POLITECNICO DI MILANO

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Life cycle assessment of GHG emissions of light duty vehicles: comparison between Internal Combustion Engine Vehicles and Battery Electric Vehicles

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This thesis is dedicated to my family and friends who had always been a continuous support through the troughs and crusts of my life.

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Abstract

The increasing contribution of transport sector, particularly lightweight vehicles, in global greenhouse gas GHG emissions over past decades is posing a major resistance towards fulfillment of global net-zero emissions. The need of decarbonization of vehicles has led to mass adoption of battery electric vehicles (BEVs) and the increasing market dominance of BEVs demands a detailed analysis of the entire life cycle LCA emissions of BEVs in comparison with Internal combustion engine vehicles (ICEVs). This study considers (i) production, (ii) well to wheel (fuel cycle and tailpipe emissions), (iii) maintenance and (iv) end of life (disposal and recycling) emissions of ICEVs and BEVs belonging to nine different model segments detailing four different geographies (Europe – EU, NA – North America, EA – East Asia, China – CH) to evaluate the impact of production and usage location, grid carbon intensity, fossil fuel cycle, and distance driven during the vehicle life. Lifetime distance driven is assumed to be 150000km with sensitivity of ±50000km and results are given in kgCO2eq/vehicle and gCO2eq/km. The study uses secondary data and emission inventories developed by previous authors as reference for developing a model to calculate emissions of different phases of the vehicle life cycle. Total vehicle production emissions are higher for BEVs than ICEVs, and overall, the highest contribution belongs to China, and for segments with higher weight and bigger battery capacities. The ICEV well to wheel (WTW) emissions are 2-3 times the amount of comparable BEV segments. Tailpipe emissions contribute to 65-80% of total ICEV LCA emissions for EU, while 25-35% for China, highlighting the different carbon footprint of vehicle production in the two regions. Battery and body production emissions range between 35-70% of total BEV LCA emissions due differences in battery size and body weight across segments. ICEV emissions are, on average, higher than corresponding BEV emissions in EU, NA and China whereas in EA, ICEV emissions are lower than BEV due to their low fossil fuel cycle emissions and high electricity grid carbon intensities. Battery recycling emissions are higher for higher range and lower energy density battery storages. The emission reduction that can be achieved by using battery packs manufactured from recycled LIBs could reach the 5-15% of the of total LCA GHG. For ICEVs used in EU, 25-46% LCA emissions increase by moving the production from EU to China. Similarly, for BEVs, moving the battery production from EU to China, the LCA emissions increase by 11-50%, while the increment reaches 78-140% if all vehicle production is moved. Changing the EU electricity mix towards 2040 (32gCO2eq/kWh), BEVs can benefit from a 65-71% LCA emission reduction versus 5% emission savings for ICEVs.

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1 Introduction

GHG emissions have been a focus of attention since last few decades due to ever increasing trend of GHG emissions and their inevitable harmful effects on health and environment. Among different sectors responsible for the emissions, energy sector is the most prominent particularly the transportation sector and road transportation, which cover 16.2% and 11.9% of the global GHG emissions respectively. *Figure 1* [1] According to the Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990–2018, transportation accounted for the largest portion (28%) of total U.S. [2] Light commercial vehicles are responsible for around 12% of total EU emissions of carbon dioxide (CO2). [3] Due to an increasing need to curb down the curve of annual GHG emissions, there has immense focus on reduction of emission from these sectors leading to discovery and adoption of different technological solutions which can be useful in this regard.

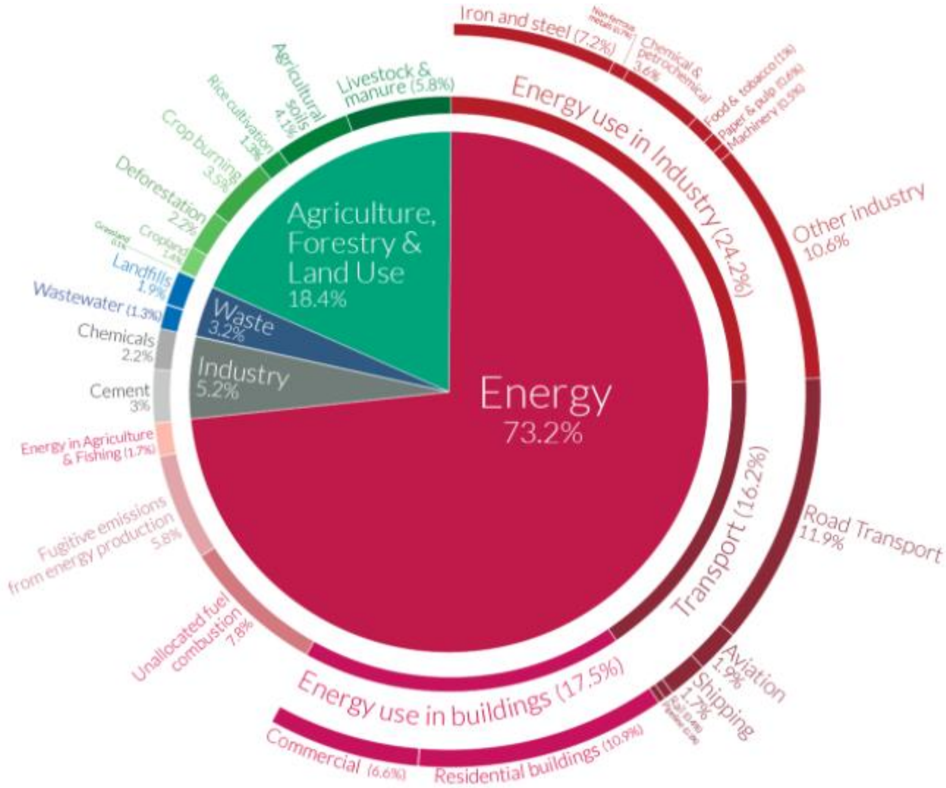


Figure 1 Global GHG Emission distribution by sector 2018 . [1]

While most sectors have managed to decrease greenhouse gas emissions in recent decades, transport sector emissions have increased in-spite of all the efforts. *Figure 2* This increase is attributed mainly to an ever-increasing demand of vehicles by consumers.

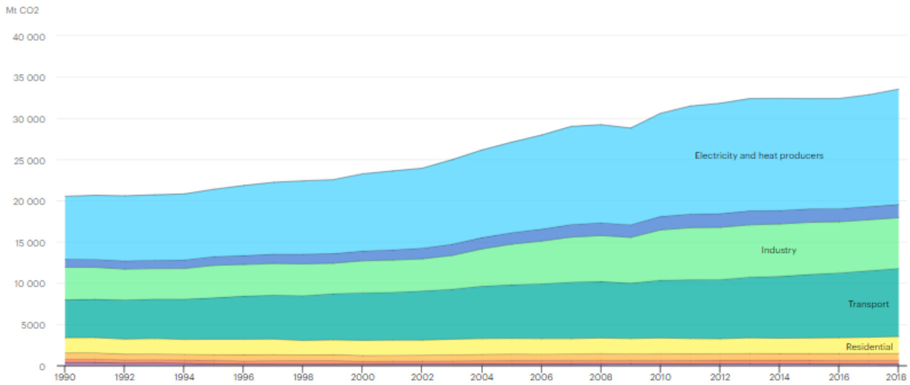


Figure 2 Increase in global emissions over last 3 decades [4]

One of the proposed solutions has been the replacement of ICEVS with PHEVs and eventually BEVs which have proved to have much lower direct GHG emissions during usage. An average battery electric and plug-in hybrid electric car using electricity characterized by the current global average carbon intensity (518 grammes of carbon-dioxide equivalent per kilowatt-hour [g CO2-eq/kWh]) emit less GHGs than a global average ICE vehicle using gasoline over their life cycle. Thus, the massive increase in GHG emission by commercial vehicles has led to huge Electric car deployment in the market which has been growing rapidly over the past ten years, with the global stock of electric passenger cars passing 5 million in 2018, an increase of 63% from the previous year. *Figure 3* [4]

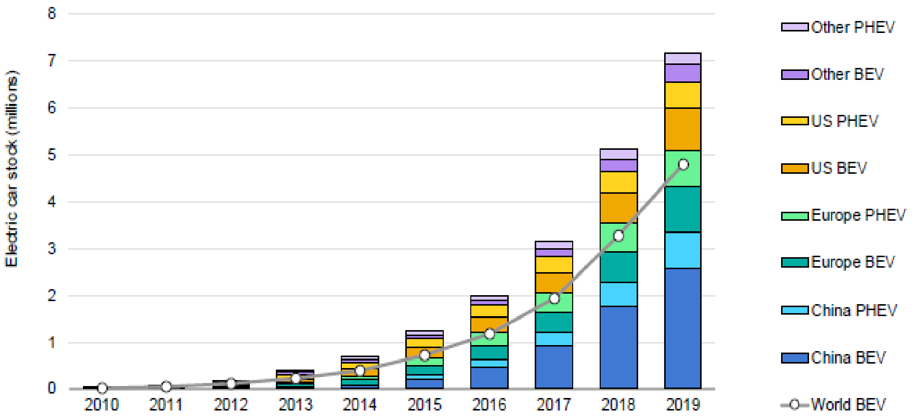


Figure 3 Increase in Electric Vehicles stock over years [4]

However, the extent of emission ultimately depends on the electric power mix of the country i.e. CO2 emissions savings are significantly higher for electric cars used in countries where the power generation mix is dominated by low-carbon sources. [4] Many researchers have even revealed that although the energy consumption and Greenhouse Gas (GHG) emissions of EVs within the vehicle production phase account for a relatively small proportion when considering the whole life cycle, the values are much higher than those of conventional vehicles and cannot be ignored. [5] Therefore, a complete life cycle analysis of the emission of vehicles provides a much better basis for the study. The goal of this study is to provide a comprehensive and comparative life cycle assessment of emissions of different vehicle technologies and to highlight the importance of certain factors which have detrimental effect on the LCA.

2 Life Cycle Assessment LCA

Life Cycle assessment is a technique to evaluate the environmental burdens associated with a product, a process or activity by identifying and quantifying the energy and materials used and released to environment. [6]

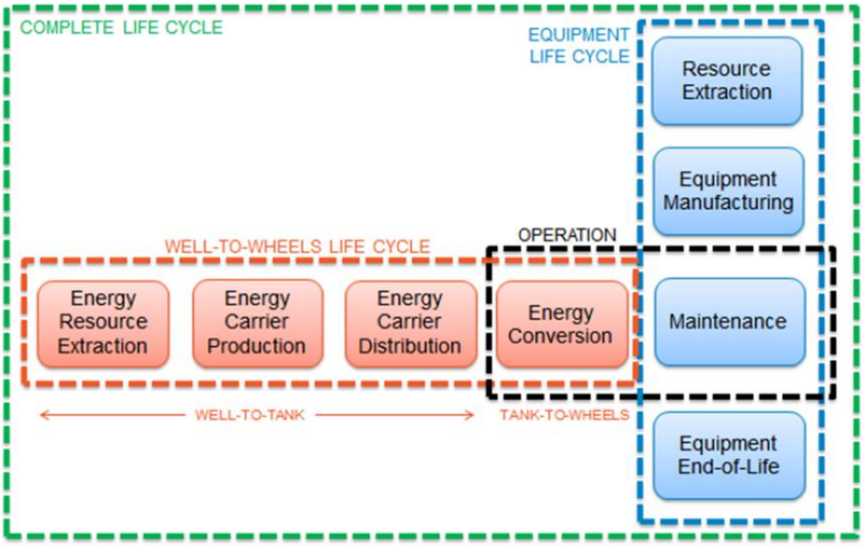


Figure 4 Complete Life Cycle Flow Diagram

A vehicle life cycle mainly consists of four stages – vehicle production, fuel production, usage, and end of life. *Figure 4* A simplified vehicle LCA flow diagram is given for reference. [7] To understand the LCA study in a deeper way, following guidance framework can be considered useful. *Figure 5*

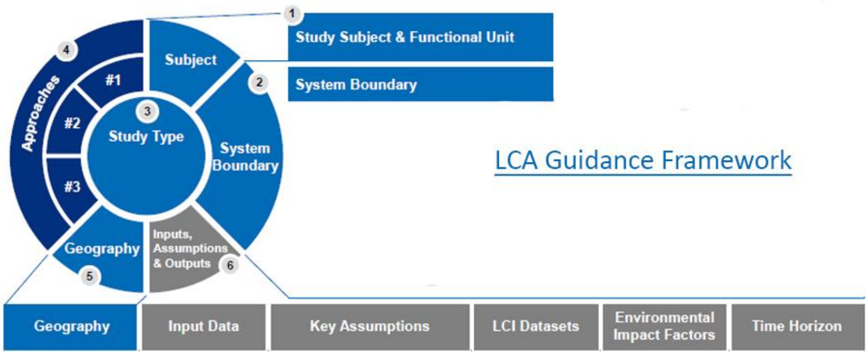


Figure 5 Life Cycle Analysis Guidance Framework [8]

2.1 LCA Study subject & Functional Unit

A LCA study can focus on any generic vehicle or it can be about specific vehicle model or fleet. It can be about certain component or subsystem as well. It can be based on energy, distance or cycles. Functional Unit of study should always be consistent throughout the study so that the input and output data are normalized. It can be given as total emissions or emission per distance unit etc.

Current study focuses provides LCA for some specific vehicle models from different segments for ICEVs and BEVs. The functional unit considered is kgCO2eq total per vehicle and gCO2eq/km. The models for each segment are given in *Table 1* below for reference.

Table 1 Vehicle segments and models considered in the study

Segment	Vehicle type	ICEV model	BEV model
A	Mini Car	Fiat500	Fiat500e
B	Small Car	VW polo	Peugeot e 208
C	Medium Car	VW Golf	ID.3 Pro
D	Large Car	Audi A4	Tesla Model 3
E	Executive Car	MB E class	Tesla Model S
F	Luxury Car	BMW 7 series	Audi e-tron Sportback 55
J	Sports Utility	Toyota RAV4	Byton M-Byte
M	Multipurpose Car	Lancia Voyager	Rivian R1T
S	Sports Car	Porsche 911	Porsche Tycan 4S

2.2 LCA System Boundary

System boundary defines the overall scope of the LCA and it can be categorized into different levels depending upon life cycle system boundary.

- Level A: considers the tail-pipe emission during vehicle usage only.
- Level B: Well to Wheel (WTW) considers fuel life cycle from primary energy source to usage in vehicle. It can be split into Well to Tank (WTT) which considers fuel production and distribution, and Tank to Wheel (TTW) which considers vehicle usage consumption.
- Level C: Considers whole vehicle life cycle (Cradle to grave) including material extraction, production, usage and end of life of vehicle. *Figure 6*
- Level D: Whole mobility system life cycle. [8]

Current LCA study considers whole life cycle and can be taken as level D study including fuel and vehicle production and transportation, vehicle usage and end of life.

2.3 LCA Study type

LCA study can be of different types depending on the person who conducts and commissions as well as the target audience of the study.

- Academic study where it can be any private organization or person who is conducting, and the target audience is general research community.
- Policy where it is commissioned by government and audience are policy makers and community.
- Environmental reporting is conducted by manufacturer or consultant for a customer audience.

Current LCA is academic study and solely for the purpose of research for the academic community in general.

2.4 Study Approach

LCA study can be Bottom-Up which focuses each production step till final product or Top-Down which focuses on macro parameters describing the overall system. It can also be a combination of both as well. It can be either attributional or consequential modeling.

This study uses combination of both depending upon the phase of life cycle. The modelling approach of current study is attributional.

2.5 Study Geographical location

The location of the product can highly influence some of the key inputs and assumptions of the life cycle assessment therefore it is very important to characterize the study on basis of geographical location. Affected parameters can be the material supply chain, fuel supply chain, fuel specifications, energy mix, vehicle mileage etc. Moreover, the resource extraction, manufacturing and assembly, and vehicle usage locations can also be different. Therefore, location plays a key role in Life cycle assessment of vehicles.

This study takes four different geographical locations which are aggregated as North America, EU, East Asia and China. All these regions have different sources of fuels and production resources due to which the fuel cycle emissions vary greatly. Furthermore, the energy mix is quite different which is an important parameter for LCA of emissions of vehicles.

2.6 Study Input Data

The Input data can be primary collected directly through experimentation and research otherwise can be secondary data taken from previous research and publications.

This study mainly focuses on data collected by previous research works, studies and publications within the time span of last 10 years.

2.7 Study Assumptions

All life cycle assessments are based on some assumptions due to the massive scale of data required and complications involved in data collection and processing. The secrecy and confidentiality of data for the manufacturers and stake holders makes it difficult for the researchers to gather all the data required for their study, thus forcing them to make adequate and suitable assumptions. This study assumes minimum fluctuations in the secondary data calculated by previous publications over the time frame of past years. For East Asia we are using aggregated values of Japanese and South Korean values. The resource extraction and component production energy consumption values are estimated from GREET2.7 model [9], [10]which is mainly based on supply chain data for North America. Due to lack of data availability, GREET model data is applied to rest of the locations but with using the local fuel cycle emission values for that respective region. Battery production cycle energy consumptions are assumed to be 70% natural gas and 30% electricity. [11] Other important assumptions are mentioned in each phase of the life cycle in detail.

2.8 Life Cycle Inventory, LCI Data Set and Time horizon

LCA studies are mostly based on some generic Life Cycle inventories for data of different life cycle stages. Time horizon definition is very important because most of the key input factors and assumptions change with time due to technological developments and change in emission standards.

This study uses GREET 2.7 model. [9], [10] The Time horizon is not much different for different stages of the life cycle and all the vehicle segments considered are recent vehicle models. The model focuses on present day time values while some data dates from around 2010 using assumption that it would not have varied much in past years as given by the authors.

2.9 Environmental Impact factors

It can be of different types depending on the impact of emissions to the environment mainly water, air and soil, and resource usage and depletion. Global Warming Potential (GWP) is the cumulative radiative forcing, both direct and indirect effects, over a specified time horizon resulting from the emission of a unit mass of gas related to some reference gas i.e. CO2. [12] It consists of GHG emissions that increase global warming potential. They contain mainly CO2, CH4 and N2O, and are measured in CO2 equivalents. Acidification Potential (AP), Eutrophication potential (EP), Photochemical Ozone Creation Potential (POCP) are other important environmental impact factors.

This study focuses on GHG emissions and gives output as kgCO2eq/vehicle and gCO2eq/km.

The *Figure 6* given shows the overall scope of this life cycle study for better understanding of the scale of LCA. It covers vehicle production, fuel production, vehicle usage and end-of-life while each phase is described in detail later in this report. [8]

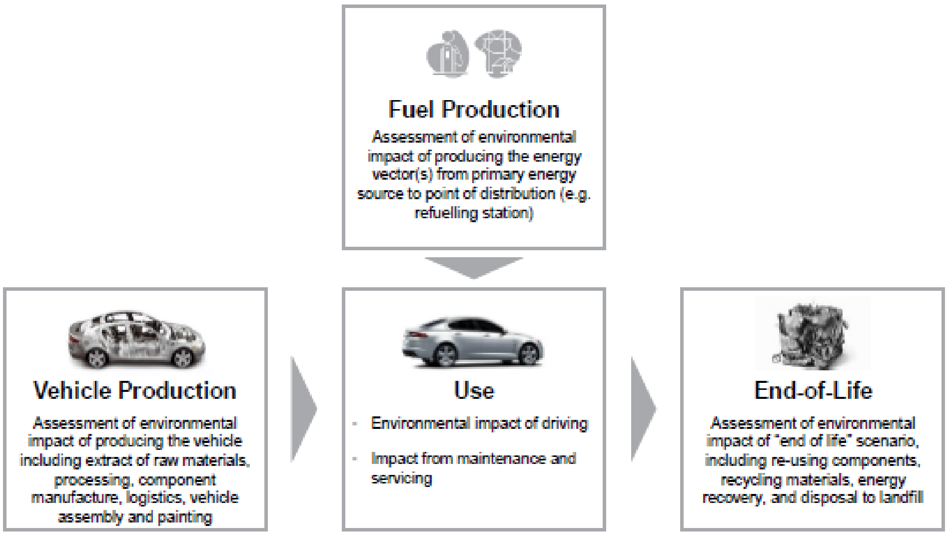


Figure 6 Vehicle Life Cycle . [8]

A complete and simplified flow diagram of the study is provided along with the references in the *Figure 7*. It shows all the phases of the study, inputs, main variables, and outputs as well.

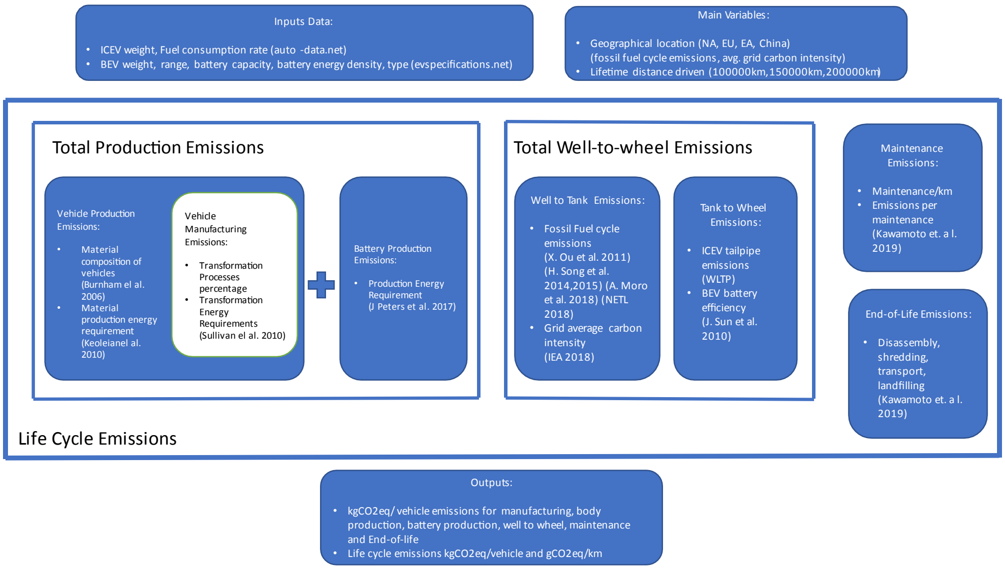


Figure 7 Complete flow diagram of LCA study

The life cycle is divided here into total production emissions (sum of production material supply chain emissions, manufacturing emissions and battery production emissions), total well to wheel emissions (sum of well to tank and tank to wheel emissions), maintenance emissions and end of life emissions. Input data mainly consists of vehicle specification data along with range for BEVs and fuel consumption data for ICEVs. Output data is in kgCO2eq emissions per vehicle for different vehicle segments considered in the study.

3 Vehicle Production Emissions

This chapter covers the environmental impact of total production process including extraction of raw materials, processing and transportation of materials, manufacturing of components and subcomponents, vehicle assembly and painting, and transportation produced vehicle. To model the vehicle emissions most of the authors have relied on the secondary data due to data sensitivity and complexity. Different models have used different categorization. Some have used top-down approach using certain production plant real world data. Top-down approach is therefore more specific and cannot be adopted for generic usage.

For this LCA study we have employed VMA vehicle manufacturing and assembly model [13] for manufacturing emissions and GREET 2.7 model for production emissions both of which are Bottom-up approach models. Vehicle Manufacturing and Assembly Model VMA model gives the vehicle body distribution based on the transformation methods used for materials in the manufacturing of the vehicle. Whereas the Greet2.7 model gives the total production emissions from material extraction till vehicle manufacture for each material component along with the material percentage of vehicle body.

The models give material composition of vehicles which can be used for modern vehicles as well as previous years. [13] VMA model splits the energy consumptions into each phase of production method and then sum them up depending upon the material composition of vehicle. The model gives energy consumption as units of fossil fuels and electricity. For simplicity of the study and lack of data, we have ignored the contributions of propane, gas oil, fuel oil, LPG and process oil, and a comparable value of natural gas is added for correction.

The energy requirements for part and production processes given by VMA model are listed in *Table 2* [13]

Table 2 Energy Demand for Part and Vehicle Production Processes [13]

Speciated Purchased Energy for Part & Vehicle Production Processes					
Resource	Coal (kg)	NG (m3)	Diesel (L)	Gasoline (L)	Electricity kWh
per kg Output					
Process stamping	0	0.035	0	0	0.292
Shape casting Aluminum	0	0.705	0	0	2.235
Shape casting Iron	0.32	0.273	0	0	0.377
Lead from Scrap	0	0.215	0	0	0
Copper Wire	0.001	0	0	0	0.524
Brass from Scrap	0	0.099	0	0	0.301
Forgings	0	1.036	0	0	0.377
Flat glass	0	0.337	0	0	0.243
Machining	0	0	0	0	0.1745
Moldings Rubber	0	0.135	0	0	0.657
Moldings Thermoset	0	0	0	0	0.417
Injection mold PP	0	0.022	0	0.025	2.096
Injection mold PVC	0	0	0.001	0	1.375
Blow mold HDPE	0	0	0	0	1.709
Calendaring PVC sheet	0	0.004	0.005	0	0.506
Extrusion HDPE pipe	0	0.001	0.001	0	0.54
per Vehicle					
Painting	0	66.3	0	0	134
HVAC & lighting	0	0	0	0	290
Heating	0	85.9	0	0	0
Material Handling	0	0	0	0	60
Welding	0	0	0	0	80

The energy requirements for resource material processing of components are given as per kg output which the energy requirements for processes like painting, heating etc. are given as per vehicle. The required fuel values were calculated based on production process in American context, however due the lack of primary data available, we will consider the same distribution for rest of the countries. Along with this data we need the material composition of vehicles in terms of its weight. *Table 3* The compositions of vehicle body would vary because of the usage of alternative of cast iron and steel to reduce the weight in modern vehicle compared to the baseline vehicles. Aluminum compositions would increase and thus the required energy values because Aluminum and processing is comparatively much more energy exhaustive process than iron. While material substitution can reduce vehicle weight, it often increases vehicle-cycle GHGs. It is likely that replacing steel (the dominant vehicle material) with wrought aluminum, carbon fiber reinforced plastic (CRFP), or magnesium will increase vehicle cycle GHGs. Lifetime fuel economy benefits often outweigh the vehicle-cycle, resulting in a net total life cycle GHG benefit. [14]

VMA model provides a more generic distribution of material which can be used for all ICEVs with high precision because of somewhat similarity in their composition. However, in case of unconventional vehicles like PHEV, BEVs there must be some careful analysis of material changes which are done for light-weighting. [13]

Table 3 Summart of Transformations and Material percentage of vehicle [13]

Summary of Transformations and Materials by Group			
Transformation	Material Group	Transformation Process Surrogate	% of Curb Weight
Metal Stamping	Steel	Steel Stamping	37.7
Metal Stamping	Aluminum	-	0.2
Castings	Iron	Iron	8.6
Castings	Aluminum	Aluminum	4.7
Castings	Brass	Brass	0.6
Castings	Lead	Lead	0.8
Forgings	Iron & Steel	Iron & Steel	3.8
Extrusions	Aluminum	Aluminum	1.4
Machining	Steel	Metals	14
Wire forming	Copper	Copper wire	1.2
Glass pane forming	Glass	Float glass	2.8
Blow Molding	Polymer	HDPE bottles	0.2
Compression Molding	Plastics & Rubber	Compression molding rubber	7.4
Thermoset Molding	Polymer Resins	PU foams	2.6
Extrusions	Plastics	HDPE pipe	1.6
Calendaring	Plastics	PVC	0.2
Injection Molding	Plastics & Rubber	PP parts	4.7

Consider the following *Table 4* provided by GREET2.7 for reference which also gives material composition as percentage of total weight. [9] This model distinguishes in the material composition for alternative and conventional vehicles which can be used for calculating production emission for alternative vehicles.

Table 4 Material Distribution percentage for different vehicle categories [9]

Component	ICEV	LW ICEV
Steel	61.7	30.5
Stainless Steel	0	1.1
Cast Iron	11.1	4.2
Wrought Al	2.2	6.9
Cast Al	4.7	14.7
Copper/brass	1.9	3.2
Magnesium	0.02	0.4
Glass	2.9	3
Avg Plastics	11.2	14
Rubber	2.4	2.6
CFRP	0	15.1
GFRP	0	2.3
Platinum	0.0005	0.0009
Others	1.9	2.2

Since in this study all the vehicles belong to recent 2020 production, therefore we assume them all to be lightweight and we assume same composition for BEVs and Light Weight LW ICEVs for the sake of simplicity.

Avg. Plastics is assumed as 24% Polypropylene Plastic (PP), 14% Polyethylene Plastic (PET), and 10% High density Polyethylene (HDPE) assumption (GREET) while remaining weight is given to an average of all the remaining plastics. [9] Platinum contributions are neglected due to lack of data availability and small contribution.

GREET2.7 model also gives the production energy requirements in terms of fuels for whole production process. The model uses the supply chain of resources for production in America and due to lack of data availability and for simplicity of calculations we will use the same production energy requirements for other locations. The detailed energy demand for producing different vehicle materials is given in the *Table 5*.

Table 5 Total production energy demand of vehicle component materials [10]

Component	MJ/kg material			kWh/kg	MJ/kg
	Coal	Natural Gas	Petroleum	Electricity	Total
Steel	39.85	12.83	3.26	0.85	59.02
Stainless Steel	39.85	12.81	3.26	0.85	59.02
Cast Iron	39.85	12.83	3.26	0.85	59.02
Wrought Al	88.28	28.89	13.86	16.88	191.84
Cast Al	58.86	22.47	9.85	11.93	134.15
Copper/brass	3.87	42.22	4.25	0	50.35
Magnesium	0	116.52	0	77.68	194.21
Glass	0	16.33	0	0.24	17.21
Avg Plastics	4.88	51.72	24.09	0.27	81.69
Rubber	0	39.53	0	0	39.53
CFRP	12.03	93.64	52.22	0.70	160.42
GFRP	10.62	53.96	17.66	0.62	84.52
Platinum	0	0	0	0	0
Others	24.84	41.98	10.97	9.24	87.05

It is important to note here that both these models do not include battery production in the model. Therefore, the total weight is to be deducted with battery weight. Battery production emission are explained in detail in next chapter.

Total ICEV and BEV manufacturing and production emissions are calculated by above mentioned models and given in the tables in supporting documents section for reference.

4 Battery Production Emissions

Battery life cycle has been a focus of a lot of attention in the recent years due to growing number of electric vehicles in the market. There has been a huge amount of research ongoing on battery life cycle recently however still a lot needs to be done in this field. Battery production emissions are of great importance particularly when life cycle analysis of electric vehicles or PHEV are considered since they cover a major portion in life cycle emissions of these alternative vehicles. Battery life cycle consists of mining resource materials, transportation and processing of materials for usage in cell, cell production, battery assembly and distribution, utilization and finally disposal or recycling and second life. *Figure 8* There has not been any success industrially yet on the second life of the battery. [15] Recycling on battery would be discussed later in this study in detail.

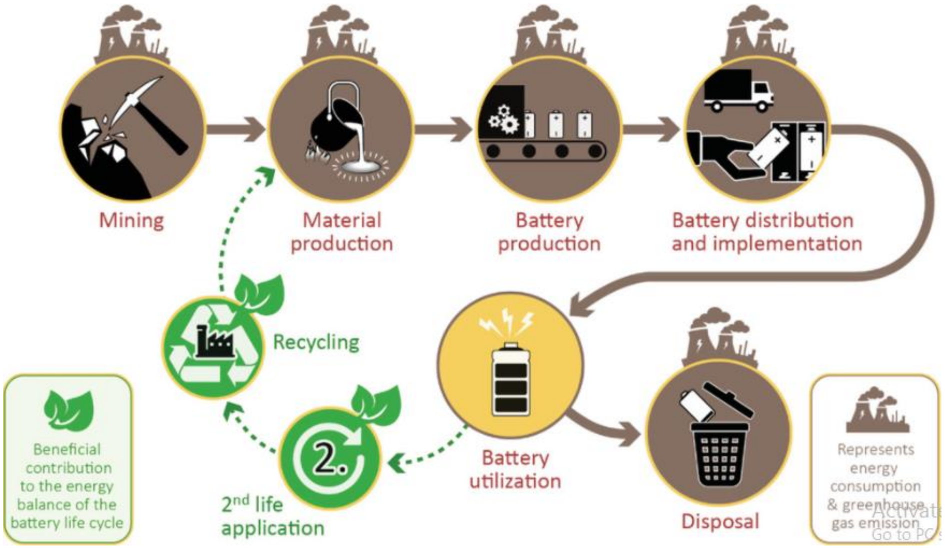


Figure 8 Battery Life Cycle Flow Diagram

Battery production emissions calculated by different authors have much difference for same battery type and capacity. Authors with Top-down approach have generally given a much higher value as compared to authors who have used bottom-up approach of categorization.

A summary of different studies and their results are given in the *Figure 9*. [16]

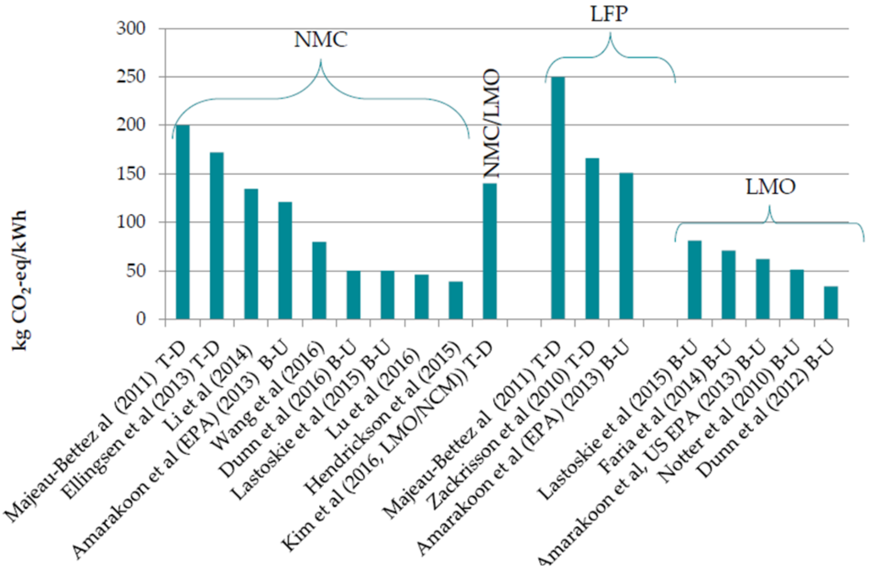


Figure 9 Battery LCA Emissions by previous authors (TD – Top Down , BU – Bottom Up) . [16]

Among all the different types of Lithium-Ion Batteries (LIBs), Nickel Manganese Cobalt (NMC), Lithium Iron Phosphate (LFP) and Lithium Manganese Oxide (LMO) are the most used in automobile industry. Among the main chemistries, NCA are used for Tesla, LFP for Chinese brands and NMC for the rest. Range is very important factor for electric vehicles however higher range means higher battery storage capacity which in turn increases weight of the battery. Therefore, research are oriented towards finding battery solutions with higher energy to weight ratio. NMC is the near-term future choice of battery chemistry for electric vehicles due to higher storage capacity per unit weight. [17] Although LFP can never achieve the same kWh/kg performance as NMC, LFP still could be a viable choice for heavy duty application where energy per kg is less important, while power per kg is more important. [16]

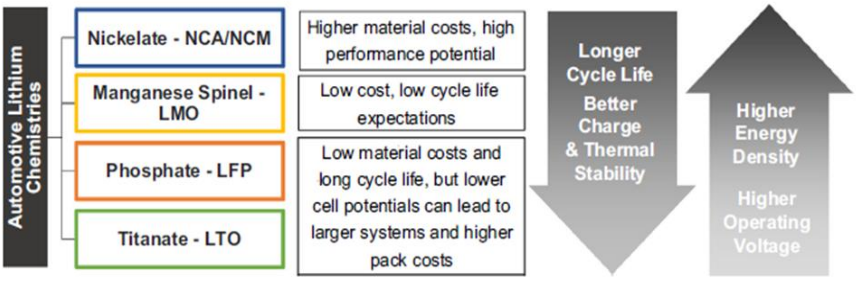


Figure 10 Comparison of different Battery Chemistries [16]

It is evident that the discrepancies are huge among different studies performed on LIB production. The reasons being that the locations of the production facilities, and the origins of the battery materials, can also significantly affect the cradle-to-gate energy and environmental impacts of LIBs. Moreover, the collective upstream production of battery materials is much more energy-intensive than the cell production process. To get more accurate battery production values, we must get the upstream emissions for material collection which varies with geography to resource material extraction. The electricity mix for materials and cell production can vary substantially across geographic regions, the energy and environmental impacts of battery production need to be discussed in tandem with the battery supply chain. The lack of data on the upstream creates discrepancies in the study. [11] The comparison of Balance of Material (BOM) and cumulative energy demand (CED) for material inputs and cell production is given in *Figure 11*

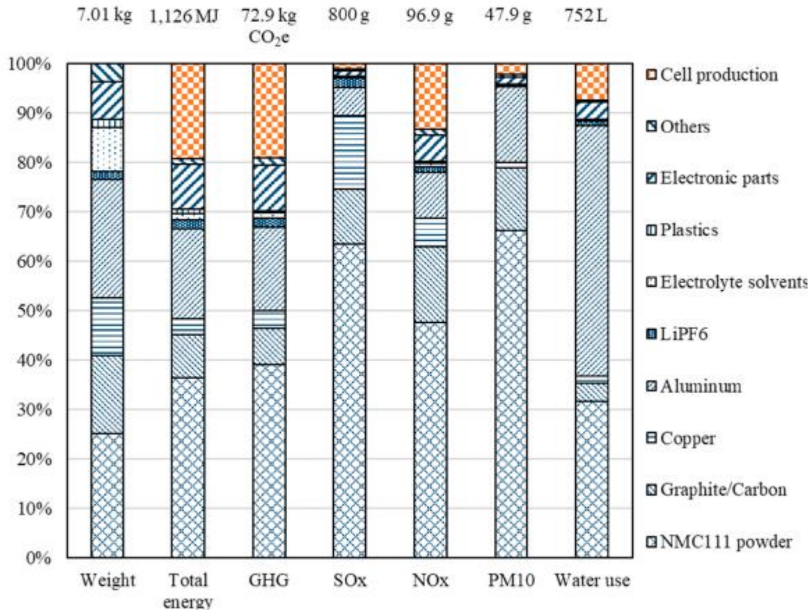


Figure 11 CED, BOM and Emissions for material inputs and cell production . [11]

The energy demand for material inputs, has a major portion in life cycle as compared to cell production. [11] It has also been found that the largest battery pack had lowest battery production emissions per kWh while the smallest had the highest. This is stated to be due to the many battery components that do not scale linearly with pack size. [16]

Another review study has found similar discrepancies among the LIB production emissions which can be seen from the *Figure 12*. [18]

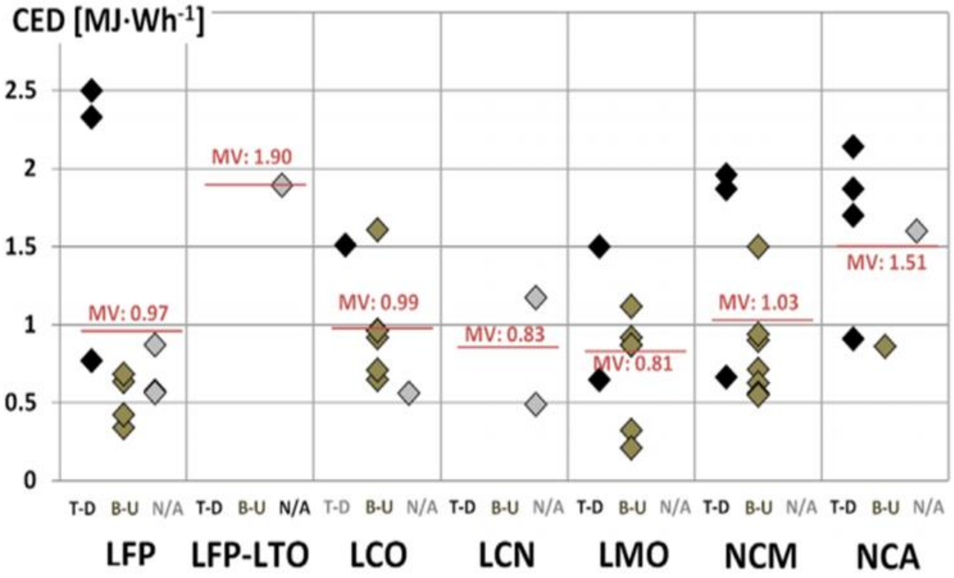


Figure 12 Energy Input for battery production of different chemistries by different studies [18]

Cumulative Energy Demand (CED) for the *Figure 12* varies a lot by the approach used for the studies. TD, BU represent top-down, and bottom-up approaches used by different studies and N/A represents unavailability of specifications. Therefore, the mean CED for each battery type can be a good estimate for the LCA of battery production. However, some studies have shown that CED does not vary for the battery type since most of the energy demanding production processes are similar for the common battery types. [19] On the contrary some studies show that LIB pack BOM and specific energy, both of which are deterministic factors for the LCA results of LIBs, can vary considerably with cell type, pack configuration, battery size, and desired EV performance metrics. [11]

For reference we use the mean values of cumulative energy demand CED for different battery types in this LCA study. [18] This energy demand is supplied by both fossil fuel and electricity. Fossil fuels cover for energy demand for mining as well as thermal energy during material processing and production.

Table 6 Mean Cumulative Energy Demand for different battery chemistries

Cumulative Energy Demand of Battery production	
Battery Type	MJ/Wh
LFP	0.97
LFP-LTO	1.9
LCO	0.99
LCN	0.83
LMO	0.81
NCM	1.03
NCA	1.51

Different studies have shown that Module and pack assembly is assumed to be manual, and therefore not associated with any energy and environmental impacts. For battery manufacturing the energy demand is around 170 MJ/kWh from which 30MJ is from electricity and 140MJ is from heat. [18] Overall, due to lack of detailed supply chain data, the energy demand is assumed to be 40 percent from electricity and 60 percent from fossil fuel based on previous literature and research. [11] Fossil fuel for energy is assumed to be natural gas for simplicity in this study. Using the grid average mix emissions and natural gas fuel cycle emissions for different production locations, we can estimate the battery production emissions directly for that specific location. Due to complications the emissions for supply chain of resource material extraction are ignored.

Total battery production emissions for all BEV segments are calculated by above assumptions and given in the table in supporting documents section along with the total production emissions for BEVs which includes both body and battery production emissions.

5 Well to Tank (Fuel Cycle) Emissions

Well to Tank (WTT) analysis involves energy consumptions and the GHG emissions during the processes associated with production, and distribution of automotive fuels. However, it excludes those associated with any kind of infrastructure construction. WTT analysis can be divided into four stages which are raw material recovery, transport, refining and distribution. A complete flow diagram of WTT is given in *Figure 13*. [20]

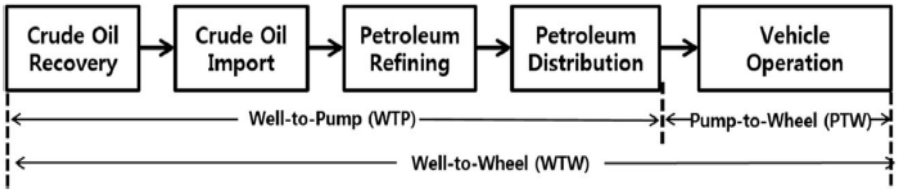


Figure 13 Well to Tank flow diagram for pertroleum based fuels [20]

Crude Oil recovery phase includes the whole process in oil fields to produce crude oil product before being exported to refineries. It mainly includes injection, extraction, processing, and storage of extracted fuel. In this phase recovery energy, flaring and venting emissions are the most emission intensive factors. Recovery energy includes the energy of process fuels used in injection, extraction, processing, and transportation of the crude oil in production fields. During the recovery process of the crude oil, considerable amounts of associated gases from the oil production field are either flared or vented. Flaring is the intentional combustion of natural gas or waste gas, mainly practiced at crude oil facilities, and the combustion products of those gases are emitted to the environment. Whereas venting refers to the intentional emission of associated gas or waste gas itself, without combustion. [20] Crude Oil transportation is done by pipelines for domestic production whereas sea or road tankers are used for importing from foreign in general depending on production location. Petroleum distribution process consists of transportation from refineries to oil storage depots and then eventually distribution to gas stations.

For this Study we have used the well to wheel emissions previously calculated by authors for different geographical locations. Gasoline and Diesel WTT emissions and natural gas WTT emissions for Japan and Korea are used as basis for East Asia. [20] [21] WTT emissions for USA are used for North America as well as GREET model. [22] Fuel cycle emissions for all fossil fuels for secondary use in China are taken from previous LCA researchers. [23] Upstream GHG emissions for fossil fuels in EU retaken from previous LCA relies in its study on findings by JEC consortium. [24] The values used from all the reference are given in the *Table 7*.

Table 7 Fossil Fuel WTT emissions for different regions

Region	Coal g/MJ	NG g/MJ	Diesel g/MJ	Gasoline g/MJ	Electricity g/kWh
North America	7.04	24.7	17.44	18.57	405
Europe	16	22.5	14.2	12.5	269
East Asia	20	30	11	12	571
China	104.5	72.73	102.4	98.86	613

Grid average electricity emissions for different locations collected from different sources and given in table. [3] [25] Due to immense amount of supply chain data required for calculating grid average emissions, it is beyond the scope of this study. The LHV values for different fuels used in the study are given in the *Table 8*.

Table 8 LHVs of different fuels used in the study

Fuel	LHV	Unit
Coal	29	MJ/kg
Natural Gas	36.6	MJ/m3
Diesel	36	MJ/L
Gasoline	32	MJ/L

6 Vehicle Usage Emissions

Vehicle usage emissions can be split into vehicle exhaust emissions and maintenance emissions. Both phases are explained in detail in this chapter.

6.1 Vehicle Maintenance Emissions

This phase involves the emissions due to maintenance of vehicle throughout the life of vehicle. The main contributions to emissions in this phase are due to replacement of tires and lead acid battery for all vehicles, engine oil and radiator coolant for conventional vehicles, and possible li-ion battery replacement in battery electric vehicles. The contributions by these factors are given in *Table 9*. [26]

Table 9 Maintenance emissions for vehicles

Assumptions for maintenance phase			
Part Name	Maintenance Interval	CO2 Emission	Applied Vehicles
	km/maintenance	kg-CO2/ Maintenance	
Tire	40000	108	GE, DE, BEV
Lead acid battery	50000	19.5	GE, DE, BEV
Engine Oil	10000	3.22	GE, DE
Radiator Coolant	27000	7.03	GE, DE
Li ion battery	160000	6337	BEV

Different battery manufacturers have mentioned their battery life in kms in their manuals and maximum found was around 160,000km. [27] Therefore, we have used a battery replacement above this distance in the LCA. For sake of simplicity, we have used an average battery production CO2 emission in this specific case. Overall manufacturing emissions for all segments of ICEVs and BEVs are calculated and given in the *Table 10*.

Table 10 Total maintenance emissions for ICEVs and BEVs

Vehicle Type	Total Maintenance Emissions		
	kg CO2 total		
	100,000 km	150,000 km	200,000 km
ICEV	308.29	465.95	731.61
BEV	255	382.5	6955

6.2 Vehicle Tail-pipe Emissions

Tail-pipe emissions of vehicles are quantified by some factors which are called emission factors. Emission factors characterize the amount of pollutant emitted in terms of mass of fuel consumed (fuel-based), distance driven (task-based) or energy used (task-based). There are different techniques for vehicle emission measurement which are street canyon measurements, road tunnel studies, remote sensing, chassis and engine dynamometer measurements and portable emission measurements systems (PEMS). Some of these techniques provide data which are closer to real world emissions compared to others. On-road chase measurements involve a mobile laboratory following the individual vehicles. They have minimum distance limitation and maximum speed boundary unless laboratory is mounted on a trailer. Portable emission measurements (PEMS) have emission measurement instruments carried onboard the vehicle under test. They can give more specific data for a particular vehicle driven under and specific set of conditions however the additional weight of apparatus and reduced range of pollutants are a limitation. Remote sensing provides instantaneous ratios of pollutant concentrations as the vehicles pass by a stationary measurement station on the roadway. Some influencing factors are the sampling sites, time, and operating mode of vehicles. Road tunnel studies use sensors placed on tunnels but due to long residence time of pollutants, the devices give over-estimation of the pollutant concentrations. Pollutant saturation at instruments can result in faulty estimation of peaks. Street Canyon measurements are influenced by traffic fluxes, wind speed, direction, and pollutant concentration levels. Short distances between the receptors and vehicles are limitation.

Other than these techniques there are some laboratory dynamometer techniques which are widely accepted and used. They provide lower consumption and emission estimations as compared to real data. Engine dynamometer simulates resistive power directly to engine power output, thus ignoring the transmission and driveline losses. Test cycles are steady state and are used worldwide for heavy duty vehicle type approval. Chassis dynamometer simulates a resistive power imposed on the wheels of vehicle. Driver controls the vehicle speed to match the cycle conditions. The test cycles are transient, but the test conditions are limited.

Driving cycles are series of data points for driving speed versus time, which can be either transient or modal. New European Driving Cycle (NEDC) is a common modal driving cycle, but it gives under-estimation of values and has become outdated. On the other hand, Worldwide Harmonized Light Vehicle Test Procedure (WLTP) is based on real-driving data and is much closer estimation for on-road performance. WLTP serves as a global test cycle across the world to get comparable data for vehicles. For sake of this study, WLTP test values are used for BEV range, ICEV tailpipe emission and fuel consumption.

The tail-pipe emissions and fuel consumption of ICEVs are taken from [28] and are given in the *Table 11*

Table 11 ICEV weight, WLTP Fuel consumption and tail-pipe emissions

Vehicle model	Curb Weight kg	Fuel Consumption combined L/100km		CO2 emissions g/km	
		min	max	min	max
Fiat500	865	5.1	5.1	113	113
VW polo	1125	4.8	4.8	108	109
VW Golf	1242	4.8	5.5	110	126
Audi A4	1465	5.7	6.4	129	139
MB E class	1960	6.3	6.7	166	166
BMW 7 series	2035	5.8	6	152	157
Toyota RAV4	1670	5.8	5.9	134	136
Lancia Voyager	2330	7.9	7.9	207	207
Porsche 911	1640	11.1	11.1	254	254

For BEV we have collected from reliable website for the data regarding vehicle weight, battery energy, and energy density. [29] For Tesla models, NCA batteries are used while for rest it is generally NMC. Due to lack of data availability on battery energy density we have assumed NMC battery type and 260 Wh/kg energy density for the vehicles whose battery data was not available. *Table 12*

Table 12 BEV data sheet for battery type, weight, energy denisty and vehicle range

Vehicle model	Battery type	Battery density	Battery weight	Electric Range WLTP
		Wh/kg	kg	km
Fiat500e	NMC	260	92.30	135
Peugeot e 208	NMC	260	192.30	340
ID.3 Pro	NMC	265	169.81	526
Tesla Model 3	NCA	260	305.76	489.2
Tesla Model S	NCA	225	444.44	622.8
Audi etron Sportback 55	NMC	260	365.38	436
Byton M-Byte	NMC	225	422.22	435
Rivian R1T	NMC	225	600	483
Porsche Tycan 4S	NMC	260	304.61	466

The life span assumed for the vehicles in this study are 100000km, 150000km and 200000km where 150000 is taken a reference while other two serve as upper and lower tolerance limit of life span.

Table 13 ICEVs Tail-pipe emissions for all segments at different life spans

ICEV Segment	Total ICEV Tailpipe Emission kgCO2eq/vehicle					
	100,000 km		150,000 km		200,000 km	
	min	max	min	max	min	max
A	11300	11300	16950	16950	22600	22600
B	10800	10900	16200	16350	21600	21800
C	11000	12600	16500	18900	22000	25200
D	12900	13900	19350	20850	25800	27800
E	16600	16600	24900	24900	33200	33200
F	15200	15700	22800	23550	30400	31400
J	13400	13600	20100	20400	26800	27200
M	20700	20700	31050	31050	41400	41400
S	25400	25400	38100	38100	50800	50800

The WLTP cycle tailpipe emissions data was available in g/km of CO2 and no data could be found for other emissions therefore due to lack of availability we have ignored the effect of other GHG emissions in the ICEVs tailpipe in the study. *Table 13*

7 Vehicle End-of-Life Emissions

End-of-life phase consists of emissions due to disposal of vehicle and its components. It includes transportation to shredder, disassembly and dismantling of vehicle, shredding, and recycling or landfilling. A flow diagram of end of life is given for reference in*Figure 14*. [30]

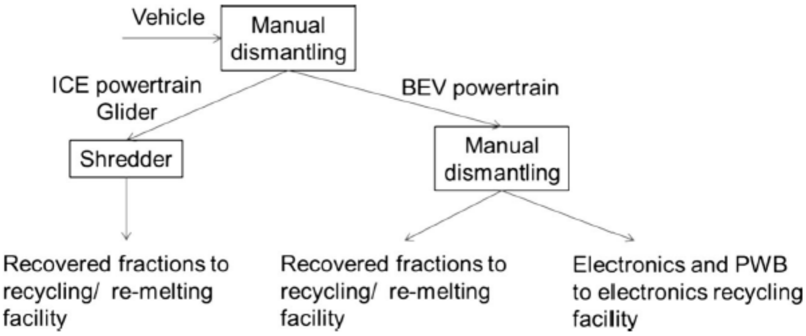


Figure 14 Main steps of end of life of vehicles [30]

7.1 Glider and Powertrain decommissioning

First step involves transport of vehicle to the shredder. ICEV powertrain and glider are shredded while BEV are dismantled manually to recover electronic components and battery for recycling. BEV glider is shredded while recovered fractions and electronics components are sent to recycling facility. Recycling of battery would be explained later with details. Quantity of material recovered from shredded and dismantled fractions are given in the *Table 14*. [30]

Table 14 Fraction of recovered material after shredding and dismantling [30]

Recovered Material Fraction	Quantity per kg shredded glider (g)	Quantity per kg dismantled BEV (g)	Quantity per kg shredded ICEV (g)
Aluminum scrap	4.2	270	409
Copper scrap	6.6	125	5.7
Ferrous Scrap	654	411	299
Plastics	155	0	135
Residue	180	0	153
Electronic component scrap	0	194	0

Emissions during different stages of decommissioning are given in the *Table 15*. [26]

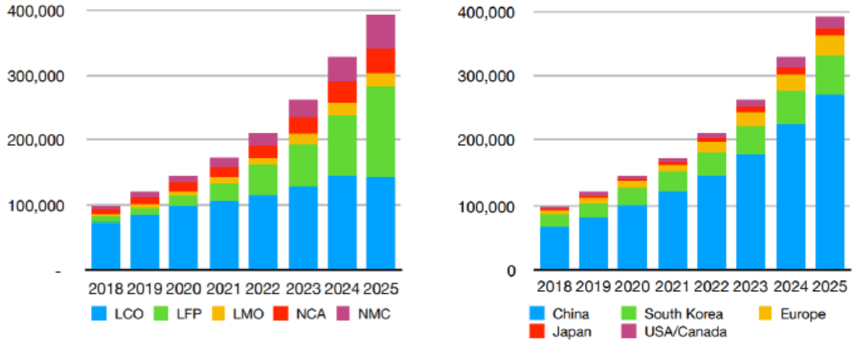
Table 15 CO2 emissions from End of Life Treatment (EOL) for GE, DE, BEV [26]

Process Name	CO2 Emissions kg CO2
Disassembly	0
Shredding & sorting	24
Transport	4
Landfilling	38
Total	65

7.2 BEV Battery decommissioning

Recycling of battery is important for long term sustainability of lithium-ion batteries in addition to economic incentive of material recycling. Moreover, spent LIBs contain harmful substances that are highly explosive and carcinogenic which cause acute toxicity, severe irritation and chemical burns. [31]

Recycling of lithium-ion batteries is currently very uncommon. This is not only due to the lack of economic incentive inherent in the battery chemistries, but this also has to do with very small battery volumes reaching end of life, poor knowledge of battery content and design, and lack of proper marking of the packs and cells. [32] *Figure 15* shows the number of batteries available and recycled by chemistry and geographical location. [31]



A. Lithium-ion batteries available for recycling by chemistry (tonnes/year)

B. Recycling of lithium-ion batteries by geographic location (tonnes/year)

Figure 15 LIB Recycling by battery chemistry and location over years [31]

While 80% of the initial capacity remains, the batteries are no longer good enough to be used in vehicles. This remaining capacity gives an opportunity for prolonging the life of the batteries by reusing them in a less demanding application, thus giving them a second life. However, it is not always easy to quality assure old batteries, making the business of second life batteries more complex and uncertain. [32]System boundary for LIB recycling process is given in*Figure 16*. [31]

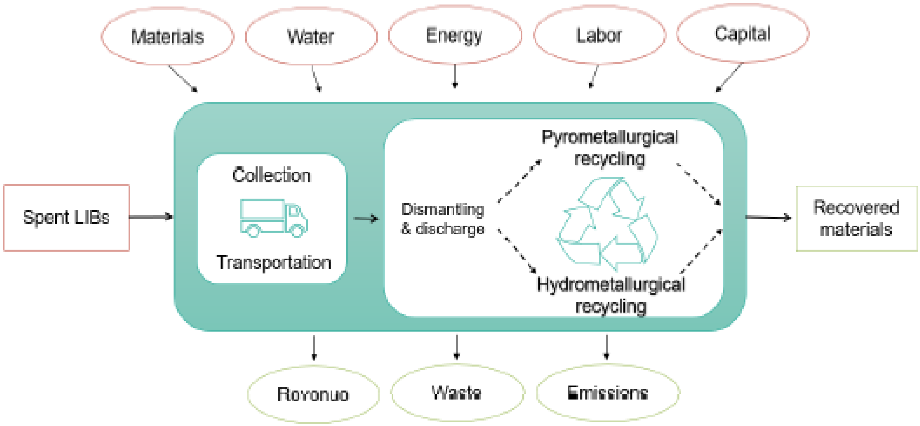


Figure 16 LIB Recycling technologies system boundary [31]

Pyrometallurgy is the major commercialized technology for LIB recycling, the other technology being hydrometallurgy. Pyrometallurgy involves application of heat for metals extraction and purification. A generic pyrometallurgical recycling flow diagram is shown in*Figure 17*. [31]

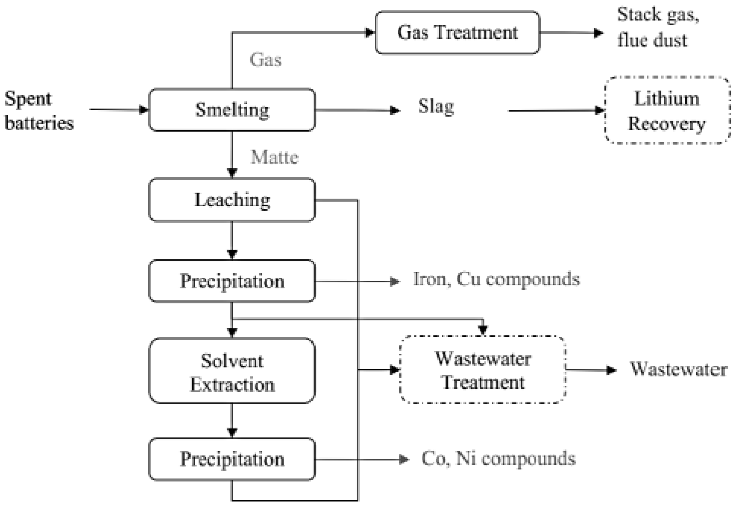


Figure 17 Process diagram of a pyrometallurgical LIB recycling [31]

Hydrometallurgical recycling uses water as a solvent to extract and recover valuable elements from various complex mixes of compounds. [31]

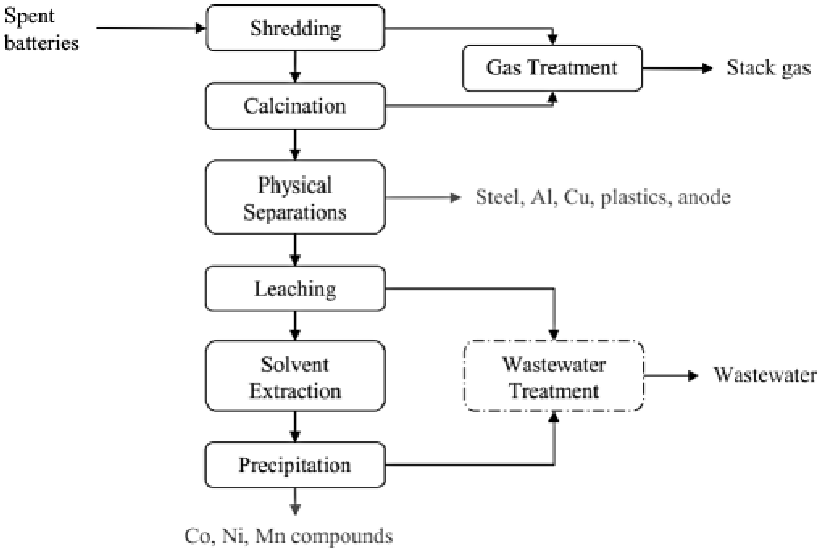


Figure 18 Process Diagram of a hydrometallurgical LIB recycling process [31]

The author has analyzed the energy expense for the recycling technologies currently used by different industries for different battery technologies. *[31]* The energy requirements for both recycling techniques are given in *Table 16*.

Table 16 Energy Usage by sources for recycling of different battery types [31]

MJ/kg cell recycled					
Technology	Battery type	Electricity	Coal	Natural Gas	Petroleum
Hydro	NMC111	2.28	5.96	20.57	1.91
	LMO	2.29	5.87	20.6	1.91
	LFP	2.29	5.87	20.6	1.91
	NCA	2.35	5.79	20.49	1.87
Pyro	NMC111	2.54	6.27	8.66	1.03
	LMO	3.34	2.64	9.86	0.92
	LFP	3.34	2.64	9.86	0.92
	NCA	3.37	2.6	9.8	0.89

Another important to consider here is the collection and transportation of spent batteries. Since the battery recycling is not very common therefore the recycling facilities are very far flung and only available in a few countries. The handling of spent batteries is a very demanding process for energy and cost. Transportation energy GHG emissions are linear with respect to the distance traveled from collection site to recycling facility. *Figure 19* [31]

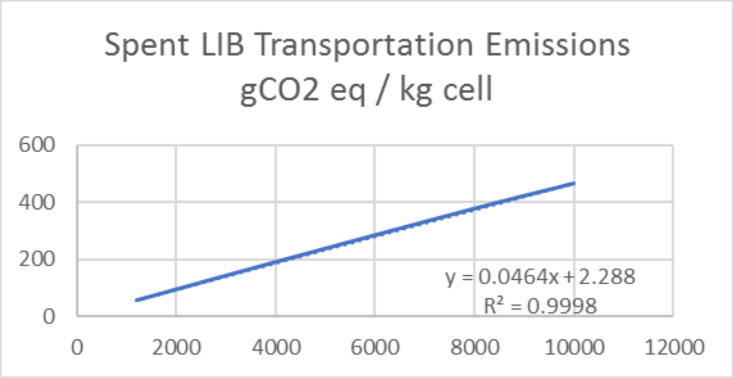


Figure 19 Transportation ghg emissions of spent batteries

Hydrometallurgical recycling generally has higher GHG emissions than pyrometallurgical recycling of LIBs due to higher percentage of other GHG emissions than CO2. The recycling process emissions are given in the *Table 17*.

Table 17 LIB Recycling process GHG emissions in kgCO2eq

Battery type	GHG recycling pyro	GHG recycling hydro
	kgCO2eq/kg cell	
NMC111	2.17	2.28
LMO	1.98	2.27
LFP	2.16	2.37
NCA	2.26	2.28

By using the above assumptions, the overall GHG emissions for LIB recycling are calculated for different locations and vehicle segments at assumed transportation distance of 1000km. The values are given in supporting tables for reference. *Table 20 Table 21 Table 22 Table 23*

8 LCA Emission Results

A summary of vehicle segments along with vehicle category is given in *Table 18* for reference before proceeding to the results.

Table 18 Vehicle Segments and category considered in current study

Vehicle Segment	A	B	C	D	E	F	J	M	S
Vehicle Type	Mini Car	Small Car	Medium Car	Large Car	Executive Car	Luxury Car	Sports Utility	Multi-purpose Car	Sports Car

Total life cycle emissions are obtained by summing the previously calculated emissions of all the LCA phases. The impact of different phases on overall LCA would be discussed periodically in detail.

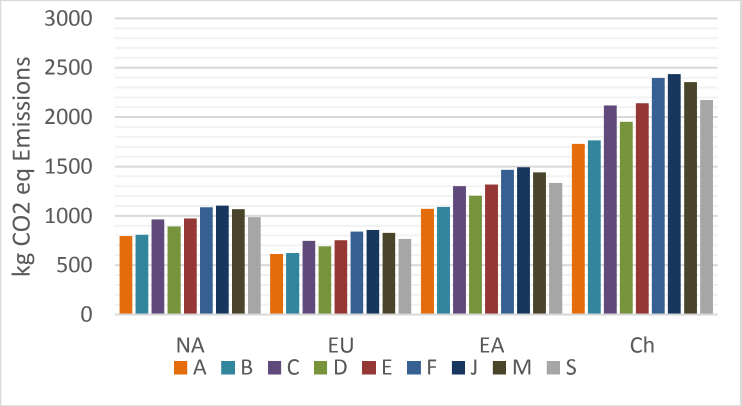


Figure 20 BEV Manufacturing Emission for all vehicle segments in different locations in kgCO2eq

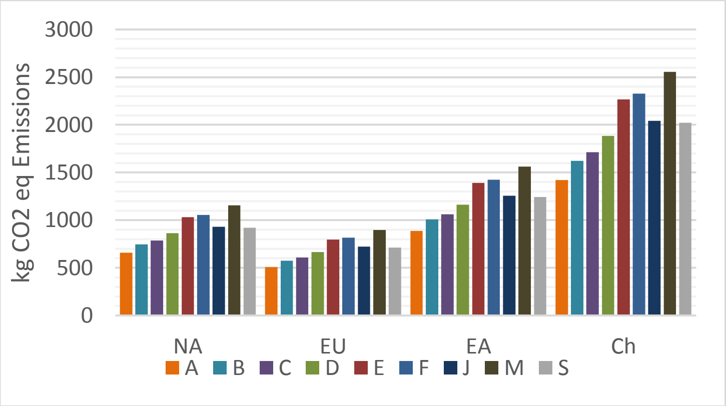


Figure 21 ICEV Manufacturing Emission for all vehicle segments in different locations in kgCO2eq

Consider the above given *Figure 20*, *Figure 23* of manufacturing emissions for ICEVs and BEVs. Both the charts have quite identical trends across the locations. The similarity exists because the manufacturing emissions are dependent only on the weight of vehicles in this study since the material composition is taken same for both type of vehicles although it might be a little different in real due to additional powertrain mass in ICEVs. The emissions are highest for China as compared to other locations due to higher fuel supply chain emissions and a much higher grid average GHG emissions for China. The emissions are gradually increasing for vehicle segments with higher weight. (segment C, F, J, M) Manufacturing emissions are 2-3 times higher for China than EU and NA.

Now consider the bar charts for total production emissions of ICEVs in different locations. *Figure 21*, *Figure 22* The production emissions have similar trend as manufacturing emissions and are higher for higher weight segments. Similarly, the production emissions are 2-3 times higher for China since the production supply chain is assumed same for all geographical locations. Only factor affecting the emissions are again fuel cycle emissions, grid carbon intensity and vehicle weight.

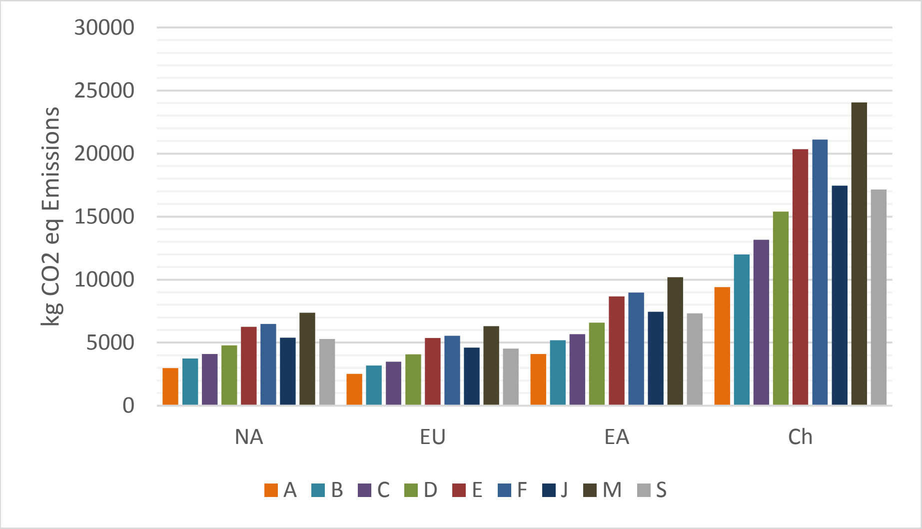


Figure 22 ICEV Production Emissions in kgCO2eq for all vehicle segments in different locations

Now consider the bar charts for total production emissions of BEVs in different locations. *Figure 23* The production emissions for BEVs are considerably higher (30-50%) for BEV as compared to ICEVs for the comparable segment and in some cases its almost double. Similar results were found by other authors as well. [33] and [34]

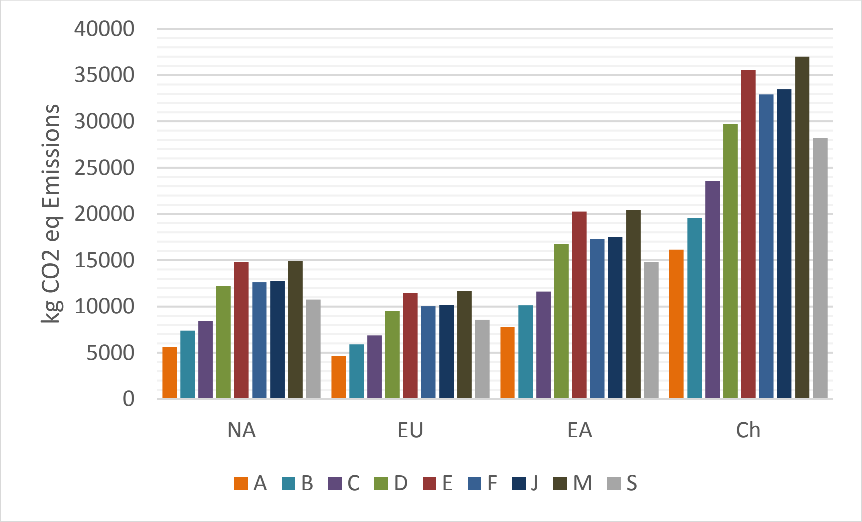


Figure 23 BEV Production emission in kgCO2eq for all vehicle segments in different location

The reason for this addition is the battery production emissions in addition to body production. The emissions are 3 times higher for China again due to high higher fuel cycle and grid carbon intensity. Battery production emission is directly dependent on the battery energy capacity and somewhat also on the battery chemistry. It is evident that the segments with higher battery capacity have higher overall production emissions. (Segment E, M)

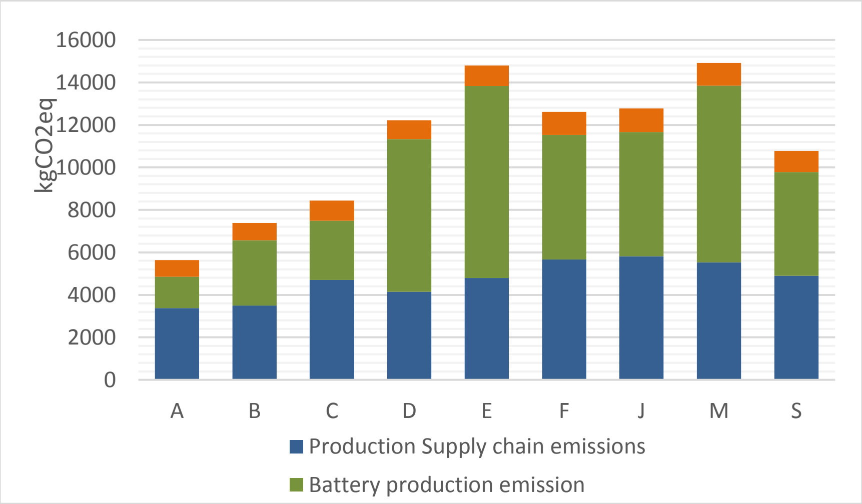


Figure 24 BEV Production emission distributions in kgCO2eq for all vehicle segments for NA

Consider the chart of BEV production in North America for example. *Figure 24* Battery production contributes from 25 to nearly 60 percent of total BEV production emissions. The contributions by battery production are much more prominent around 50 to 60 percent for vehicle segments (Segment D, E and M) with large battery capacity. Body manufacturing emissions contribute 10-15% which is only a small fraction of total BEV production emissions. Important thing to note here is that the production supply chain contributes a major chunk to the total production emissions (30-60%) specially for BEVs with small battery capacity and ICEVs in general.

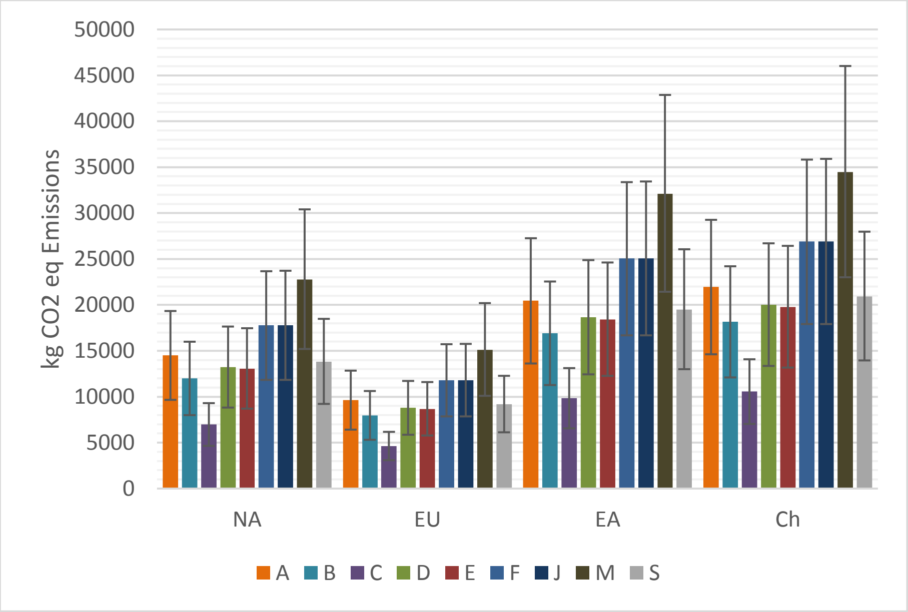


Figure 25 BEV Well to Wheel Emissions in kgCO2eq for all segments and regions for 150000km life span

Now consider the BEV well to wheel emissions for 150000km life span given in the *Figure 25*. The upper and lower tolerance limits show the well to wheel emissions for life spans of 200000km and 100000km respectively which represent the maximum and minimum life of vehicle in terms of distance. The BEV well to wheel emissions only contain the grid average CO2eq emissions since the tailpipe emissions of BEVs are considered zero. Thus, the well to wheel emissions are much greater for China as compare to other locations. Vehicle segments with lower battery energy density (segment J, M) and vehicles with higher weight (segment F, J, M) have higher WTW emissions since the range of BEV is dependent on these factors. Important thing to mention here is the battery well to wheel efficiency. For BEV, battery charging discharging efficiency, grid efficiency and, processing/recovery efficiency are assumed to be 0.86, 0.92 and 0.94. [35]

Now consider the well to wheel emissions chart for ICEV segments in different locations. *Figure 26* ICEV well to wheel emissions are much higher compared to BEVs. ICEV well to wheel emissions range from 2 to 3 times the amount for comparable BEV segment. The reasons for this gap are the high tailpipe emissions and fuel cycle emissions for fossil fuels. Secondly, ICEVs with higher weight (segment E, F, M) and vehicle segments with higher fuel consumption (segment S) have higher WTW emissions since well to wheel emissions are directly dependent on the fuel consumption. Lastly the emissions increase linearly with increasing lifetime distance.

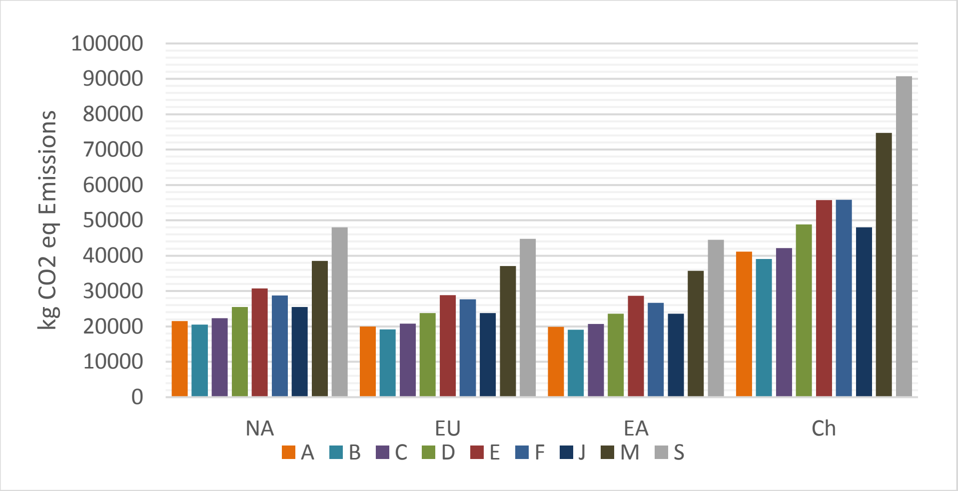


Figure 26 ICEV Well to Wheel emissions for all segments at all locations for 150000km

Consider the ICEV well to wheel emission contributions in percentage for EU and China for 150000km life span. *Figure 27* The tailpipe emissions contribute around 82% while fuel cycle emissions contribute only 18% of the total well to wheel emissions for ICEVs in EU. In contrast, fuel cycle emissions contribute 55-60% of total well to wheel emissions for China while tailpipe emissions are nearly 40%. The reason for this difference is very high carbon intensity of fuel cycle in China. The transportation and refining of petroleum-based fuels is much more carbon intensive in China as compared to EU.

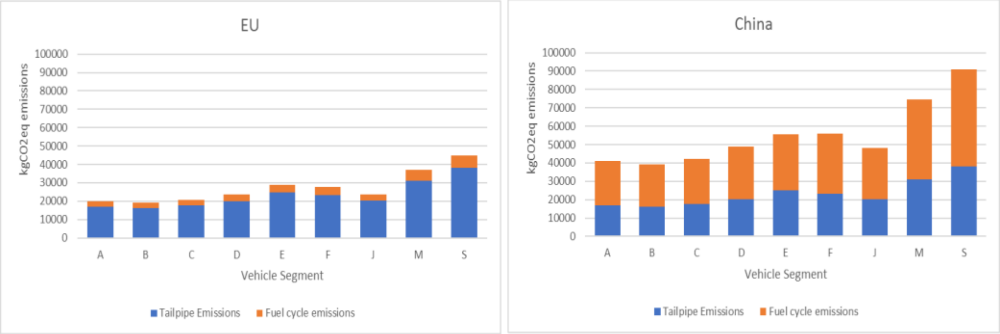


Figure 27 ICEV well to wheel contribution comparison between EU and China

Consider the total life cycle emissions by all segments of ICEVs and BEVs at different locations for 150000km life with upper and lower tolerance limits at 100000km and 200000km. *Figure 28*

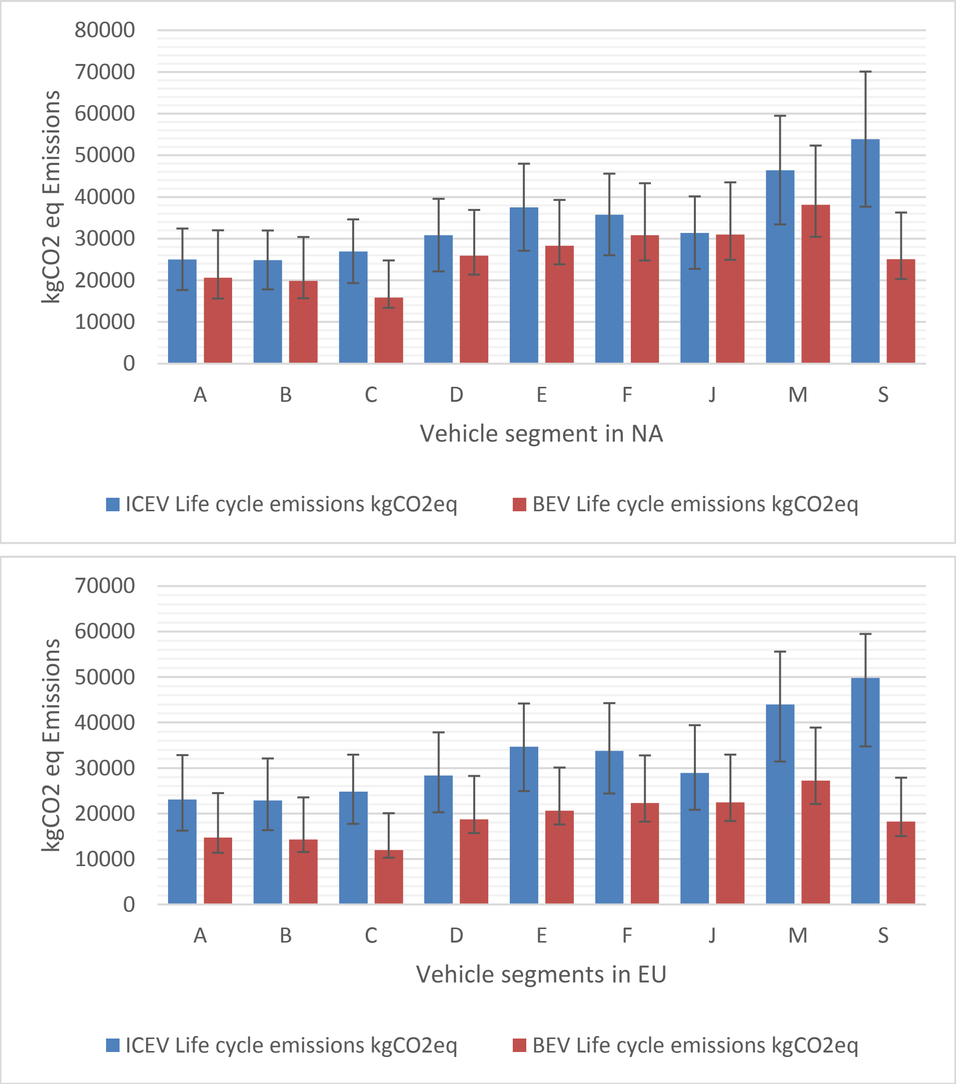


Figure 28 ICEV vs BEV life cycle GHG emissions in kgCO2eq for all segments for NA and EU

ICEV emissions are more than double for all segments for EU as compare with BEV equivalents. Whereas for EA, ICEV emissions are less than BEV. This is due to high grid carbon intensity and low fossil fuel cycle emissions. ICEV emissions are also higher for NA and China than BEV. For sports segments ICEV emissions are even more than double.

The increase in LCA emissions from 100,000km to 150,000km does not give much rise to overall LCA emissions of BEVs whereas for ICEVs 25-30% increase of emissions occurs if we increase the distance by same amount. This can be attributed to much higher contribution of tailpipe emissions and fuel cycle emissions (well to wheel emissions) in ICEV life cycle as compared with BEVs. Increase to 200000km distance increase the BEV life cycle emissions considerably due to battery replacement required for such a long life. Battery life of maximum 160,000km has been mentioned by most manufacturers after which the battery loses more than 20% of its overall capacity and is no more deemed usable. This puts a limit on the life of BEVs since the secondary usage of LIB is

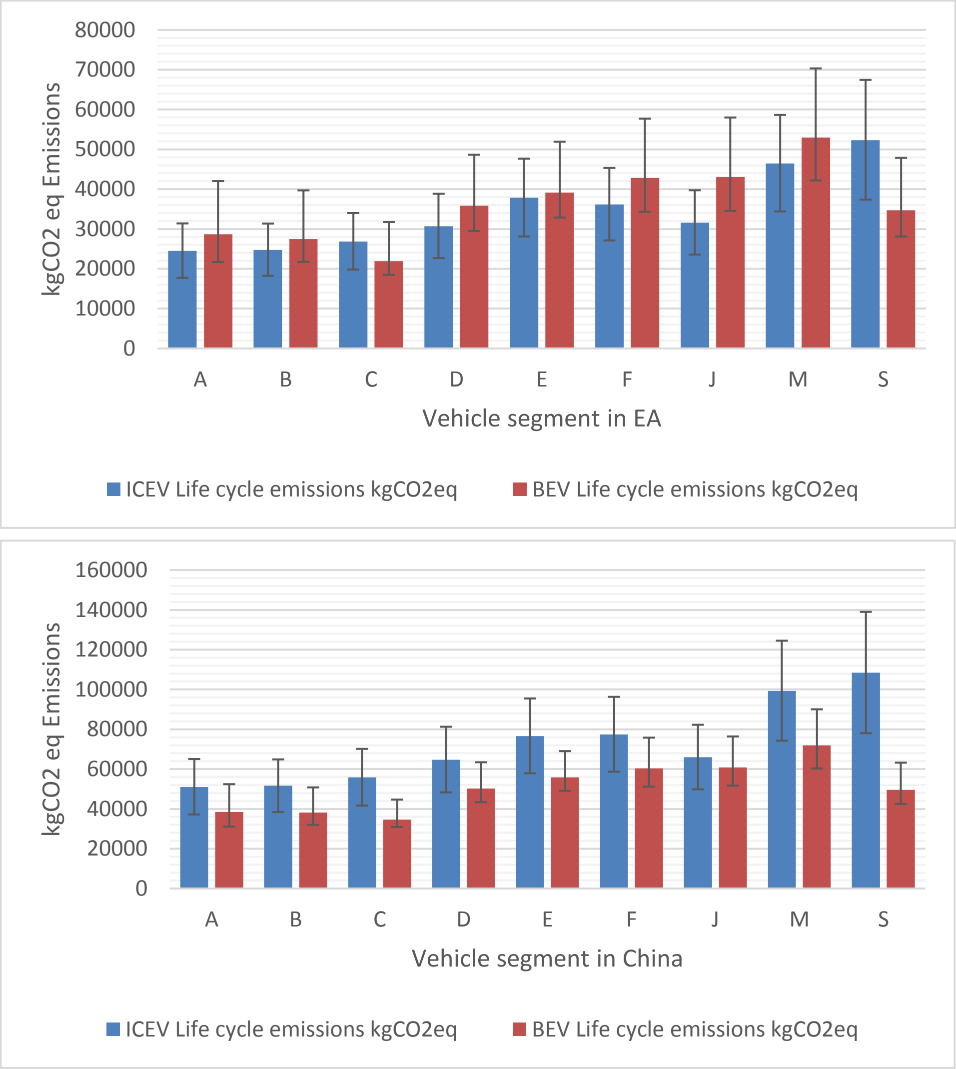


Figure 29 ICEV vs BEV life cycle GHG emissions in kgCO2eq for all segment for EA and China

not commercial yet. However, with the growth of LIB industry and increase in BEV usage across the globe, the secondary usage of LIBs has been sought out.

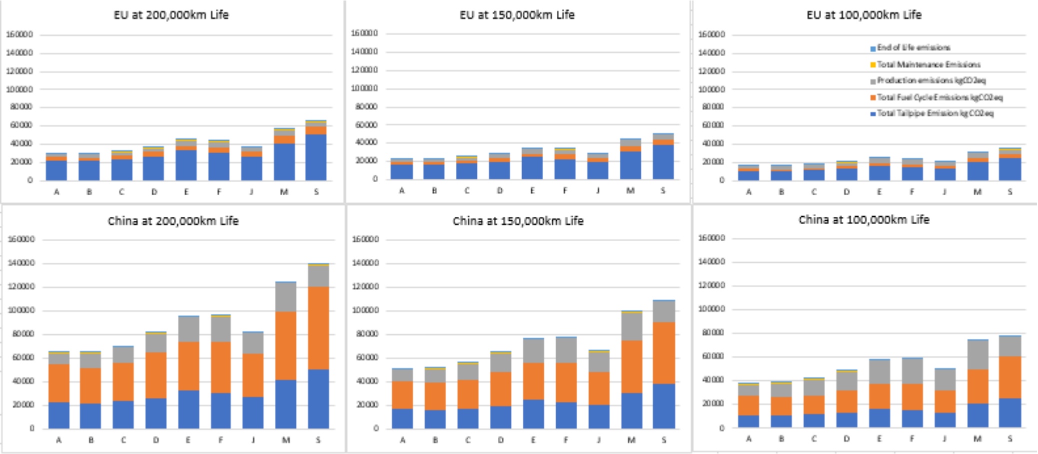


Figure 30 ICEV LCA contribution in kgCO2eq of different stages for EU and China

For ICEV LCA emissions for EU, tailpipe emissions contribute 65-80% of total life cycle emissions. The contribution is higher for higher 200,000km life and for luxury and sports segment vehicles. Production emissions are the second biggest contributor for 100000 km and 150000 km life while Fuel cycle emissions contribute only around 10 percent. For 200000km life fuel cycle emissions have second biggest contribution due to very large distance traveled.

For China, tailpipe emissions contribute roughly 25-30% of total life cycle emissions. In contrast to EU, fuel cycle emissions are the biggest contributor of around 25-40% to total emissions in China. Production emissions are important contributor with 15-30% of total emissions. They become particularly important in case of shorter 100k km life tenure and for segments with heavy weight. End of life and maintenance emission contributions are very minute for ICEVs in general. *Figure 30*

Now consider the BEV life cycle emissions contributions by different stages for EU and China for all segments. *Figure 31*

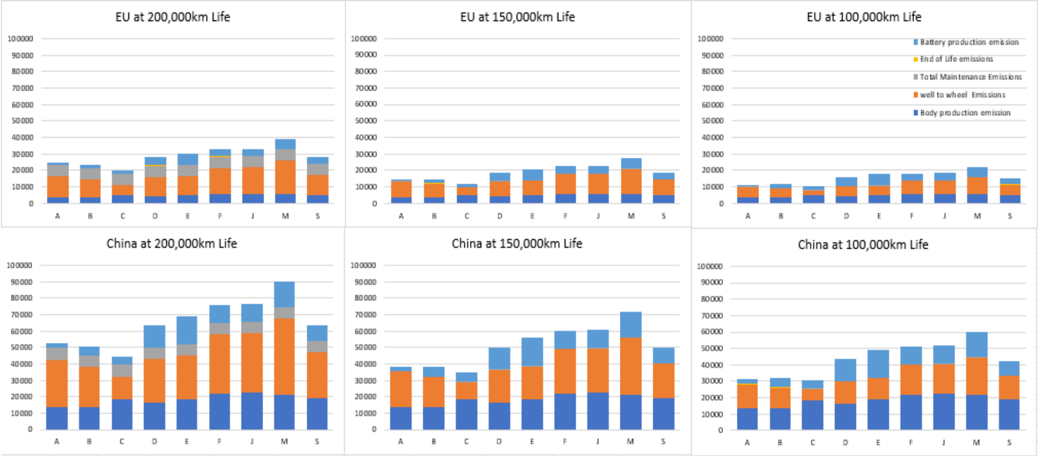


Figure 31 BEV LCA contribution in kgCO2eq of different stages for EU and China

For BEVs in EU, well to wheel emissions are significant part of LCA due to high gird average CO2eq emissions in general and particularly for China. Battery and body production emissions are significant ranging from 35% to 70% depending on vehicle weight and battery capacity for 100k km, however they are less significant for higher distances.

For BEVs in China, body production and battery production emissions are much significant due to high grid carbon intensity specially at lower life spans. WTW emissions are important at higher life spans due to same factor.

End of life and maintenance emission contributions are minute except 200000 km life where maintenance emissions become significant due to LIB replacement at 160,000km.

Now consider the emissions for LIB recycling in different locations by using both available technology options. 1000km spent LIB transportation distance is taken as reference for all the charts. Upper and lower tolerance limits are for transportation distance of 500km and 10000km which give maximum and minimum values. The recycling emissions are directly dependent on LIB cell weight (kg), therefore vehicle segments with higher range and lower energy density vehicles have higher recycling emissions. Recycling emissions are higher for China due to higher carbon intensity of grid and fossil fuel cycle.

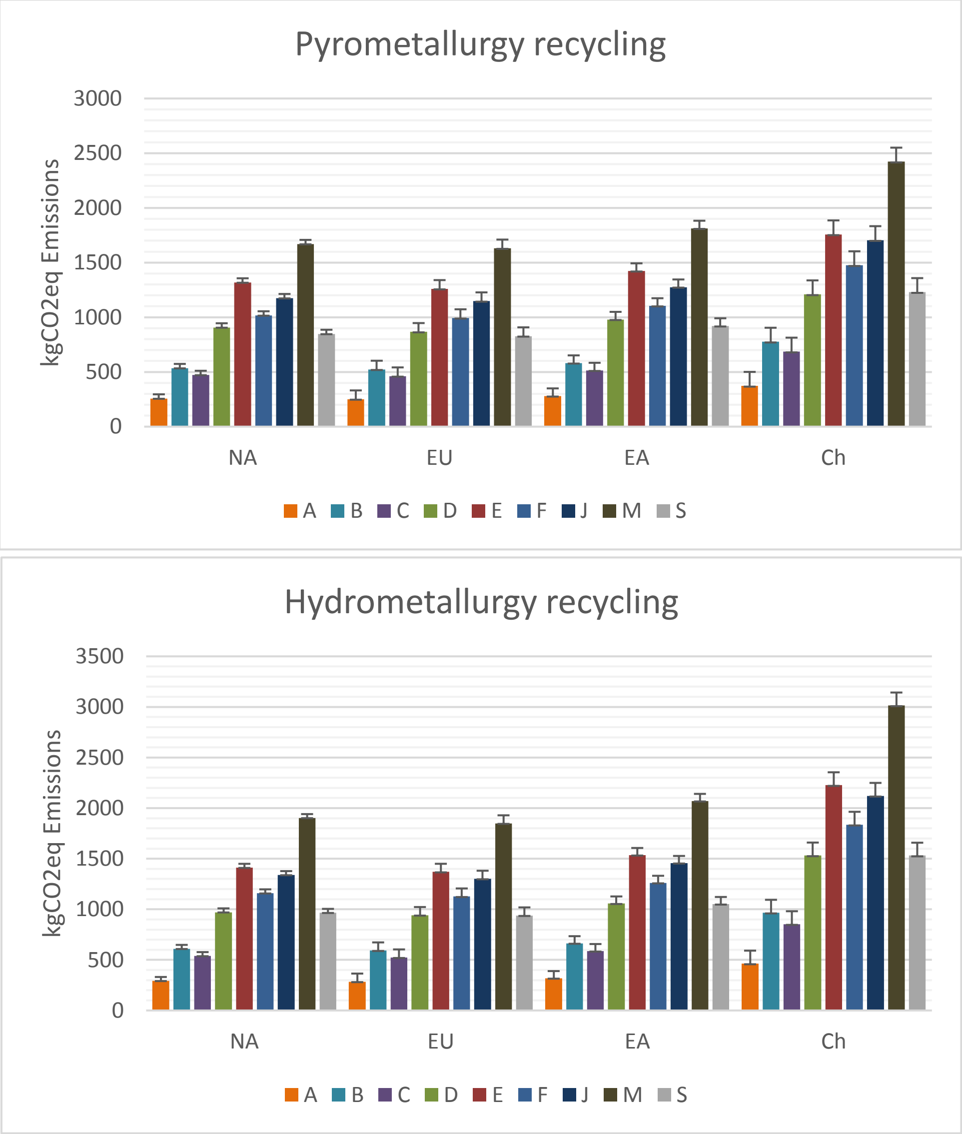


Figure 32 LIB Recycling emissions in kgCO2eq for all segments by pyro and hydro metallurgy in different regions

Pyrometallurgical recycling has higher use of utilities in the recycling process. However, hydrometallurgical recycling has higher total energy intensity due to high energy consumption in materials production and transportation. Hydro recycling has overall lower CO2 emissions but the increased GHG impact comes from high SOx, NOx and CH4 emissions during the process. Although the emissions are higher for hydrometallurgy, the quality of recycling is much better. Emissions for both technologies are compared in the chart for all segments in EU.

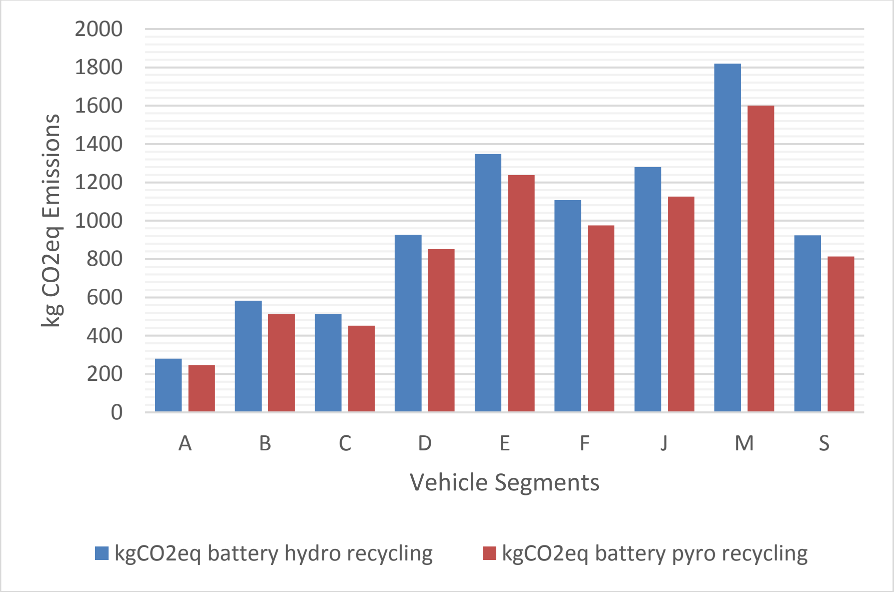


Figure 33 Battery recycling emissions in kgCO2eq for pyro and hydro metallurgy in EU

The LIB recycling facilities are scarce and not easily available therefore the collection and transportation distance of spent LIBs would be considerably high. Since battery pack are inflammable therefore their transportation and handling require special care. Thus, long distance transportations are not commercially feasible. It is only feasible if the transportation distances are much lower than 1000km.

Overall positive effect of battery recycling on BEV life cycle emissions is considerably high regardless of the technology used for the recycling and location of recycling facility.

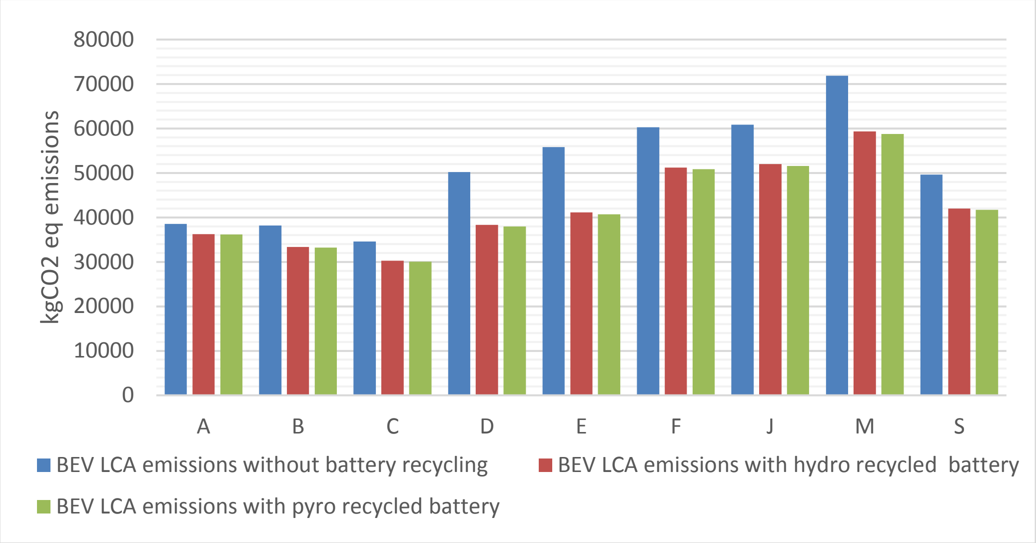


Figure 34 BEV life cycle comparison with and without recycling for all segments for EU

BEV LCA emissions with LIB recycling are not much lower for smaller segment vehicles while for segments with bigger battery packs, it is quite considerable. This is mainly due to large battery capacities of these segments and thus much higher battery production emissions. There can be 5 to 15% overall LCA GHG emission reduction by using battery packs manufactured from recycled LIBs as seen from the chart. Another important factor to consider is the secondary usage of batteries which are yet very common commercially since there is not much demand of used batteries. However, BEV batteries are deemed unusable after losing 20% of their maximum potential, they still have 80% potential left which can be used for some secondary use. Recently there have been some developments in this regard but nothing particular to mention. Therefore, secondary usage of spent LIBs is not considered the study.

Another important perspective to consider is the breakeven point for LCA emissions of BEVs and ICEVs which is the point where total LCA emissions of ICEVs become equal to the total LCA emissions of BEVs. Taking the current values of grid average CO2 emissions for all locations we can find the distance traveled for which breakeven would occur.

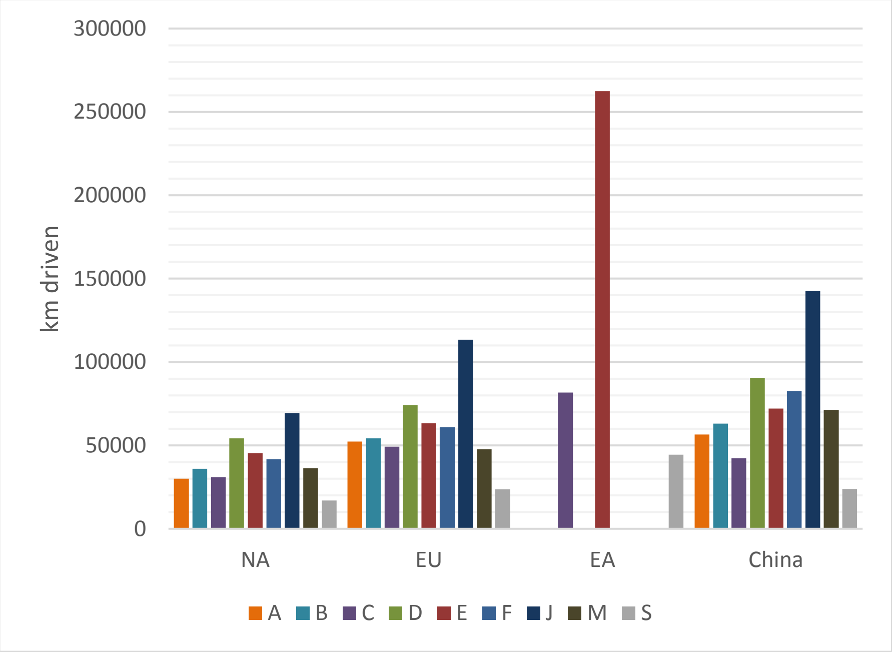


Figure 35 Breakeven distance driven in km for LCA emission of ICEVs and BEVs for all locations and segments

Consider the chart which gives breakeven point distance for all segments at different locations. For EA, the breakeven distance is not possible or extremely high if possible, due to very high grid carbon intensity and comparatively low fossil fuel cycle CO2eq emissions. For the remaining locations, breakeven occurs at very low distances compared with the total vehicle life which is taken between 100000km and 200000km in this study. The breakeven distance is lower than 75000km for of the conditions. Higher distance for segment D and J is mainly due to high battery production emissions and due to their high weight. It is observed to be extremely low for sports vehicles which can be related to high fuel consumption and high tail-pipe emissions of sports ICEVs. Moreover, higher distance values for China are due to its higher grid carbon intensity although its fuel cycle emissions are also high.

Another factor consider is that the grid CO2 emissions are not constant for any country. These emissions vary not only from one region to another within a country, but they vary considerably from one day to the other and even on hourly timeframe. Therefore, we have used the average grid CO2 emissions for all the locations. However, it is important to find the breakeven grid carbon intensity for all locations if the comparison of ICEVs and BEVs is studied.

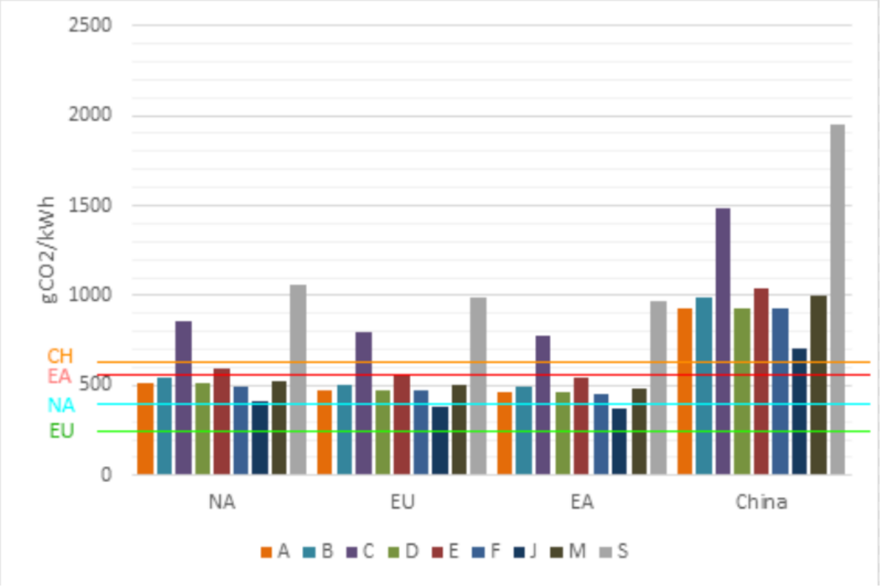


Figure 36 Breakeven grid carbon intensity gCO2/kWh for different lcoations and segments at 150000 driven distance

The values are calculated for all segments at different locations keeping their fossil fuel cycle carbon intensity constant and total traveled distance constant at 150000km. The only variable considered is just the grid average carbon intensity change. First thing to observe is that the breakeven points for sports vehicles are extremely high due to excessive fuel consumption and tail-pipe emissions for ICEV sports segment vehicles. Segment C is also anomaly mainly due to its very high weight. For all the locations, breakeven values are higher than current carbon intensity except EA which means that at current grid carbon intensity the BEV LCA emissions are lower than ICEV emissions. EA has lower breakeven point than its actual average grid carbon intensity which means it has to improve its high grid carbon intensity to utilize the LCA emission reduction potential of BEVs. Breakeven values range 410-610g/kWh for NA, 380-560g/kWh for EU, 360-500g/kWh for EA, 700-1050g/kWh for China for different segments except anomalies.

Another point to discuss here is the importance of vehicle production plant location on the overall LCA specially for vehicle used in EU and NA. For BEVs both the location of vehicle body production plant as well as battery production plant are important. To understand this concept, we have studied the effect of changing location of production from EU to China for the vehicle used in EU. There are two different cases for BEV. Firstly, case-I with total production in China, and secondly, case-II with only the battery production in China while case-III is total production in EU.

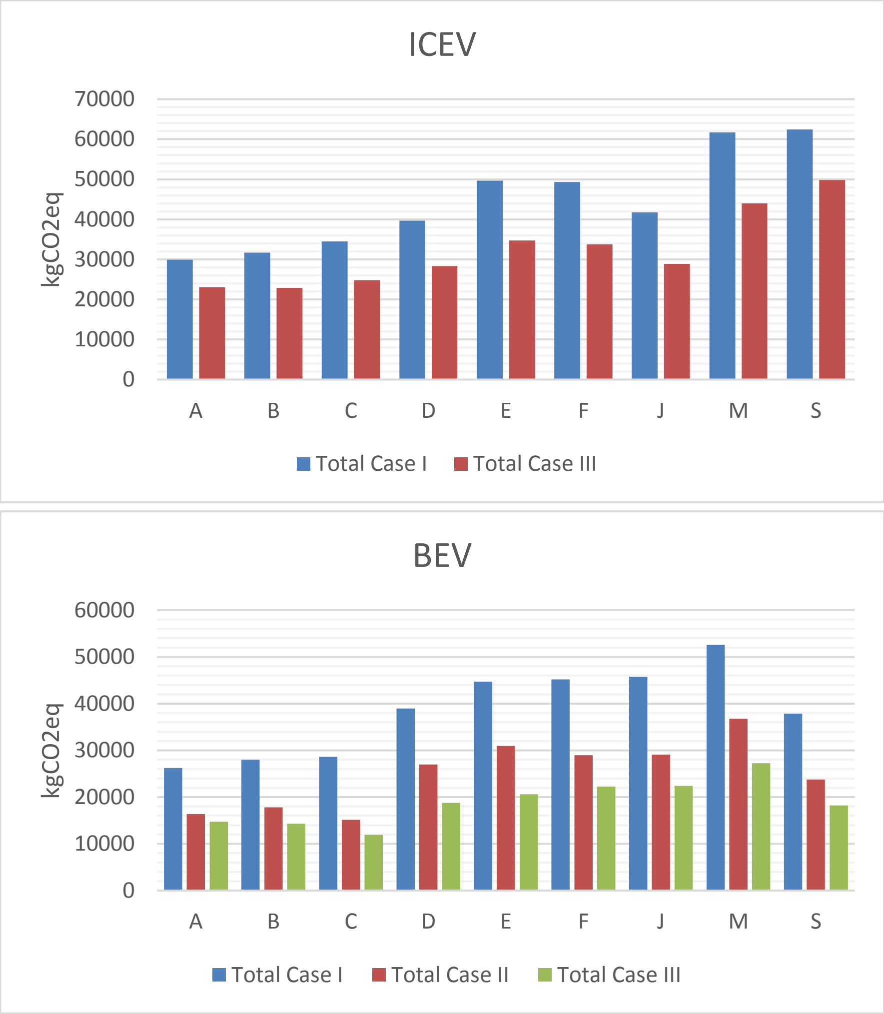


Figure 37 Production location effect on LCA emissions of ICEVs and BEVs for EU scenario for 150000km distance. Case I: Total production in China, Case II: Only BEV battery produced in China, Case III: Total production in EU

Bar charts show the LCA emissions for both ICEVs and BEVs for 150000km distance life for EU. The calculations reveal that 25-46% increase of ICEVs LCA emissions occur by moving vehicle production location from EU to China. The impact is particularly important for vehicles with heavy body weight. For BEVs, an increase of 11-50% occur by moving only battery production to China while 78-140% increase occur if we move both battery and vehicle production from EU to China for vehicle used in EU. This point is important to discuss due to the cost effectiveness of having manufacturing plants in Asia rather than Europe and the main reason behind which is cheap and less demanding labor in Asian states as compared to EU.

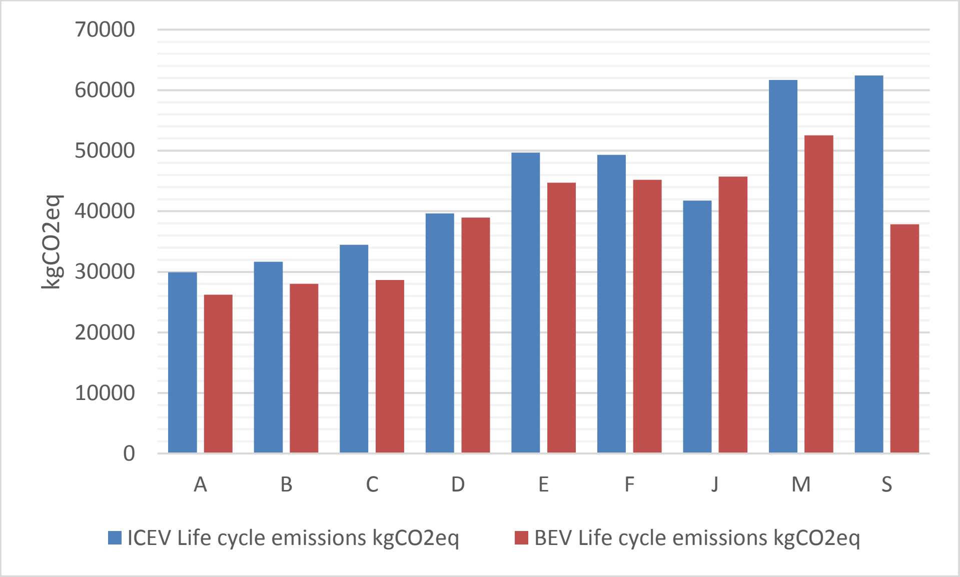


Figure 38 ICEV vs BEV LCA emissions for EU at 150000km life with total production (including battery for BEV) in China

A comparison of LCA emissions of BEVs and ICEVs for vehicles used in EU and 150000km distance life is given when the vehicles are produced completely is China. The effect of vehicle transportation is not included in the study for simplicity. For total vehicle production in EU, BEV LCA emissions are around 40-60% lesser than ICEV LCA emissions. Whereas for total vehicle production in China, ICEV LCA emissions are almost comparable with BEV although still a bit higher. The values become comparable due to high carbon intensity of electricity grid in China. For sports segment ICEV emissions still are much higher than BEVs of same segment.

A comprehensive summary of life cycle emission data from different studies is given in *Table 19* for reference and comparable values of this study are also given.

Table 19 Comparison with past LCA studies on ICEVs and BEVs

Alternate study	Vehicle type	Location, life span	LCA Values	This Study corresponding value
[36]	ICEV	North America, 250000km	336.7gCO2eq/km	192 gCO2eq/km at 200000 km (seg D)
	BEV		122.6gCO2eq/km	152 gCO2eq/km at 200000 (seg B)
[37]	ICEV	North America, 150000km	240-400 gCO2eq/km	165-358 gCO2eq/km at 150000 km
	BEV		140-200 gCO2eq/km	120-292 gCO2eq/km at 150000 km
[30]	BEV	Global 150,000km	239 gCO2eq/km	182 gCO2eq/km at 150000km (seg D)
[38]	ICEV	Germany 150,000km	25000-30000 kgCO2eq	24400-53200 kgCO2eq at 150000km EU
	BEV	Germany 150,000km	17000-27000 kgCO2eq	13400-31500 kgCO2eq at 150000km EU
[39]	BEV	EU 200000km	82gCO2eq/km	100 gCO2eq/km EU (seg A)
[40]	ICEV	NA 290000 km	280gCO2eq/km	198 gCO2eq/km at 200000 km (seg D)
	BEV		211gCO2eq/km	184 gCO2eq/km at 200000 km (seg D)
[41]	ICEV	China 150000km	49985 kgCO2eq	55800 kgCO2eq at 150000 China (seg C)
	BEV		40983 kgCO2eq	38200 kgCO2eq at 150000 China (seg B)
[42]	ICEV	China 200000km	170 gCO2eq/km	324 gCO2eq/km (seg A)
	ICEV	US 200000km	130.88 gCO2eq/km	160 gCO2eq/km (seg A)
	ICEV	EU 200000km	55.51 gCO2eq/km	152 gCO2eq/km (seg A)

	ICEV	Asia 200000km	125.28 gCO2eq/km	163 gCO2eq/km (seg A)
	BEV	China 200000km	248.28 gCO2eq/km	262 gCO2eq/km (seg A)
	BEV	US 200000km	262.9 gCO2eq/km	160 gCO2eq/km (seg A)
	BEV	EU 200000km	195.33 gCO2eq/km	122 gCO2eq/km (seg A)
	BEV	Asia	194.3 gCO2eq/km	210 gCO2eq/km (seg A)
[43]	ICEV	china 250000km	2290 kgCO2eq	64800 kgCO2eq at 200000 (seg A)
	BEV		8620-12300 kgCO2eq	52430 kgCO2eq at 200000 (seg A)

Values of LCA emissions by most of the authors resonate with the value range of this study. Discrepancies are present for some studies and there are several reasons for that. This study is found to give overestimated values in some cases when compared with other studies. This study relies mostly on bottom-up approach for different phases which generally gives higher-end value as compare with top-down approach. [43] does not take into account the well to tank emissions in their study that’s why there is a huge difference in results. LCA values by [42] for BEVs are higher than this study but for ICEVs they give a bit lower estimate. One reason is that they have used an average fuel/vehicle consumption data for the study. They also do not consider the vehicle cycle in their study and that is why all their ICEV LCA values are considerably lesser than this study. A complete vehicle LCA is studied by [41] for China and their values are concurrent with this study. The values by [40] are also similar if we use same distance in this study. Values by all other studies lie within the range of emission values for different segments studied here. The reasons for discrepancies with other studies are mainly due to different set of assumptions taken by different studies for simplicity and due to lack of data availability.

9 Conclusion

Life cycle assessment in the study includes emissions during production (material extraction, supply chain and transformation) of vehicle and battery, well to wheel (well to tank and tailpipe) emissions, maintenance, and End of life emissions. The study relies on secondary data provided by past researchers to build a model that gives emissions during all phase of LCA. The results are collected and compared for nine different vehicle segments at four different geological locations with different fossil fuel cycle emissions and different electricity grid average CO2 emissions. The results are taken assuming total driven distance of 150000km with a sensitivity of ±50000km and results are given in kgCO2eq/vehicle and gCO2eq/km. The results from the study suggest that BEVs can provide a solution to the problem of increasing emissions by transportation sector. However, it is only feasible if certain conditions and requirements are met.

Manufacturing emissions trend for ICEV and BEV are same due to constant body composition assumed in the study. Total production emissions for BEVs are higher than ICEVs due to additional battery production emission contributions. Production emissions are higher for segments with higher weight and higher battery capacities. Total production emissions are higher for China due to higher grid average CO2 emissions compared to other locations. The BEV well to wheel emissions depend mainly on the grid average CO2eq emissions and are thus much greater for China and EA. The ICEV well to wheel emissions are found to be 2-3 times higher as compared to BEVs WTW emissions, but it depends on the difference of grid average CO2eq emissions and petroleum fuel cycle emissions. Total life cycle ICEV emissions are almost double than BEV emissions for all segments for EU whereas for EA, ICEV emissions are less than BEVs. This discrepancy is due to high grid carbon intensity and low fossil fuel cycle emissions in EA. Following the same trend, ICEV emissions are also higher for NA and China as compared to BEV counterparts. For sports segments, ICEV emissions are even more than double in all cases. LCA emission reduction effect after LIB recycling is not much prominent for smaller segment vehicles while for segments with bigger battery packs, it is quite considerable and 5-15% overall LCA GHG emission reduction is possible by using battery packs manufactured from recycled LIBs.

The location of battery and vehicle production location was studies case of vehicle used within EU for 150000km distance life. ICEV LCA emissions increase by 25 to 46% by shifting the production location from EU to China while BEV LCA emissions increase by 11-50% by moving battery production to China and 78-140% increase by moving total vehicle and battery production from EU to China. For total vehicle production in EU, BEV LCA emissions are around 40-60% lesser than ICEV whereas for total vehicle production in China, ICEV LCA emissions almost comparable with BEV LCA emissions although they are still a bit higher. The increase is due to higher fossil fuel cycle emissions and grid carbon intensity of China as compared to EU. The ICEV and BEV LCA emissions are extrapolated to be equal at certain grid carbon intensity values for all locations. For all the locations, these points are higher than the current carbon intensity except EA which has low fuel cycle emissions but very high grid carbon intensity. Breakeven values range is 410-610g/kWh for NA, 380-560g/kWh for EU, 360-500g/kWh for EA, 700-1050g/kWh for China for different segments except sports vehicles which are anomalies. Similarly, total distance driven can change the breakeven point. For EA breakeven distance is not possible or extremely high due to its very high grid carbon intensity. For remaining locations, breakeven occurs at very low distances compared with total vehicle life and found to be lower than 75000km for most part. BEV LCA emissions are extrapolated and future LCA values are calculated by using EU electricity carbon intensity goals provided by IEA. Total BEV LCA emissions decrease by 49-59% and 65-71% from current emissions till 2030 and 2040. However, only a maximum of up to 5% change in LCA emissions is observed for ICEVs even at 2040 electricity carbon intensity.

The battery production emissions, which are 25 to 60% to total BEV LCA emissions, should be minimized by reducing the electricity grid average carbon emissions. Similarly, if grid carbon intensity is controlled and kept under a certain level, the well to wheel emissions of BEVs would also be directly reduced. It is beneficial to use BEVs in countries with lower grid average carbon intensities. However, to use the maximum potential of BEVs, it is advisable to produce their batteries as well as vehicle bodies in regions with low grid average carbon intensities. Another important factor is to consider battery recycling and secondary life of batteries in BEV life cycle. If the battery recycling methods are performed with lower emission costs and secondary usage of batteries is made commercial, the life cycle emissions of BEVs can be considerably reduced further. Ongoing research works to increase the total battery lifetime beyond 160000km can also be useful to avoid the battery replacement emissions for longer life distances. Cleaner and green energy production methods should be adopted globally to reduce the grid average carbon intensities and to realize long term net zero-emission goals.

10 Future Work

Although this study tries to cover wide range of variables within the LCA of emissions of vehicles, still there is a massive room of research potential in the subject. The room occurs mainly due to ongoing research in the field of BEVs and particularly in LIBs to increase their range, overall life, charge/discharge efficiency and energy density and to reduce to weight of batteries and the vehicle in general. There is not much reduction potential in the reduction of emissions from fuel cycle of conventional fuels, but alternative fuels are being sought out and a lot of research is ongoing about their emissions. Recycling of batteries is still comparatively a new topic and has a big potential in the future to decrease the battery production emissions. Secondary life of batteries has also been in the highlights, which if made possible on commercial scale, can greatly impact overall BEV life cycle. New advancements in vehicle design and material compositions have already proved to impact the life cycle a big deal by replacement of ferrous metals with aluminum. Improvements in production methods can be a factor to consider. Furthermore, the improvement in overall grid carbon intensity by adopting renewable particularly hydro and wind power production can greatly impact the overall life cycle.

Keeping in mind all the above-mentioned factors, a more specific approach can be taken to analyze the life cycle emissions of BEVs and ICEVs in a specific country. For BEVs, the charging time is also important since the grid carbon intensity also varies with the hour of the day. Availability of the data on the production material supply chain for a particular country and their fuel cycle carbon intensity can be helpful to get a more specific LCA emissions inventory for that country. The values can be used to compare and compute LCA values relative to 2030 and 2050 GHG emission reduction goals and thus better recommendation can be provided regarding the matter. The whole production cycle for different vehicle producers should be considered to understand the exact contribution of production phase in whole LCA of emissions. Transportation of vehicles prior to usage should also be considered once the manufacturing and assembly locations of manufacturers are known. Lastly, the study can be extended to PHEVs to study the effect of utility factor on the LCA and fuel cell vehicles and other alternative fuel vehicles LCA can also be added to list. Sports vehicles can also be studies separately from others due to massive change in scale of LCA emissions for their case.

11 Bibliography

[1] M. Jarraud and A. Steiner, *Summary for policymakers*, vol. 9781107025. 2012.

[2] U. S. E. P. Agency, “EPA.” https://www.epa.gov/.

[3] European Commission, “European Commission,” 2021. https://ec.europa.eu/.

[4] IEA, “Internation Energy Agency,” 2021.

[5] H. Hao, Q. Qiao, Z. Liu, and F. Zhao, “Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The China 2025 case,” *Resources, Conservation and Recycling*, vol. 122, pp. 114–125, 2017, doi: 10.1016/j.resconrec.2017.02.005.

[6] SETAC, “SETAC,” 1991. https://www.setac.org/.

[7] A. Nordelöf, M. Messagie, A. M. Tillman, M. Ljunggren Söderman, and J. van Mierlo, “Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment?,” *International Journal of Life Cycle Assessment*, vol. 19, no. 11. Springer Verlag, pp. 1866–1890, Oct. 14, 2014, doi: 10.1007/s11367-014-0788-0.

[8] J. Patterson and A. Johnson, “Final Report for LowCVP Confidential LowCVP and Project Steering Group Report by Understanding the life cycle GHG emissions for different vehicle types and powertrain technologies,” 2018.

[9] A. Burnham, M. Wang, and Y. Wu, “Development and Applications of GREET 2.7-The Transportation Vehicle-Cycle Model Energy Systems Division.” [Online]. Available: www.anl.gov.

[10] G. Keoleian, S. Miller, R. de Kleine, A. Fang, and J. Mosley, “Life Cycle Material Data Update for GREET Model,” 2012. [Online]. Available: http://css.snre.umich.edu.

[11] Q. Dai, J. C. Kelly, L. Gaines, and M. Wang, “Life cycle analysis of lithium-ion batteries for automotive applications,” *Batteries*, vol. 5, no. 2, Jun. 2019, doi: 10.3390/batteries5020048.

[12] IPCC, “IPCC,” 1996. https://www.ipcc.ch/.

[13] and M. W. J.L. Sullivan, A. Burnham, “Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing Energy Systems Division.” [Online]. Available: www.anl.gov.

[14] J. C. Kelly, J. L. Sullivan, A. Burnham, and A. Elgowainy, “Impacts of Vehicle Weight Reduction via Material Substitution on Life-Cycle Greenhouse Gas Emissions,” *Environmental Science and Technology*, vol. 49, no. 20, pp. 12535–12542, Oct. 2015, doi: 10.1021/acs.est.5b03192.

[15] S. Dühnen, J. Betz, M. Kolek, R. Schmuch, M. Winter, and T. Placke, “Toward Green Battery Cells: Perspective on Materials and Technologies,” *Small Methods*, vol. 4, no. 7, 2020, doi: 10.1002/smtd.202000039.

[16] M. Romare and L. Dahllöf, *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries A Study with Focus on Current Technology and Batteries for light-duty vehicles*. 2017.

[17] H. Ambrose and A. Kendall, “Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility,” *Transportation Research Part D: Transport and Environment*, vol. 47, pp. 182–194, Aug. 2016, doi: 10.1016/j.trd.2016.05.009.

[18] J. F. Peters, M. Baumann, B. Zimmermann, J. Braun, and M. Weil, “The environmental impact of Li-Ion batteries and the role of key parameters – A review,” *Renewable and Sustainable Energy Reviews*, vol. 67. Elsevier Ltd, pp. 491–506, Jan. 01, 2017, doi: 10.1016/j.rser.2016.08.039.

[19] H. C. Kim, T. J. Wallington, R. Arsenault, C. Bae, S. Ahn, and J. Lee, “Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis,” *Environmental Science and Technology*, vol. 50, no. 14, pp. 7715–7722, Jul. 2016, doi: 10.1021/acs.est.6b00830.

[20] J. J. Jang and H. H. Song, “Well-to-wheel analysis on greenhouse gas emission and energy use with petroleum-based fuels in Korea: gasoline and diesel,” *International Journal of Life Cycle Assessment*, vol. 20, no. 8, pp. 1102–1116, Aug. 2015, doi: 10.1007/s11367-015-0911-x.

[21] W. Choi and H. H. Song, “Well-to-wheel analysis on greenhouse gas emission and energy use with natural gas in Korea,” *International Journal of Life Cycle Assessment*, vol. 19, no. 4, pp. 850–860, Apr. 2014, doi: 10.1007/s11367-014-0704-7.

[22] “Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels,” 2008. [Online]. Available: www.netl.doe.gov.

[23] X. Ou, X. Yan, X. Zhang, and Z. Liu, “Life-cycle analysis on energy consumption and GHG emission intensities of alternative vehicle fuels in China,” *Applied Energy*, vol. 90, no. 1, pp. 218–224, 2012, doi: 10.1016/j.apenergy.2011.03.032.

[24] A. Moro and L. Lonza, “Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles,” *Transportation Research Part D: Transport and Environment*, vol. 64, pp. 5–14, Oct. 2018, doi: 10.1016/j.trd.2017.07.012.

[25] Energy Atlas IEA, “Energy Atlas,” 2021. http://energyatlas.iea.org/.

[26] R. Kawamoto *et al.*, “Estimation of CO2 Emissions of internal combustion engine vehicle and battery electric vehicle using LCA,” *Sustainability (Switzerland)*, vol. 11, no. 9, May 2019, doi: 10.3390/su11092690.

[27] Electrek, “Electrek.net,” 2020. https://electrek.co/2020/06/06/tesla-battery-degradation-replacement/#:~:text=With an update to its,miles depending on the model.

[28] Auto-data.net, “Auto-Data.net,” 2021. https://www.auto-data.net/en/.

[29] EVspecifications.net, “EVspecifications.net,” 2021. https://www.evspecifications.com.

[30] A. del Duce, M. Gauch, and H. J. Althaus, “Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3,” *International Journal of Life Cycle Assessment*, vol. 21, no. 9, pp. 1314–1326, Sep. 2016, doi: 10.1007/s11367-014-0792-4.

[31] I. Samarukha, “Recycling strategies for End-of-Life Li-ion Batteries from Heavy Electric Vehicles,” 2020.

[32] M. Romare and L. Dahllöf, *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries A Study with Focus on Current Technology and Batteries for light-duty vehicles*. 2017.

[33] T. R. Hawkins, B. Singh, G. Majeau-Bettez, and A. H. Strømman, “Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles,” *Journal of Industrial Ecology*, vol. 17, no. 1, pp. 53–64, 2013, doi: 10.1111/j.1530-9290.2012.00532.x.

[34] Q. Qiao, F. Zhao, Z. Liu, S. Jiang, and H. Hao, “Comparative Study on Life Cycle CO2 Emissions from the Production of Electric and Conventional Vehicles in China,” in *Energy Procedia*, 2017, vol. 105, pp. 3584–3595, doi: 10.1016/j.egypro.2017.03.827.

[35] J. Sun, “Car Battery Efficiencies,” 2010. [Online]. Available: http://large.stanford.edu/courses/2010/ph240/sun1/.

[36] B. Kukreja, “Life Cycle Analysis of Electric Vehicles Quantifying the Impact,” 2018.

[37] M. Miotti, G. J. Supran, E. J. Kim, and J. E. Trancik, “Personal Vehicles Evaluated against Climate Change Mitigation Targets,” *Environmental Science and Technology*, vol. 50, no. 20, pp. 10795–10804, Oct. 2016, doi: 10.1021/acs.est.6b00177.

[38] M. Baumann, M. Salzinger, S. Remppis, B. Schober, M. Held, and R. Graf, “Reducing the environmental impacts of electric vehicles and electricity supply: How hourly defined life cycle assessment and smart charging can contribute,” *World Electric Vehicle Journal*, vol. 10, no. 1, Mar. 2019, doi: 10.3390/wevj10010013.

[39] Maarten, “Life Cycle Analysis of the Climate Impact of Electric Vehicles,” 2017.

[40] A. Elgowainy *et al.*, “Current and Future United States Light-Duty Vehicle Pathways: Cradle-to-Grave Lifecycle Greenhouse Gas Emissions and Economic Assessment,” *Environmental Science and Technology*, vol. 52, no. 4, pp. 2392–2399, 2018, doi: 10.1021/acs.est.7b06006.

[41] Q. Qiao, F. Zhao, Z. Liu, X. He, and H. Hao, “Life cycle greenhouse gas emissions of Electric Vehicles in China: Combining the vehicle cycle and fuel cycle,” *Energy*, vol. 177, pp. 222–233, 2019, doi: 10.1016/j.energy.2019.04.080.

[42] T. Peng, X. Ou, and X. Yan, “Development and application of an electric vehicles life-cycle energy consumption and greenhouse gas emissions analysis model,” *Chemical Engineering Research and Design*, vol. 131, pp. 699–708, 2018, doi: 10.1016/j.cherd.2017.12.018.

[43] A. Yu, Y. Wei, W. Chen, N. Peng, and L. Peng, “Life cycle environmental impacts and carbon emissions: A case study of electric and gasoline vehicles in China,” *Transportation Research Part D: Transport and Environment*, vol. 65, no. September, pp. 409–420, 2018, doi: 10.1016/j.trd.2018.09.009.

Nomenclature

Acronyms and symbols	**Definitions and units of measure**
GHG	Green House Gas emissions taken as CO_2 equivalent. (1 x CO_2, 84 x CH_4, 298 N_2O)
ICEV	Internal Combustion Engine Vehicle
PHEV	Plug-in hybrid electric vehicle
BEV	Battery Electric Vehicle
BOM	Balance of materials
NMC	Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) Battery
LFP	Lithium Iron Phosphate ($LiFePO_4$) Battery
LMO	Lithium Manganese Oxide ($LiMn_2O_4$) Battery
NCA	Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) Battery
LIB	Lithium-Ion Batteries
CED	Cumulative energy demand
LCO	Lithium Cobalt Oxide ($LiCoO_2$) Battery
LTO	Lithium Titanate (Li_2TiO_3) Battery
VMA	Vehicle Manufacturing and Assembly
EU	European Union
EA	East Asia
NA	North America

Supplementary Data

Table 20 ICEV Manufacturing Emissions

Vehicle Segments	ICEV Manufacturing Emissions kgCO2eq/vehicle			
	NA	EU	EA	Ch
A	659.07	506.91	887.15	1420.41
B	747.15	576.00	1006.77	1621.66
C	786.79	607.09	1060.60	1712.23
D	862.35	666.35	1163.21	1884.84
E	1030.05	797.88	1390.96	2267.99
F	1055.46	817.81	1425.47	2326.04
J	931.80	720.82	1257.53	2043.51
M	1155.41	896.21	1561.20	2554.38
S	921.63	712.85	1243.73	2020.29

Table 21 ICEV Total Production Emissions

Vehicle Segments	ICEV Production Emissions kgCO2eq/vehicle			
	NA	EU	EA	Ch
A	2967.96	2519.02	4095.18	9401.67
B	3750.06	3192.90	5179.07	12001.91
C	4102.00	3496.15	5666.82	13172.02
D	4772.79	4074.14	6596.47	15402.22
E	6261.77	5357.12	8660.03	20352.68
F	6487.37	5551.51	8972.69	21102.75
J	5389.44	4605.47	7451.07	17452.41
M	7374.75	6316.11	10202.49	24053.02
S	5299.20	4527.72	7326.01	17152.39

Table 22 BEV Battery Production Emissions

Vehicle Segments	BEV Battery Production Emissions kgCO2eq/vehicle			
	NA	EU	EA	Ch
A	1478.75	1072.57	2013.30	2762.43
B	3080.73	2234.52	4194.38	5755.07
C	2772.65	2011.07	3774.95	5179.57
D	7181.09	5208.61	9776.99	13414.92
E	9032.82	6551.72	12298.11	16874.11
F	5853.38	4245.60	7969.33	10934.65
J	5853.38	4245.60	7969.33	10934.65
M	8317.97	6033.22	11324.85	15538.71
S	4879.87	3539.49	6643.91	9116.04

Table 23 BEV Total Production Emissions

Vehicle Segments	BEV Total Production Emissions kgCO2eq/vehicle			
	NA	EU	EA	Ch
A	5642.99	4622.36	7766.39	16141.40
B	7380.33	5900.95	10135.07	19584.08
C	8445.42	6860.67	11618.68	23573.96
D	12222.29	9514.03	16745.45	29709.54
E	14802.94	11485.21	20276.77	35592.20
F	12610.33	10029.38	17315.62	32933.64
J	12770.24	10167.17	17537.24	33465.31
M	14910.63	11675.45	20443.45	36991.50
S	10766.80	8573.62	14784.44	28222.46

Table 24 Total Battery recycling emissions for hydrometallurgical recycling at 1000km

Vehicle Segment	Total recycling at 1000km for hydro - kg CO2eq/battery			
	NA	EU	EA	Ch
A	292.67	284.41	318.41	463.81
B	609.74	592.52	663.37	966.27
C	538.41	523.20	585.77	853.23
D	970.75	942.20	1056.26	1531.81
E	1411.01	1369.51	1535.31	2226.53
F	1158.52	1125.79	1260.40	1835.91
J	1338.73	1300.91	1456.47	2121.50
M	1902.41	1848.66	2069.72	3014.77
S	965.84	938.55	1050.78	1530.57

Table 25 Total Battery recycling emissions for pyrometallurgical recycling at 1000km

Vehicle Segment	Total recycling at 1000km for pyro - kg CO2eq/battery			
	NA	EU	EA	Ch
A	256.76	250.75	278.68	372.74
B	534.92	522.40	580.60	776.55
C	472.34	461.29	512.68	685.71
D	906.51	866.46	978.42	1209.30
E	1317.64	1259.43	1422.17	1757.76
F	1016.35	992.57	1103.14	1475.45
J	1174.45	1146.97	1274.73	1704.96
M	1668.96	1629.91	1811.47	2422.84
S	847.32	827.49	919.67	1230.06

Table 26 BEV LCA Emissions in kgCO2eq for all segments

Vehicle Segments	BEV Life cycle emissions kgCO2eq/vehicle											
	NA			EUU			EA			Ch		
	100000	150000	200000	100000	150000	200000	100000	150000	200000	100000	150000	200000
A	15625	20597	32000	11360	14705	24486	21709	28666	42049	31086	38545	52430
B	15698	19824	30395	11533	14316	23545	21730	27495	39705	32009	38188	50813
C	13417	15870	24768	10270	11942	20060	18497	21903	31755	30934	34582	44675
D	21365	25904	36889	15694	18752	28255	29505	35852	48644	43384	50189	63439
E	23827	28307	39286	17587	20605	30104	32869	39133	51918	49087	55802	69045
F	24766	30837	43301	18210	22286	32772	34322	42829	57709	51168	60291	75781
J	24926	30997	43513	18348	22423	32944	34544	43051	58003	51699	60823	76391
M	30434	38126	52337	22093	27245	38891	42198	52991	70332	60322	71900	90033
S	20308	25045	36271	15018	18208	27871	28105	34732	47865	42499	49604	63220

Table 27 ICEV LCA Emissions in kgCO2eq for all segments

Vehicle Segments	ICEV Life cycle emissions kgCO2eq/vehicle											
	NA			EUU			EA			Ch		
	100000	150000	200000	100000	150000	200000	100000	150000	200000	100000	150000	200000
A	17672	24995	32426	16232	23060	29996	17727	24514	31409	37209	51084	65066
B	17826	24835	31951	16336	22879	29530	18246	24750	31362	38410	51585	64868
C	19336	26923	34619	17729	24817	32013	19818	26864	34019	41637	55841	70153
D	22141	30796	39560	20267	28335	36511	22693	30712	38839	48315	64742	81277
E	27098	37487	47984	24930	34688	44554	28129	37835	47649	57889	76628	95475
F	26015	35750	45593	24391	33782	43280	27132	36183	45342	58676	77433	96299
J	22739	31385	40139	20819	28896	37082	23571	31602	39740	49832	65993	82262
M	33408	46396	59491	31428	43955	56590	34404	46476	58656	74249	99318	124495
S	37669	53824	70088	34741	49819	65004	37362	52351	67447	78041	108456	138979

Table 28 BEV LCA emissions in gCO2eq/km for all segments

Vehicle Segments	BEV Life cycle emissions gCO2eq/km											
	NA			EUU			EA			Ch		
	100000	150000	200000	100000	150000	200000	100000	150000	200000	100000	150000	200000
A	156.25	137.31	160.00	113.60	98.03	122.43	217.09	191.10	210.25	310.86	256.97	262.15
B	156.98	132.16	151.97	115.33	95.44	117.72	217.30	183.30	198.53	320.09	254.59	254.07
C	134.17	105.80	123.84	102.70	79.62	100.30	184.97	146.02	158.77	309.34	230.55	223.37
D	213.65	172.70	184.44	156.94	125.01	141.27	295.05	239.01	243.22	433.84	334.59	317.19
E	238.27	188.71	196.43	175.87	137.37	150.52	328.69	260.88	259.59	490.87	372.01	345.22
F	247.66	205.58	216.51	182.10	148.57	163.86	343.22	285.53	288.54	511.68	401.94	378.91
J	249.26	206.64	217.56	183.48	149.49	164.72	345.44	287.01	290.02	516.99	405.49	381.96
M	304.34	254.17	261.68	220.93	181.64	194.46	421.98	353.27	351.66	603.22	479.33	450.17
S	203.08	166.97	181.36	150.18	121.38	139.35	281.05	231.55	239.33	424.99	330.70	316.10

Table 29 ICEV LCA emissions in gCO2eq/km for all segments

Vehicle Segments	ICEV Life cycle emissions gCO2eq/km											
	NA			EU			EA			Ch		
	100000	150000	200000	100000	150000	200000	100000	150000	200000	100000	150000	200000
A	176.72	166.63	162.13	162.32	153.73	149.98	177.27	163.42	157.04	372.09	340.56	325.33
B	178.26	165.56	159.76	163.36	152.53	147.65	182.46	165.00	156.81	384.10	343.90	324.34
C	193.36	179.49	173.10	177.29	165.45	160.06	198.18	179.09	170.09	416.37	372.27	350.76
D	221.41	205.31	197.80	202.67	188.90	182.55	226.93	204.75	194.20	483.15	431.61	406.39
E	270.98	249.91	239.92	249.30	231.25	222.77	281.29	252.23	238.24	578.89	510.85	477.38
F	260.15	238.33	227.96	243.91	225.21	216.40	271.32	241.22	226.71	586.76	516.22	481.49
J	227.39	209.23	200.69	208.19	192.64	185.41	235.71	210.68	198.70	498.32	439.96	411.31
M	334.08	309.30	297.46	314.28	293.03	282.95	344.04	309.84	293.28	742.49	662.12	622.47
S	376.69	358.83	350.44	347.41	332.12	325.02	373.62	349.00	337.24	780.41	723.04	694.90