumption along automobile life cycles. *Environmental Science & Technology*, *46*(7), 4091–4099. https://doi.org/10.1021/es203459e

Boulay, A.-M., Bare, J., Benini, L., & others. (2018). The WULCA consensus characterization model for water scarcity footprints (AWARE). *International Journal of Life Cycle Assessment*, *23*(2), 368–378. https://doi.org/10.1007/s11367-017-1333-8

Boulay, A.-M., Motoshita, M., Margni, M., & others. (2014). Analysis of water use impact assessment methods (Part A): Evaluation of modeling choices based on a quantitative comparison of scarcity and human health indicators. *International Journal of Life Cycle Assessment*, *20*(1), 139–160. https://doi.org/10.1007/s11367-014-0814-2

Bras, B., & Fang, A. (2012). Quantifying the life cycle water consumption of a passenger vehicle. *Proceedings of SAE World Congress*. https://doi.org/10.4271/2012-01-0646

Bras, B., & Fang, A. (2017). An analysis of indirect water withdrawal and consumption due to electricity and workers in automotive manufacturing facilities. *Journal of Industrial Ecology*, *21*(2), 412–423. https://doi.org/10.1111/jiec.12515

Bulle, C., Margni, M., Patouillard, L., & others. (2019). IMPACT World+: A globally regionalized life cycle impact assessment method. *International Journal of Life Cycle Assessment*, *24*(9), 1653–1674. https://doi.org/10.1007/s11367-019-01583-0

Carbon Disclosure Project. (2023). *CDP scoring methodology 2023*. https://www.cdp.net

Ciroth, A., & Arvidsson, R. (Eds.). (2021). *Life Cycle Inventory Analysis: Methods and Data*. Springer International Publishing. https://doi.org/10.1007/978-3-030-62270-1

Curran, M. A. (2015). *Life cycle assessment student handbook*. Wiley. https://doi.org/10.1002/9781119084181

De Schryver, A. M. & others. (2010). Uncertainties in the application of the species–area relationship for characterisation factors of land occupation in life cycle assessment. *International Journal of Life Cycle Assessment*, *15*(7), 682–691. https://doi.org/10.1007/s11367-010-0209-z

Debarre, L., Motoshita, M., Pfister, S., Boulay, A.-M., & Margni, M. (2025). Assessing the potential human health impacts of freshwater consumption: Considering inequalities in water availability to assess the consequences of domestic water deprivation. *The International Journal of Life Cycle Assessment*, *30*(2), 273–284. https://doi.org/10.1007/s11367-024-02395-7

Dreyer, L. C., Niemann, A. L., & Hauschild, M. Z. (2003). Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-indicator 99. *International*

Journal of Life Cycle Assessment, *8*(4), 191–200. https://doi.org/10.1007/BF02978471

Ekvall, T., & Weidema, B. P. (2004). System boundaries and input data in consequential life cycle inventory analysis. *International Journal of Life Cycle Assessment*, *9*(3), 161–171. https://doi.org/10.1007/BF02994190

European Commission. (2022). *Corporate Sustainability Reporting Directive (CSRD)*.

Geng, Y., Chen, W., Xue, B., Ren, W., Fujita, T., & Xi, F. (2019). Water resources in China: Scarcity and management. *Journal of Cleaner Production*, *207*, 259–272. https://doi.org/10.1016/j.jclepro.2018.09.239

Gerbens-Leenes, P. W., Hoekstra, A. Y., & van der Meer, T. H. (2010). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, *106*(25), 10219–10223. https://doi.org/10.1073/pnas.0812619106

Gerbens-Leenes, W., Hoekstra, A. Y., & Van Der Meer, T. H. (2009). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences*, *106*(25), 10219–10223. https://doi.org/10.1073/pnas.0812619106

Global Reporting Initiative. (2018). *GRI 303: Water and effluents 2018*. https://www.globalreporting.org

Goedkoop, M., Heijungs, R., & Huijbregts, M. (n.d.). *First edition (version 1.08)*.

Gonzalez, V., Lou, X., & Chi, T. (2023). Evaluating Environmental Impact of Natural and Synthetic Fibers: A Life Cycle Assessment Approach. *Sustainability*, *15*(9), 7670. https://doi.org/10.3390/su15097670

Hay, C., Nöthiger-Koch, U., & Schmitt, H. H. (2006). *The Ecological Scarcity Method – Eco-Factors 2006*.

Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). *The water footprint assessment manual: Setting the global standard*. Earthscan. https://doi.org/10.4324/9781849775526

Hofstetter, P. (1998). *Perspectives in life cycle impact assessment: A structured approach to combine models of the technosphere, ecosphere and valuesphere*. Springer. https://doi.org/10.1007/978-94-015-9060-1

Huijbregts, M. A. J., Steinmann, Z. J. N., & others. (2017). ReCiPe2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment*, *22*(2), 138–147. https://doi.org/10.1007/s11367-016-1246-y

International Organization for Standardization. (2006a). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. ISO.

International Organization for Standardization. (2006b). *ISO 14040: Environmental management—Life cycle assessment—Principles and framework*. ISO.

International Organization for Standardization. (2006c). *ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines*. ISO.

Kim, H. C., Wallington, T. J., Arsenault, R., Bae, C., Ahn, S., & Lee, J. (2016). Life cycle water use of Ford Focus gasoline and electric vehicles. *Journal of Industrial Ecology*, *20*(5), 1002–1015. https://doi.org/10.1111/jiec.12376

Kounina, A., Margni, M., Bayart, J.-B., Boulay, A.-M., Berger, M., Bulle, C., Frischknecht, R., Koehler, A., Milà I Canals, L., Motoshita, M., Núñez, M., Peters, G., Pfister, S., Ridoutt, B., Van Zelm, R., Verones, F., & Humbert, S. (2013). Review of methods addressing freshwater use in life cycle inventory and impact assessment. *The International Journal of Life Cycle Assessment*, *18*(3), 707–721. https://doi.org/10.1007/s11367-012-0519-3

Lawson, L., Degenstein, L. M., Bates, B., Chute, W., King, D., & Dolez, P. I. (2022). Cellulose Textiles from Hemp Biomass: Opportunities and Challenges. *Sustainability*, *14*(22), 15337. https://doi.org/10.3390/su142215337

Liu, Y., Lask, J., Kupfer, R., Gude, M., & Feldner, A. (2024). A Comparative Life Cycle Assessment of a New Cellulose-Based Composite and Glass Fibre Reinforced Composites. *Journal of Polymers and the Environment*, *32*(5), 2207–2220. https://doi.org/10.1007/s10924-023-03059-7

Mir, B. A., Nurdiawati, A., & Al-Ghamdi, S. G. (2025). Assessing the environmental impact of freshwater use in LCA: Established practices and current methods. *Environmental Science: Water Research & Technology*, *11*(2), 196–221. https://doi.org/10.1039/D4EW00641K

Noori, M., Tatari, O., & Rahman, S. (2015). Water and greenhouse gas footprints of electric vehicles in the United States. *Energy*, *89*, 448–461. https://doi.org/10.1016/j.energy.2015.05.140

Onat, N. C., Kucukvar, M., & Tatari, O. (2018). Uncertainty-embedded dynamic life cycle sustainability assessment framework: An application to the U.S. automotive industry. *The International Journal of Life Cycle Assessment*, *23*(10), 2055–2072. https://doi.org/10.1007/s11367-017-1380-1

Organisation for Economic Co-operation and Development. (2012). *Environmental outlook to 2050: The consequences of inaction*. OECD Publishing. https://doi.org/10.1787/9789264122246-en

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the environmental impacts of freshwater consumption in LCA. *Environmental Science & Technology*, *43*(11), 4098–4104. https://doi.org/10.1021/es802423e

Sala, S., Fawer, M., Benini, L., Manfredi, S., & Pant, R. (2012). Methodology for building LCA midpoint to endpoint impact assessment methods. *The International Journal of Life Cycle Assessment*, *17*(5), 555–573. https://doi.org/10.1007/s11367-012-0395-3

Semmens, J., Bras, B., & Guldberg, T. (2014). Vehicle manufacturing water use and consumption: An analysis based on data in automotive manufacturers' sustainability reports. *The International Journal of Life Cycle Assessment*, *19*(1), 246–256. https://doi.org/10.1007/s11367-013-0612-2

Semmens, M., & Brasnu, E. (2013). *Water use in vehicle manufacturing: An analysis of direct and indirect water consumption in automotive production* (Nos. 2013-01–1272). SAE International. https://doi.org/10.4271/2013-01-1272

Sheikholeslami, Z., & Ebrahimi, M. (2023). The uncertainty analysis of life cycle assessment for water and waste water system: Review of literature. *Alexandria Engineering Journal*, *73*, 131–143. https://doi.org/10.1016/j.aej.2023.04.039

Wang, M., Sun, P., Zhao, H., & Wei, W. (2020). Life cycle water use of lithium-ion batteries for electric vehicles in China. *Resources, Conservation and Recycling*, *162*, 105011. https://doi.org/10.1016/j.resconrec.2020.105011

Yang, Y., Yu, Y., Zhang, J., & Li, X. (2023a). Life cycle water footprint of electric and internal combustion engine vehicles in China. *Journal of Cleaner Production*, *412*, 137316. https://doi.org/10.1016/j.jclepro.2023.137316

Yang, Y., Yu, Y., Zhang, J., & Li, X. (2023b). Water footprint of lithium-ion batteries: A life cycle assessment perspective. *Resources, Conservation and Recycling*, *189*, 106692. https://doi.org/10.1016/j.resconrec.2023.106692

Appendix-A

Table 9: Weight of materials in an average BEV car

Materials	Material Weight (Kg)
ABS	4.54
Aluminium	356.75
Anode	82.85
Aramid	0.43
ASA	0.41
Brake fluid	0.65
Cast iron	67.01
Catalytic coating	0.03
Cathode	112.69
Ceramic	0.12
Copper	48.28
Copper alloys	2.79
Cotton	2.01
Damper	12
E/P	63.77
Elastomer	2.74
Electrolyte	47.42
Electronics	4.43
EPDM	17.04
EVAC	0.8
Ferrite magnet	5
Float glass	31.1
Friction	1.27
GF-Fibre	2.35
Glycol	7.15
Lead, battery	14.19
Lubricants	2.87
Magnesium	3.48
NdFeB	2.54
NR	2.49
PA	34.1
PBT	7.41
PC	20.52
PC+ABS	8.59
PE	7.47
PET	14.88
PMMA	1.3
Polyester	4.36
Polyurethane	28.89
POM	3.23

PP	53.88
PVC	9.57
R-1234yf	0.73
SBR	1.12
Separator, Li battery	3.24
Silicone rubber	1.94
Steel, Sintered	1.68
Steel, Stainless, Austenitic	3.23
Steel, Stainless, Ferritic	0.85
Steel, Unalloyed	768.05
Sulphuric acid	4.66
Thermoplastic elastomers	6.23
Thermoplastics	13.6
Tyre	40.36
Undefined	31.1
Washer fluid	9.65
Wood (paper, cellulose ...)	1.03
Zinc	3.25
Grand Total	**1974.45**

Table 10: Weight of materials in an average ICEV car

Material	**Material Weight (Kg)**
ABS	4.72
Aluminium	241.52
Aramid	0.17
ASA	0.43
Brake fluid	0.65
Cast iron	86.65
Catalytic coating	0.34
Ceramic	0.02
Copper	24.06
Copper alloys	2.70
Cotton	0.57
Damper	13.80
E/P	68.38
Elastomer	13.72
Electronics	5.64
EPDM	21.76
EVAC	0.71
Ferrite magnet	3.14
Float glass	41.90
Friction	0.90

GF-Fibre	2.96
Glycol	3.48
Lead, battery	18.52
Leather	3.54
Lubricants	15.53
Magnesium	0.93
NdFeB	0.42
NR	2.32
PA	36.92
PBT	5.71
PC	7.96
PC+ABS	9.15
PE	4.10
PET	13.32
Petrol	37.42
PMMA	1.40
Polyester	1.08
Polyurethane (matcat)	24.17
POM	3.89
PP	58.95
PVB	0.97
PVC	9.00
R-134a	0.54
SBR	0.09
Silicone rubber	0.49
Steel, Sintered	4.64
Steel, Stainless, Austenitic	16.01
Steel, Stainless, Ferritic	22.51
Steel, Unalloyed	884.92
Sulphuric acid	5.15
Thermoplastic elastomers	6.53
Thermoplastics	15.59
Tyre	42.31
Undefined	13.60
Washer fluid	5.53
Wood (paper, cellulose ...)	1.29
Zinc	2.39
Grand Total	**1805.31**

Table 11: Material classification

Material name	Material Classification
Aluminium (matcat)	Aluminium
Copper	Copper
Copper alloys	Copper
ceramic	Electronics
Electronics	Electronics
Brake fluid	Fluids and Undefined
Glycol	Fluids and Undefined
Lubricants (matcat)	Fluids and Undefined
R-1234yf	Fluids and Undefined
Sulphuric acid	Fluids and Undefined
Washer fluid	Fluids and Undefined
Catalytic coating	Glass
Float glass	Glass
GF-Fibre	Glass
Electrolyte	Li-ion battery
Separator, Li battery	Li-ion battery
Anode	Li-ion battery
Cathode	Li-ion battery
Cotton	Natural Materials
Wood (paper, cellulose ...)	Natural Materials
Ferrite magnet	Other Metals
Lead, battery	Other Metals
Magnesium	Other Metals
Friction	Other Metals
NdFeB	Other Metals
Zinc	Other Metals
Elastomer	Polymers
EPDM	Polymers
NR	Polymers
SBR	Polymers
Silicone rubber	Polymers
Undefined	Polymers
Polyurethane (matcat)	Polymers
Aramid	Polymers
Polyester	Polymers
Damper	Polymers
Thermoplastic elastomers (matcat)	Polymers
Thermoplastics (matcat)	Polymers
ABS	Polymers
E/P	Polymers
EVAC	Polymers
PA	Polymers

PBT	Polymers
PC	Polymers
PC+ABS	Polymers
PE	Polymers
PET	Polymers
POM	Polymers
PP	Polymers
PVC	Polymers
PMMA	Polymers
ASA	Polymers
Cast iron (matcat)	Steel and Iron
Steel, Stainless, Austenitic	Steel and Iron
Steel, Stainless, Ferritic	Steel and Iron
Steel, Sintered	Steel and Iron
Steel, Unalloyed	Steel and Iron
Tyre	Tyres

Table 12: Material Composition of material and description from database

Materials	**Material composition**	**Description from database**	**Percentage**	**Provider**	**Geography**
Aluminium	Aluminium	Aluminium (primary, ingot)	2%	CA	Canada
		Aluminium (primary, ingot)	4%	CN	China
		Recycled Content-treatment of aluminium scrap, post-consumer, prepared for recycling, at remelter	22%	Glo	Global
		Unknown primary source	72%	Glo	Global
Brake Fluid	Cabin	Market For diethylene glycol		Glo	Global
Cast Iron	Cast Iron	Cast Iron production		RER	Rest of Europe
Ceramic / glass (unspecified)	Catalytic coating	Market for platinum group metal concentrate		ZA	South Africa

Materials	Material composition	Description from database	Percentage	Provider	Geography
	Ceramic	Market for printed wiring board, for power supply unit, desktop computer, PB		GLO	Global
	Ferrite magnet	Market for ferrite		GLO	Global
	Float glass	Coat, Flat glass		ROW	Rest Of the World
	GF-Fibre	Market for glass fibre		GLO	Global
Coolant	Glycol	Market for ethylene glycol		ROW	Rest Of the World
Copper	Copper	Copper Cathode		GLO	Global
Copper Alloys	Brass	Market for Brass	49%	ROW	Rest Of the World
	Bronze	Market for Bronze	33%	GLO	Global
	Nickel	Market for Nickel	5%	GLO	Global
	Copper	Market for Copper	14%	GLO	Global
Elastomer	Elastomer	Tube Installation for Elastomer		DE	Germany
	EPDM	Synthetic rubber		GLO	Global
	NR	Synthetic rubber		GLO	Global
	SBR	Synthetic rubber		GLO	Global
	Silicone rubber	Synthetic rubber		RER	Rest of Europe
Electronics	Electronics	Market for printed wiring board, for power supply unit, desktop computer, PB		GLO	Global
Stainless Steel	Steel, Stainless, Ferrite	Market for steel low alloyed		GLO	Global

Materials	Material composition	Description from database	Percentage	Provider	Geography
	Steel, Stainless, Austenitic	steel production, chromium steel 18/8, hot rolled			RER
Lead, battery	Lead, battery	battery production, lead acid, rechargeable, stationary		ROW	Rest Of the World
Magnesium	Magnesium	Pidgeon process		CN	China
Modified organic natural materials (unspecified)	Cotton	Market for textile, woven cotton		Glo	Global
	Wood (Cellulose, paper)	Market for cellulose		ROW	Rest Of the World
Other fuels and auxiliary means (unspecified)	Electrolyte	Market for dimethyl carbonate	7%	GLO	Global
		Market for ethylene carbonate	80%	GLO	Global
		Market for lithium hexafluorophosphate	13%	GLO	Global
Li-ion battery	Separator, Li battery	Battery Separator		GLO	Global
	Undefined	Market for nylon 6		ROW	Rest Of the World
Other materials and material compounds (unspecified)	Anode			CN	China
	Cathode	Market for cathode, NMC111; for Liion battery		CN	China
	Friction	Market for cast iron	48%	GLO	Global
		Market for zirconium oxide	12%	GLO	Global
		Market for graphite	11%	GLO	Global
		Market for barium sulfide	1%	GLO	Global
		Market for barite	7%	GLO	Global

Materials	Material composition	Description from database	Percentage	Provider	Geography
		Market for aluminium hydroxide	5%	GLO	Global
		Market for magnesium oxide	4%	GLO	Global
		Market for expanded vermiculite	2%	GLO	Global
		Calcined petroleum coke	2%	CN	China
Polyurethane (unspecified)	Polyurethane (matcat)	Market for polyurethane		ROW	Rest Of the World
Refrigerant	R1234 YF	Tetrafluroethane R134a		GLO	Global
Special Metals	NdFeB	Market for permanent magnet, electric passenger car motor		GLO	Global
Steel Sinterted	Hot Steel Sintered	Market for steel unalloyed		GLO	Global
		Market for steel production		GLO	Global
Textiles	Aramid	Terephthalic Acid (TPA)	50%	GLO	Global
		1,4-Phenylenediamine (PPD)	50%	GLO	Global
Thermoplastic elastomer	Polyester	Market For polyester		GLO	Global
Thermoplastic	Polyprolyene, granulate	Market for Polyprolyene, granualte		GLO	Global
Polymer	ABS	Market for acrylonitrile-butadiene-styrene copolymer		GLO	Global

Materials	Material composition	Description from database	Percentage	Provider	Geography
	ASA	Market for acrylonitrile-butadiene-styrene copolymer		GLO	Global
	E/P	polyethylene production, low density, granulate		ROW	Rest Of the World
	EVAC	Market for ethylene vinyl acetate		GLO	Global
	PA	Market for nylon 6		ROW	Rest Of the World
	PBT	Polybutylene terephthalate granulate (PBT) Mix			
		Market for 1,4-Butanediol (BDO)	40.90%	GLO	Global
		Market for Terephthalic Acid (TPA)	59.10%	GLO	Global
	PC	Market for polycarbonate	65%	ROW	Rest Of the World
	PC+ABS	Market for polycarbonate	35%	ROW	Rest Of the World
		Market for acrylonitrile-butadiene-styrene copolymer		GLO	Global
	PE	Polyethylene production, Low density granulate		ROW	Rest Of the World
	PET	Market for polyethylene terephthalate, granulate, amorphous		GLO	Global

Materials	Material composition	Description from database	Percentage	Provider	Geography
	PMMA	Market for Polymethylmethacrylate		ROW	Rest Of the World
	POM	Market for formaldehyde	99.50%	ROW	Rest Of the World
		market for ETHYLENE OXIDE	0.50%	ROW	Rest Of the World
	PP	Market for polypropylene, granulate		GLO	Global
	PVC	Polyvinylchloride production, suspension polymerisation		ROW	Rest Of the World
Unalloyed, low alloyed (unspecified)	Steel, Unalloyed	Market for steel unalloyed		GLO	Global
Underseal (unspecified) -Damper	PMMA	Market for Polymethylmethacrylate	60%	ROW	Rest Of the World
	Lime	Market for lime	40%	GLO	Global
Washing water, battery acids (unspecified)	Sulphuric acid	Market for Sulfuric acid		ROW	Rest Of the World
	Washer fluid	Ethanol, without water, in 99.7% solution state, from fermentation, vehicle grade		ROW	Rest Of the World
Zinc alloys (unspecified)	Zinc	Market for Zinc		GLO	Global
Lubricant	Lubricant	Market for lubrication oil		ROW	Rest Of the World
Tyre	Synthetic rubber	Market for synthetic rubber	50%	GLO	Global
	Natural Rubber	Market for seal rubber	35%	GLO	Global

Materials	Material composition	Description from database	Percentage	Provider	Geography
	Market for Carbon black	Market for carbon black	10%	GLO	Global
	Lubricant at refinery	Lubrication oil	5%	ROW	Rest Of the world

Table 13: Water Consumption per kg material for BEV and ICEV

Materials (BEV)	Water Consumption [m^3]
Natural Materials	3.64
Lithium-ion battery	1.25
Electronics	0.51
Copper and alloys	0.20
Metals	0.06
Aluminium	0.06
Fluids	0.05
Tyre	0.05
Polymer	0.04
Steel and Iron	0.01
Glass	0.01
Materials (ICEV)	**Water Consumption [m^3]**
Natural Materials	5.77
Polymers	1.73
Other Materials	1.02
Copper	0.79
Other Metals	0.46
Aluminium	0.30
Fluids	0.29
Electronics	0.28
Glass	0.22
Steel	0.10

Table 14: Details about the assumption in water consumption of a car wash procedure

Sl no	Description	Quantity	Unit	Assumptions /Comments
1	Water Withdrawal for a Car Wash	0.150	m^3	Single Wash (0.15-0.2 m^3)
2	Water Withdrawal in a month	150	litres	Assuming car is washed once a month
3	Water Withdrawal in a 15-year lifetime	27	m^3	Assuming 15 years of lifetime for a car
4	Water Consumption in a month in a 15-year lifetime	1.350	m^3	Assuming consumption is 5% of Withdrawal
5	Total Water Consumption of a car - life cycle	680	m^3	From car company internal report
	Ratio of Water Consumption in 15 years Car Wash/ Total water consumption	0.19 %		

Table 15: The water consumption of the material production stage-BEV car based on respective weight

Materials	Weight (Kg)	Water Consumption [m^3]
Aluminium	356.75	20.53
Steel and Iron	840.81	8.79
Tyre	40.36	2.03
Copper + Copper Alloy	50.99	10.09
Electronics	4.55	2.32
Fluids and Undefined	25.71	1.34
Glass	33.47	0.25
Li-ion battery	246.2	308.23
Natural Material	3.04	11.08
Metals (Other)	29.73	1.76
Polymer	335.74	13.63

Table 16: Total water consumption in Recipe 2016 Midpoint method (BEV)

Regions	Material Production (Model) -m^3	Use Phase-m^3	Manufacturing for BEV Car m^3	Maintenance of BEV car – m^3	Total Water Consumption -m^3
China	380	340	2	13	734
USA	380	434	2	13	829
Sweden	380	581	2	13	976
Germany	380	201	2	13	596
UK	380	309	2	13	704

Table 17:Total water consumption results - AWARE 1.2 (BEV)

Description	China	USA	Sweden	Germany	UK
Use-Electricity Mix	27490	2983	1771	2400	3687
Material Production (Model)	16325	16325	16325	16326	16325
Maintenance of BEV car (New)	577	577	577	577	577
Manufacturing for BEV Car	50.4	50.4	50.4	50.4	50.4
Total	44442	19936	18723	19353	20639

Table 18: The Electricity Distribution Mix

Electricity Mix	China	USA	Sweden	Germany	UK
Coal	56%	16%	1%	25%	1%
Hydropower	18%	5%	40%	3%	1%
Wind	10%	11%	20%	31%	25%
Solar	5%	5%	0%	12%	4%
Nuclear	5%	18%	30%	0%	15%
Natural Gas	0%	40%	0%	12%	30%
Biomass	0%	0%	0%	8%	5%
Others	0.06	0	0	0.09	0
Renewables	0%	4%	9%	0%	0%
Imports	0%	0%	0%	0%	19%
Provider	China+D3:D7-State Grid corporation	Next Extra Energy	Vatenfall	RWE	National Grid
Source	(China Energy portal, 2023)	(Institute of energy research, 2023)	(Swedish energy agency report, 2023)	(Germany - Agora Energiewende, n.d.)	(UK goverment Energy Statistics, 2023)

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