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NITI Aayog

Comparative Analysis of Electric Vehicles and Internal Combustion Engine Vehicles from Resource Efficiency Perspective

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Comparative Analysis of Electric Vehicles and Internal Combustion Engine Vehicles from Resource Efficiency Perspective

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The study was initiated given the high relevance in addressing EV's environmental impact across its entire life cycle. We hope the outcome and recommendations from this detailed study will encourage and benefit industry and policy makers in India to make informed decisions.

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List of Abbreviations

3W	Three-Wheeler
4W	Four-Wheeler
ADP	Abiotic Depletion Potential
ARAI	Automotive Research Association of India
BEV	Battery Electric Vehicle
CBG	Compressed Biogas
CEA	Central electricity authority
CNG	Compressed natural gas
CO2	Carbon dioxide
CO2	Carbon dioxide equivalent
EOL	End-of-life
EV	Electric vehicle
EVSE	Electric Vehicle Supply Equipment
FAME	Faster Adoption and Manufacturing of Hybrid and Electric Vehicles
FDI	Foreign direct investment
GHG	Greenhouse gas
GLO	global
GWP	Global Warming Potential
ICE	Internal combustion engine
ICEV	Internal Combustion Engine Vehicles
IIT	Indian Institute of Technology
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	life cycle inventory
LCIA	Life cycle impact assessment
LDPV	Light Duty Passenger Vehicles
LFP	Lithium-Iron-Phosphate
LMO	Lithium Manganese Oxide
MoEFCC	Ministry of Environment, Forest, and Climate Change
MoPNG	Ministry of Petroleum and Natural Gas
NCA	Nickel, Cobalt, Aluminium
NCM	Nickel, Cobalt, Manganese
NEERI	National Environmental Engineering Research Institute
NEMMP 2020	National Electric Mobility Mission Plan 2020
NOx	Nitrogen oxides
ODP	Ozone Depletion Potential
OEM	Original Equipment Manufacturer
PEV	Plug-in electric vehicle
PLI scheme	Production linked incentive scheme
PM	Particulate Matter
R&D	Research and Development
RoW	rest-of-world
SOx	Sulfur oxides
TTW	Tank to Wheel
WTT	Well to Tank

Glossary

Terms	
Active material intensity	The amount of essential components of a device or reaction like in a battery
Payload capacity	The capacity in terms of weight the vehicle can carry but does not include the weight of the vehicle itself
Kerb weight	Weight of the vehicle without any occupants or any other load
Ethanol Blending Programme (EBP)	Scheme of Government of India to blend ethanol to motor spirit with the aim of reducing air pollution and carbon emissions
E5	5% ethanol blend to petrol
E10	10% ethanol bend to petrol
Substitution Approach	In the EOL analysis, the substation approach involves giving credit and burden of recycling to the same product
Cut off Approach	In the EOL analysis, the cut off approach involves giving neither credit and burden of recycling to the same product but to somewhere else in the economy
Research Octane Number (RON)	Percentage (v/v) of iso-octane in a mixture of iso-octane and n-heptane. Higher the octane number, stable the fuel.

01 Introduction

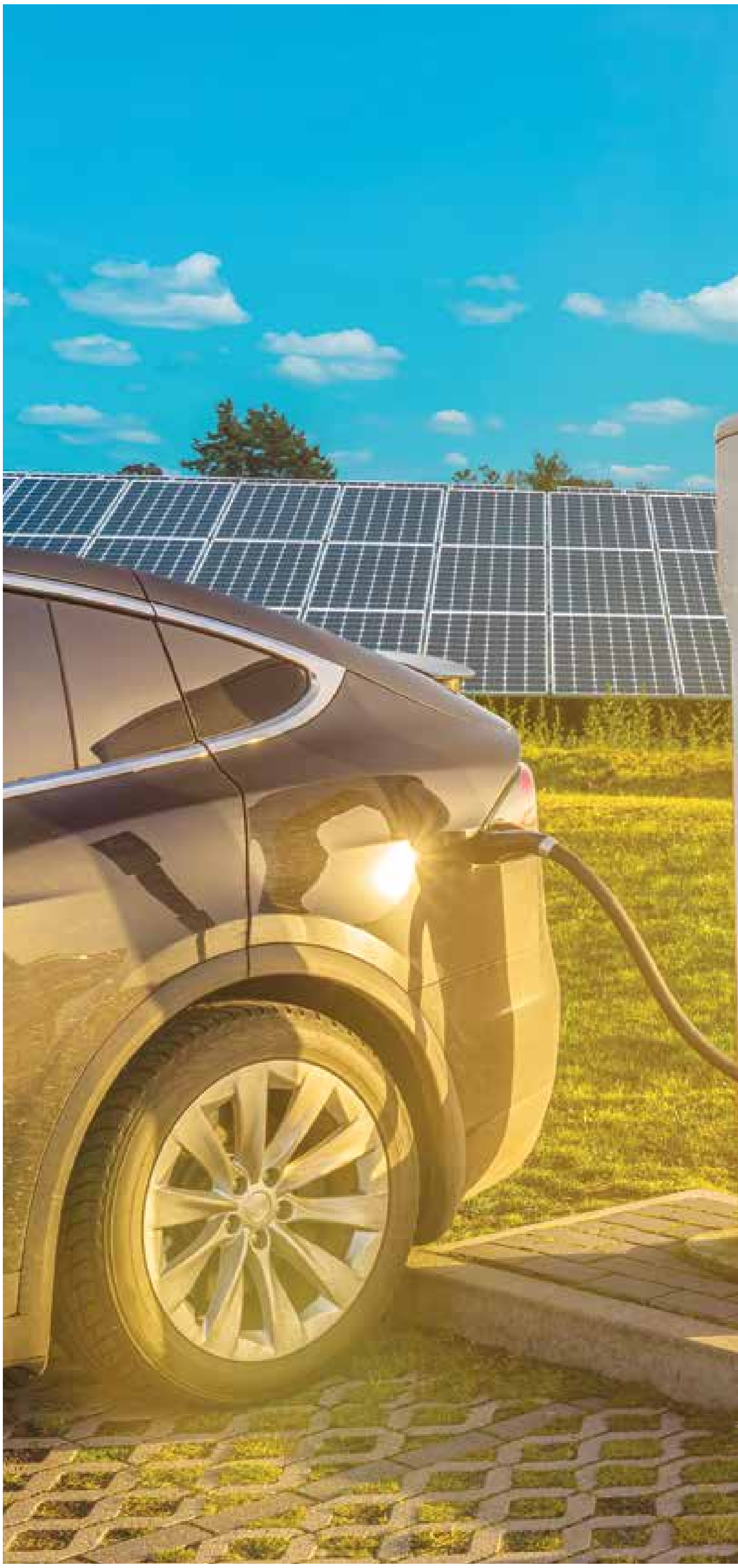
There is an overwhelming number of studies that indicate that human activity is causing rapid changes to the climate, which is causing severe environmental damage. As the scientific consensus on this fact has grown stronger, the global community has come together to implement several measures to halt anthropogenic climate change.

One of the sectors that have drawn particular attention has been the automotive sector, largely because of its fossil fuel dependence and the contribution to global GHG emission. As per UNEP's estimates, the transport sector contributes approximately 25% of all energy related GHG emissions. This has attracted the attention of key stakeholders across the world (including India) leading to a univocal call to decarbonize the transport sector.

The Indian automotive industry is fifth largest in the world and is slated to be the third largest by 2030. India's transportation sector contributes about 10 percent of total national GHG emission and road transportation contributes about 87 percent of the total emissions in the sector. Although the share is still less than the global average, the sheer growth and in the absence any action would have serious outcomes.

There however has been efforts by India to decarbonize the transport sector. One of the significant initiatives in this regard has been the focus on e-mobility. National Electric Mobility Mission Plan (NEMMP) 2020 was launched in 2013 as a mission to provide vision and the roadmap for the faster adoption of electric vehicles and their manufacturing in the country. As part of the NEMMP 2020, the Department of Heavy Industry formulated a Scheme viz. Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India (FAME India) Scheme in the year 2015 to promote manufacturing of electric and hybrid vehicle technology and to ensure sustainable growth of the same.

In 2019, FAME II was approved with an outlay of INR 100 Bn to be implemented for a period of 3 years commencing from 1st April 2019. Out of total budgetary support, about 86 percent of funds has been allocated for Demand Incentive so as to create demand for xEVs in the country. This phase aims to generate demand by way of supporting 7000 e-Buses, 5 lakh e-3 Wheelers, 55000 e-4 Wheeler Passenger Cars (including Strong Hybrid) and 10 lakh e-2 Wheelers.



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The major focus of this transition is on e-mobility which is evident through several schemes like Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) II which covers from electric 2-wheelers to electric buses and charging infrastructure. More recently the production linked incentive (PLI) scheme for the automotive sector was launched to encourage domestic production of batteries to support the EV industry with requisite infrastructure and reduction in costs. While there is 100% FDI in the auto sector, the domestic policies seem to be partisan to EVs while bypassing technologies like hybrid vehicles during this transition.

India's biofuel policy too is expected to play an important role in decarbonization of the transport sector. India came up with the National Policy on Biofuels in 2018 with a thrust on advanced biofuels. It planned an ethanol blending target of 20% of petrol containing ethanol by 2025-26 and 5% biodiesel. However, recently, the cabinet approved the Amendments to the National Policy on Biofuels -2018 advance the ethanol blending target of 20% blending of ethanol in petrol to 2023.

The government has also initiated "Sustainable Alternative Towards Affordable Transportation" (SATAT) scheme to extract economic value from biomass waste in the form of Compressed Bio Gas (CBG) and bio-manure. Municipal solid waste, sugar industry waste (press mud) and agricultural residue have significant potential for production of the same. India's oil and gas CPSEs have come forward to promote the use of CBG by offering floor price to offtake CBG for the first 10 years through upfront commercial agreements. Given the abundance of biomass in the country, particularly in rural India, CBG has the potential to support the development of alternate clean fuel in automotive, industrial, and commercial uses in the coming years.

02 Rationale

As the EV industry is on the brink of a major transition, environmental performance of EVs has become a highly debated topic. While EVs are preferred for their on road reduced emissions, they involve usage of critical minerals that are highly energy intensive at the time of extraction and manufacturing. Additionally, the electricity used for charging the batteries has a high share of thermal based generation. In India, the grid constitutes a major portion of coal-based electricity. If the environmental footprints of these factors are to be considered, envisaged benefits of EVs may not be as high as perceived. This calls for the need to conduct a detailed life cycle assessment of EVs and their comparison with ICE vehicles.

3-wheeler and 4-wheeler vehicles are likely to lead the transition to electric technology in India during the coming decade as the cost difference with combustion engine vehicles is narrowing. Electric 3-wheeler segments have relatively lower dependency on commercial charging infrastructure (owing to limited span of commute) and can also adopt battery swapping to allay charging related concerns for commercial applications. While the consumer preference is inclining towards four-wheel BEVs due to lower running cost per km, benefits before and after purchase, and growing number of models to choose from. Also, a number of companies have begun to manufacture electric 3-Wheelers and 4-wheelers compared to the limited number of players in the high commercial vehicle segment. Thus, it is important to focus on 3-W and 4-W for this study.

Thus, as EVs gain momentum in the Indian market, it is important to understand whether the technical and monetary resources that are put behind the e-transition project will produce desired results. This can effectively be determined through a Life Cycle Analysis (LCA) exercise of EVs (motor and battery) and compare the carbon emissions involved with a similar analysis for ICE vehicles for three different types of fuel (petrol, diesel and CNG) that fuels Indian vehicles.

A LCA exercise will help to determine the carbon emissions and other environmental impacts involved in each stage of the value chains of above-mentioned components. Thus, a holistic picture of environmental benefits of EVs over ICE vehicles can be understood instead of just accounting for tailpipe emissions.

03 Literature Review

Abdul-Manan, Zavaleta, et al (2022) have found that India's GHG reduction potential of electric 4-wheelers principally depends on the time and location where they are charged. It has been observed that a 40% reduction in the north-eastern states and 15% increase in the western/eastern states with more overall GHGs emission when charged in summer overnight, owing to their respective regional electricity grid mix. They commented India's 4W BEV potential lies in decarbonising the power sector by phasing out the coal-based generation.

The ICEV engines require redesigning and remodelling to be more efficient and provide maximum performance. Pawar and Desale (2018), redesigned and optimised the ICE-vehicles suspension spring coil systems to resolve the problem of vehicle's one side drift, this led to coils' mass reduction by 189-296 gm.

Peroa, Delogua, and Pierinia (2018) concluded in their study that environmental impacts (acidification, human toxicity, particulate matter, photochemical ozone formation and resource depletion etc) result higher for the BEV than the ICEV, primarily due to the major environmental loads of powertrain construction and manufacturing.

Rose et al (2012) mentioned in their work that in case of CNG powered heavy duty vehicles comparative to their diesel powered counterparts, an approximate 24% CO2-equivalent reductions were observed.

Hawkins et al (2012) showed in their study that EVs possess the potential of Global warming reductions by about 10%to 24% depending on the electricity mix relative to conventional diesel or gasoline vehicles assuming lifetimes of 150,000 km. However, EVs exhibit the potential for significant increases in human toxicity, freshwater ecotoxicity, freshwater eutrophication, and metal depletion impacts, largely emanating from the vehicle supply chain. The study stresses on the more specific definition of how a complete state-of-the-art LCA of electrified vehicles should be conducted, and hence request more rigorous and complete inventories and studies.

According to International Energy Agency report: "Global EV Outlook 2020, their analysis found that the average EV in Europe produces about half the CO2 emissions of an equivalent ICE vehicle, even when taking into account the emissions from battery production and electricity generation.

Cucinotta et al (2021) in their comparative life cycle assessment study between full electric and traditional petrol engines concluded that with a small exceptions in countries which are heavily dependent on fossil fuels, BEVs follows to well to wheel reduction until 50% compared to the traditional ICE vehicles.

The effectiveness of the emission reduction dramatically varies in BEVs due to the difference in electricity generation mix. Therefore, the regions with high carbon emissions from vehicles need to increase the proportion of renewable generation as a priority rather than promoting BEVs unlike the case with regions high with renewable energy percentage in the electricity generation mix along with this Tang et al (2022) also concluded in their study that promotion of BEVs considerably help in reducing the carbon emission in most regions but keeping in mind how high the carbon emission from batteries in material extraction and processing, and vehicle manufacturing phase,. the there is a need to improve battery production technology and extend battery life of OEMs of BEVs to achieve the maximum reduction in carbon emission.

Lalwani et al (2019) identified that maximum impact on the environment occur during the use phase followed by manufacturing phase and End of Life phase of a 4W passenger vehicle except for ADP, ODP, and blue water consumption and recommended that the usage of lightweight materials leads to lesser emission and fuel efficiency enhancement.

Zheng et al (2021) indicated in their study that though the energy consumption rate of EVs are much lower than their fossil fuel driven counterparts but their lifecycle CO2 emission is variable and majorly dependent on power generation mix and in order to have lower life cycle CO2 emission generation from BEVs the average CO2 emission from their power generation mix should be at least at the level about 320 g/kWh.

Contrary Yang et al., stated in their study on "life cycle environmental assessment of electric and internal combustion engine vehicles in China" that EVs have lower carbon footprints than gasoline vehicles, even when the electricity used to charge them is generated from coal-fired power plants.

Ellingsen et al (2013) with their sensitivity analysis of electricity used for manufacture of battery cells showed that the powertrain efficiency and cycle numbers are pertinent for assessing the environmental impacts of traction batteries and indicated that the efficient approach to reduce the GWP is via reducing the energy demand in cell manufacturing and the carbon intensity of the electricity used in production.

The carbon emission of the production of batteries using recycled materials from direct physical recycling is 51.8% lower than that using raw materials. Based on the above discussion, it can be seen that only relying on the recycling of battery materials cannot achieve net-zero carbon emission of battery production in China, and the upgrading of the electricity mix is a crucial factor It can be observed that the carbon emission of battery remanufacturing with recycled materials under the electricity mix structure in 2030 will be 53.6 kg CO_2-eq/kWh, which is 11.8% lower than that in 2020.

To considerably reduce carbon emissions in production of lithium ion batteries Chen et al (2022) stressed on increasing the renewable proportion in the electricity mix and improving production efficiency along with gradual increase in the use of the negative carbon technologies. It was seen that carbon emission of battery production can be reduced by about 40% when the production efficiency is changed from 30 ppm to 50 ppm. Manufacturing of the batteries using the recycled materials reduced the carbon emissions by 51.8%. The study only focused on the LCA of battery components though in respect of China.

Jani Das (2022) focused on the life cycle GHG emissions of electric vehicles in terms of equivalent carbon emission (kgCO2eq) and compared it with conventional vehicles for a life cycle inventory in Indian conditions. It was found that there was a reduction of about 40% embodied equivalent carbon in an ICEV in comparison with an EV in Indian conditions. Only the emission factor was considered for the study, and it lacked the consideration of other factors for the overall comparison.

Jhunjhunwala et al (2018) concluded that the cost of EVs can be brought down by increasing the efficiency of the drivetrains to upscale the electrification in India, though the study lacked the primary data.

Moon et al (2018) considered the social aspect by analyzing consumers' charging patterns and elaborated on the changing pattern in electricity charging & types of electric vehicle supply equipment (EVSE) demand based on consumer preferences for EVs and concluded that the charging during the evening was mostly preferred but in case of EVSEs (public and private), charging during day was preferential.

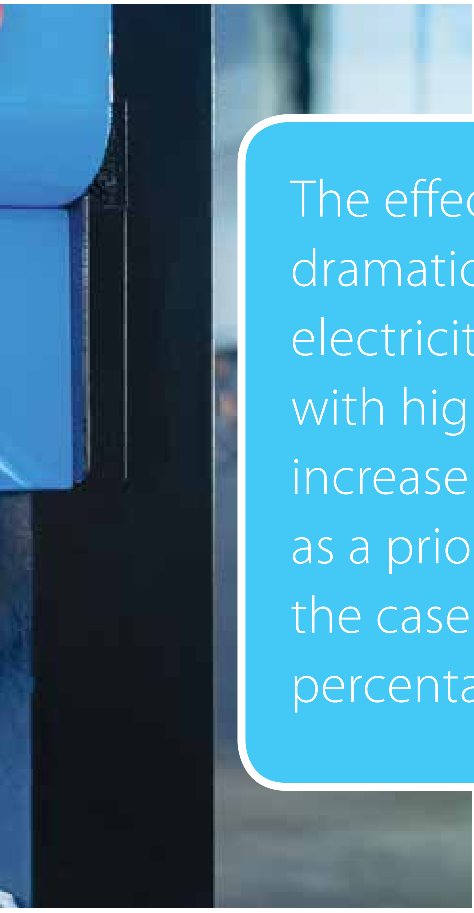
Shi et al showed that per kilometer petroleum use can be mitigated by 98% and fossil fuel use by 25%- 50% relative to gasoline LDPVs via promotion of BEVs. Though the study shows the gap as the calculation of total amount of energy consumption, CO_2 emissions and air pollutants emissions without considering the vehicle life-cycle process.

The primary energy consumption and GHG emissions of electric vehicles in the vehicle lifecycle is significantly higher as compared to ICE and fuel cell vehicle due to the high energy consumption and emissions of battery production as concluded by Yang et al.

Dunn et al. (2014) found that the BEVs and PEVs result in fewer GHG emissions than the average gasoline car by modelling the LCA of EVs with various battery chemistries and electricity grids.

Though all EVs reduce emissions compared to the average gasoline vehicle in their base case and optimistic case. EVs with larger battery packs are more heavier, and more emissions-intensive to produce, and provide emissions benefits less than HEVs and PEVs with comparably smaller battery packs as researched by Michalek et al. (2011) by assessing the lifecycle GHG emissions, criteria pollutants of EVs and oil displacement benefits.

Notter DA et al (2010) compiled a detailed lifecycle inventory of a Li-ion battery and a rough LCA of BEV based mobility and elucidated that the environmental burdens of mobility are dominated by the operation phase regardless of whether a gasoline-fueled ICEV or electricity fuelled BEV is used. The share of the total environmental impact of E-mobility caused by the battery is 15%, by the extraction of lithium for the components of the Li-ion battery is less than 2.3%. Though they had uncertainties adhere to the LCI.



The effectiveness of the emission reduction dramatically varies in BEVs due to the difference in electricity generation mix. Therefore, the regions with high carbon emissions from vehicles need to increase the proportion of renewable generation as a priority rather than promoting BEVs unlike the case with regions high with renewable energy percentage in the electricity generation mix

The aging process is dependent both on the number of charging cycles, i.e. how much the battery is used, and on calendar time. According to studies conducted by Corrigan and Masias (2011)[20] & Vetter et al. (2005)[21] battery's lifespan is influenced by a number of intricate and interconnected mechanisms related to cell chemistry, as well as storage, discharging and charging, other criteria like temperature, cycle depth, and different chemical degradation.

With the longer vehicle life further shifting the efficiency balance toward the electric vehicle as concluded via Sensitivity analysis with a vehicle life of 100,000 km and 250,000 km. (Kukreja, 2018).

End of life management of EVs have strong sustainability implications of this vehicle technology. A number of studies have addressed the environmental effects of battery recycling (Dunn et al., 2012; Amarakoon et al., 2013; Hendrickson et al., 2015; Ciez and Whitacre, 2019; Gaines, 2018); however, much uncertainty remains about the end-of-life phase. Ciez et al. (2019) estimated that while no significant mitigation is possible through hydrometallurgical and pyrometallurgical methods, direct recycling could be viable for lithium nickel manganese cobalt oxide (NMC) and lithium nickel cobalt aluminum oxide (NCA) chemistries.

On the other hand, Hendrickson et al. (2015) concluded that both pyrometallurgical and hydrometallurgical recycling methods lead to decreased environmental impacts in most categories in comparison to the use of virgin raw materials. Amarakoon et al. (2013) modeled hydrometallurgical, pyrometallurgical, and direct physical recycling methods and presented the environmental mitigation as an average of the three processes; the greenhouse gas (GHG) savings obtained by recycling were only 3.6% on average compared to primary production, depending on the battery chemistry. The results calculated by Gaines (2018), on the other hand, would suggest that increasing the amount of recycled material in battery cells decreases the overall energy consumption significantly, especially when aluminium is also recovered.

04 Approach

The project is a technical study aimed to create knowledge for all stakeholders associated with the automotive industry in India. Owing to the major shift occurring in India's mobility sector, it is crucial that evidence-based results guide such transition. In such a scenario, a comparative Life Cycle Assessment has several benefits because it produces comprehensive results that can help in product development, marketing, strategic planning and policymaking.

The two prime products of comparison in this study are Internal Combustion Engine Vehicles (ICEVs) and Electric Vehicles (EVs). However, study only considers the powertrain of the vehicles and not the glider components. Such a decision is based on two factors: i) Glider components are not key to the current transition and their environmental impacts are hence not relevant to the study's objectives. ii) Glider components of both categories of vehicles are not likely to be vastly different and hence their impacts are assumed to cancel out one another. Among the powertrain components the study considers the entire life cycle of fuel and engine for ICE vehicles and battery and motor for EVs. A detailed description of the Life Cycle Assessment framework along with goal and scope of the study is explained in the following sections:

Life Cycle Assessment Framework

Life cycle assessment (LCA) has emerged as a leading tool for driving sustainability decisions in the fields of research, industry, and policy decisions. It is considered to be a powerful and robust tool for quantifying the various environmental impacts of a product or service throughout its life cycle. Based on the systematic life cycle (cradle to gate/grave/cradle) approaches it aids stakeholders in comprehending the true impacts of any given product or service. LCA results mainly help to compare products and identify hotspots in a product's life cycle. The analysis also simultaneously draws designers', engineers', and management's attention towards improvement opportunities to offset energy and emission savings obtained while sourcing raw materials and manufacturing products. It reduces the risk of problem shifting (from one life cycle to another) and helps stakeholders in locating the visible difference between an environmentally sustainable product and a less sustainable alternative. It provides clear insights on how making fundamental changes in the supply chain (replaced with sustainable material or using a renewable energy source) can potentially lead to impact in another stage of the product's life cycle. Calculation and communication of key environmental sustainability metrics improve an organization's transparency, thus convincing consumers to make improved choices.

According to International Organization for Standardization (ISO) 14044/40 standards LCA should be carried out in four key phases as presented in Figure 1.

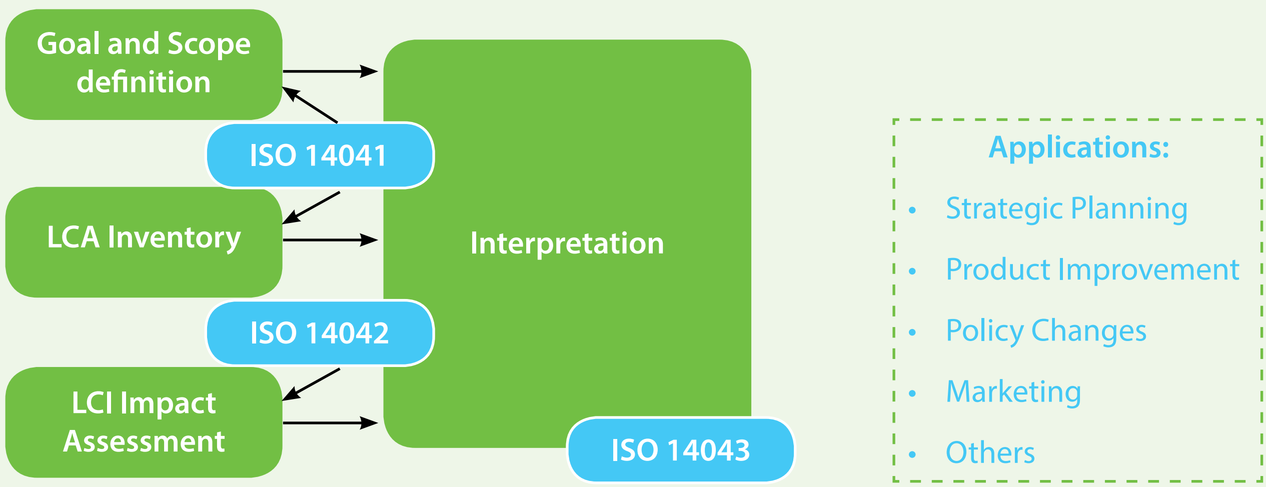


Figure 1: Life Cycle Assessment Framework

Goal and Scope Definition

Under the goal and scope; the product system, in terms of the system boundaries of the study and a functional unit is defined. A functional unit is extremely critical as it helps in facilitating direct comparison of alternative goods or services with reference products.

Inventory Analysis (LCI)

The life cycle inventory (LCI) is the methodology for estimating use of various resources, quantities of wastes generated, emissions and discharges during production, use and disposal phases, associated with each stage in a product's life cycle. The material and energy flows are modelled between the processes within a life cycle. The overall models provide mass and energy balances for the product system, its total inputs and outputs into the environment, on a per functional unit basis. Details of inventory for current study are given in the inventory chapter.

Life Cycle Impact Assessment (LCIA)

The LCIA provides indicators for the interpretation of the inventory data, in terms of contributions to different impact categories. The indicator results of an LCIA facilitate the evaluation of a product, and each stage in its life cycle, in terms of climate change, toxicological stress, noise, land use, water consumption, and others. The scope of the evaluation, with some exceptions, impacts at both regional and global scales.

The overall indicator results of an LCIA reject cumulative contributions to different impact categories that are summed over time and space. Unlike some other assessment approaches, these indicator results usually do not reflect risks or impacts at any particular location or point in me. The consumption of resources and the generation of wastes, emissions, and so on, often occur in a product's life cycle, for example, (i) multiple sites and in multiple locations, (ii) as different fractions of the total emissions at any one site, (iii) at different times (like the manufacturing or use phase of a vehicle), and (iv) over short and long me periods (for instance, multiple generations in the case of emissions of persistent chemicals and from landfills).

The scope of the study covers the Indian market, the scientific community in India uses ReCiPe LCIA methodology. This method translates emissions and resource extractions into a limited number of environmental impact scores by means of characterisation factors. Two prime ways of deriving characterisation factors are at mid-point and end-point levels. As per ReCiPe, there are

- 18 mid-point indicators
- 3 end-point indicators

Mid-point indicators focus on a single environmental problem, for example, global warming potential, acidification or water footprint. End-point indicators show environmental impacts on three higher aggregation levels: (1) effect on human health, (2) biodiversity, and (3) resource scarcity. Converting midpoints to end-points simplifies the interpretation of LCIA results. Figure 2 provides an overview of the structure of ReCiPe.

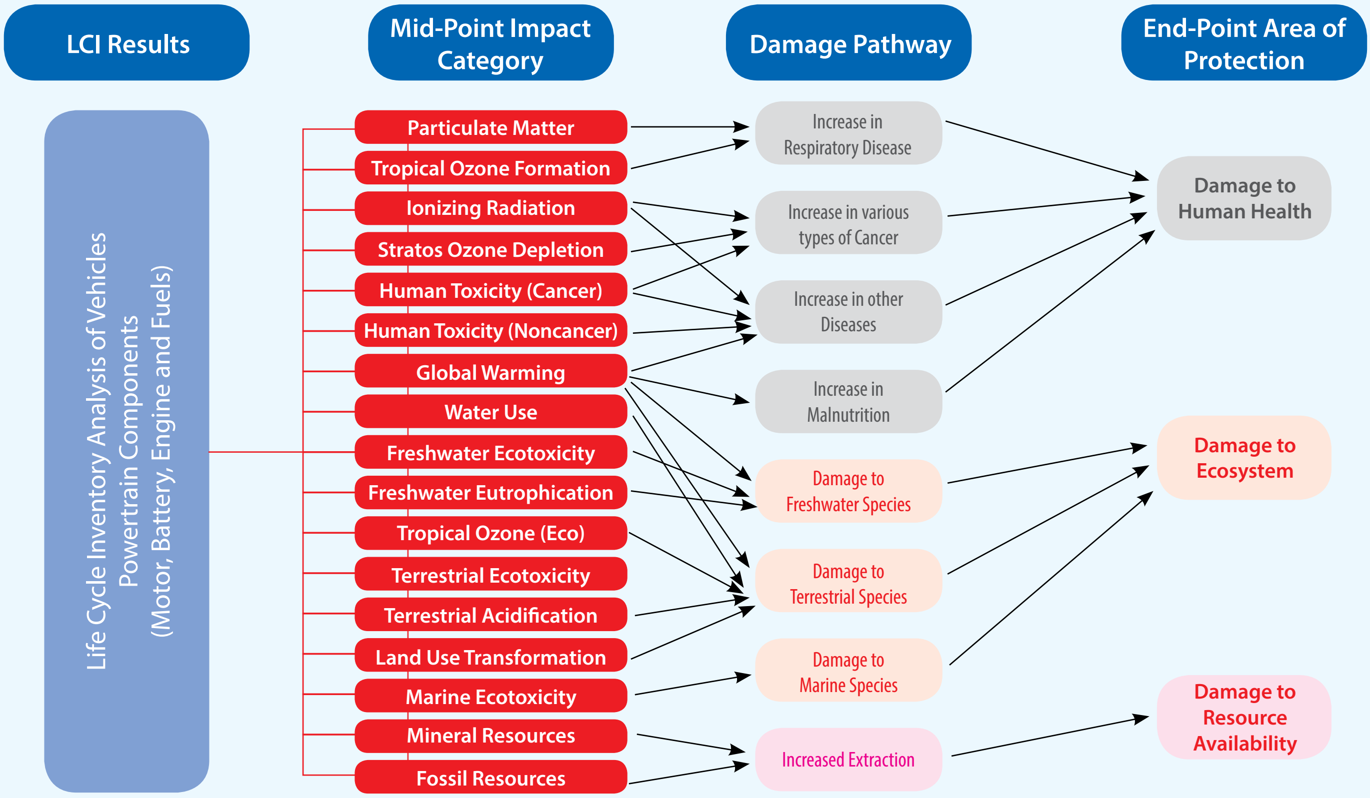


Figure 2: Overview of ReCiPe methodology

Interpretation

Interpretation occurs at every stage in an LCA. If two product alternatives are compared and one alternative has a higher consumption of each resource, for example, an interpretation purely based on the LCI can be conclusive. In other studies, drawing conclusions will require at least an LCIA, a sensitivity analysis, and consideration of the statistical significance of differences in each impact category.

Some category indicators can be further cross-aggregated and compared on a natural science basis. Further, aggregation can be utilized to calculate the overall sum of years of human life lost, for example, the years of life lost that are attributable to climate change, potential carcinogenic effects, noise, traffic accidents, and others.

Goal of the study

The present study presents a comprehensive LCA of powertrain components of Internal Combustion Engine Vehicles (ICEVs) and Electric Vehicles (EVs). The powertrain components of ICEVs include three types of ICE fuels (Petrol, Diesel, Compressed Natural Gas (CNG)) and engine, while powertrain components of EVs include battery and motor of the vehicles. The objective is to assess the various environmental impacts of each category of product across their life cycle.

The goal of the study is to conduct a comparative LCA, analyzing environmental performance of existing vehicle technologies running on Indian roads so as to identify the technology that is environmentally more sustainable and accordingly needs focus from a policy perspective.

The goals of the study are enumerated here:

To provide up-to-date results of various environmental metrics for specific powertrain components of two vehicle technologies that are running on Indian roads

To provide a comprehensive overview of product sustainability and potential for overall improvement by complementing LCA results with sensitivity analysis of scenarios that are currently prevalent in the mobility sector.

To identify the potential advantages and disadvantages of electric vehicles over internal combustion engine vehicles and to identify a point of inflexion where a particular vehicle technology becomes competitive over the other.

A generic input output flow of various life cycle stages of a vehicle technology is presented in Figure 3.

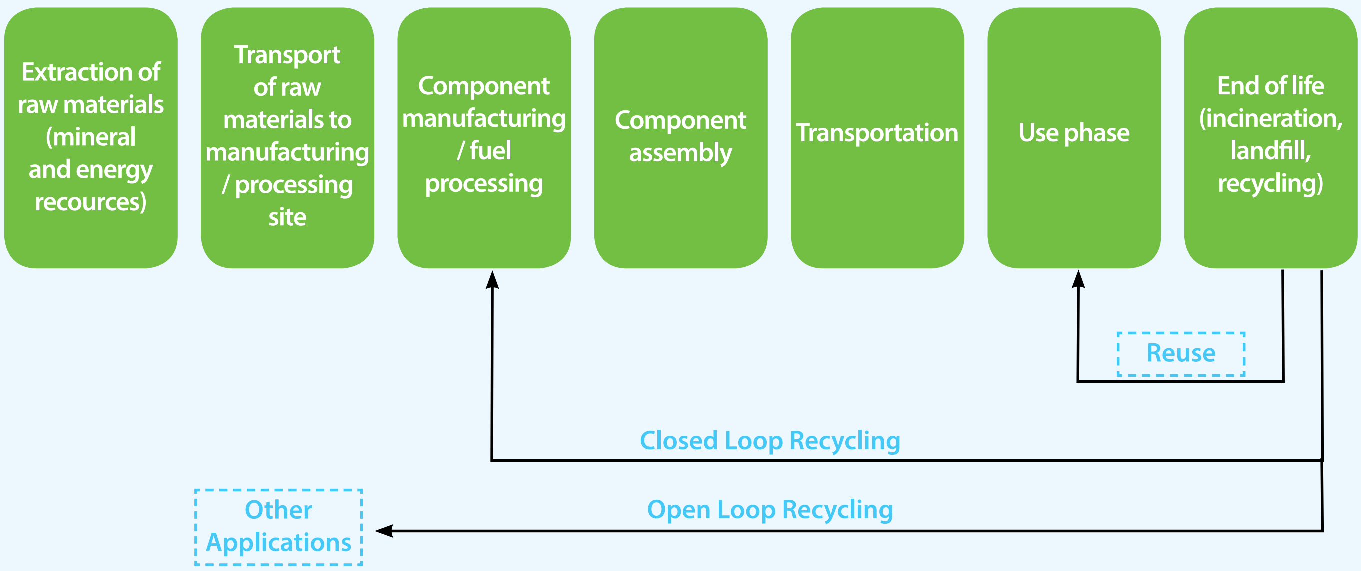


Figure 3: Generic life cycle stages of vehicle technologies

The study has been commissioned by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and is intended to be disclosed to the public. This excludes confidential primary data obtained from industry stakeholders.

The study meets the requirements of the international standards for LCA according to ISO 14040 (ISO, 2006)/ISO 14044 (ISO, 2006).

This study is extremely relevant and has been carried out at a time when there is growing environmental consciousness among Indian consumers and significant policy thrust by the Indian government towards promotion of circularity across various sectors with special emphasis on automobiles. At the EU–India summit held in 2020, Hon'ble Prime Minister of India and the European Commission President adopted a joint declaration to scale-up EU–India cooperation in the areas of resource efficiency and circular economy. The declaration establishes India–EU Resource Efficiency and Circular Economy Partnership, bringing together representatives of relevant stakeholders from both sides, including governments, businesses (including start-ups), academia and research institutes. India has already drafted the National Resource Efficiency Policy to identify the imperative of achieving complete circularity in various sectors. TERI under the Resource Efficiency Initiative project, supported by the European Union had developed and submitted the technical reference document for resource efficiency to the Resource Efficiency Cell constituted under the MoEFCC.

In the more recent Glasgow Climate Summit, Hon'ble Prime Minister of India declared an ambitious target of attaining net zero emissions by India by the year 2070. He also made the commitment of bringing down carbon emissions by 1 billion tons by 2030 along with reducing the carbon intensity of the Indian economy by 45%.

The study will significantly contribute towards this ambitious goal of the Government of India, thereby helping them in making sound decisions towards strengthening resource and energy efficiency in the automobile sector. The current Indian grid is coal intensive but Hon'ble PM's declared target of 50%

renewable grid mix with a capacity of 500 GW by 2030, does create a case for pushing EV manufacturing and marketing from a policymaking perspective. However, such reality is yet to be realized and this study is a very important contribution to what could be some alternative perspectives.

This study will also help to identify environmental hotspots for vehicle technology's life cycle and related optimisation potential, and understand environmental impacts associated with individual stages of vehicle components. Further, through the various sensitivity analysis, the sustainability implications can best be understood through adoption of resource recovery and enhanced recycling rates of different materials, inclusion of various biofuel blending proportions and consideration of different renewable composition of the Indian grid. The scientific data-driven analysis will encourage industry and policy makers in India to make informed choices.

Scope of the study

The overall scope of the study is to achieve the stated goals, detailed in this section. This includes, but is not limited to identification of relevant product categories to be assessed, the product function, functional unit, the system boundary, end-of-life methodology, allocation and cut-off criteria.

4.1.1 Product System

The product system analysed in this study are powertrain components of ICEVs and EVs that are plying on Indian roads. A comparative LCA needs product that can be compared across the necessary categories of the baseline scenario. Accordingly for the Four-Wheeler passenger car segment, Tata Nexon is identified as a suitable product for this study. And Piaggio Ape is identified as a representative model in the three-wheeler passenger vehicle category. Tata Nexon has its ICE product running on both petrol and diesel fuel, while its CNG variant is yet to enter the market. The highest share of TATA Nexon EV in the electric four-wheeler sales, comparative to other models such as TATA Tigor, Mahindra e-Kona, MG ZS EV, Audi e-Tron, etc. made it a good representative of trending powertrain requirements. Similarly, among the three-wheeler passenger auto vehicle category, even though Bajaj captures major market share, its EV counterparts are under research. Piaggio being the second highest shareholder in vehicle sales and its electric model Ape e-city fulfils the crucial technological mandate for successful completion of this study. In order to get a good amount of use phase data points, the study required models that have an adequate number of fleet sizes plying on Indian roads. Considering the study region to be NCR-Delhi, the analysis included only CNG and electric variants in the three-wheeler category, and ICE-Petrol, Diesel and electric variants for the passenger car segment. The engine of the CNG variant is assumed to be similar to its petrol product as both are powered by spark-ignited internal combustion engines. Hence the upstream impacts associated with CNG fuel will be the relevant point of focus separating the CNG variant from its crude oil driven counterparts. Table 1 and 2 summaries the product specification and performance parameters of identified models.

Table 1: Specification and performance parameters of Tata Nexon

Specification	Tata Nexon		
	Petrol	Diesel	EV
Power	120 HP	110 HP	129 HP
Torque	170 Nm	260 Nm	245 Nm
Acceleration			9.9 sec.
Max Speed	180 km/h	180 km/h	120 km/h
Range	17.5 km/l	21.2 km/l	312 km/ charge
Engine Capacity	1.2 l	1.5 l	
Motor Capacity			
Motor Type			PMSM
Battery Type			Li-ion

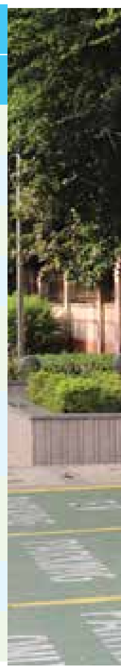
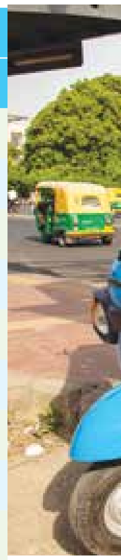


Table 2: Specification and performance parameters of Piaggio Ape

Specification	Piaggio Ape	
	(CITY+) CNG	(E-City) EV
Max. Power	6.84 kW	5.44 kW
Torque	17 Nm	29 Nm
Displacement	230cc	
Max Speed	60 km/h	45 km/h
Range		110 ± 5 km
Fuel Tank Capacity	40 L	
Battery Capacity		7.5 kWh
Motor Type		PMSM
Battery Type		Li-ion



4.1.2 Product Function

Powertrain components functionality:

i) **ICE engines:** The function of ICE engines is ignition and combustion of fuel that occurs within the engine itself. There are two types of ICE engines: i) petrol vehicles have a spark ignition mechanism where the fuel is mixed with air and then the piston compresses it, which causes combustion. The expanding combustion gasses push the piston during the power stroke which in turn rotates the crankshaft. ii) Diesel engines have a compression mechanism where only air is injected into the engine at first and fuel is sprayed into the hot compressed air at a suitable measured rate which causes combustion. ICEV engine converts the energy released from fuel to work that drives the vehicle wheels.

ii) **ICE fuel:** Petrol and Diesel is obtained by refining petroleum or crude oil which is a hydrocarbon found in geological formations. It is formed over millions of years from dead bodies of buried zooplankton and algae and the high carbon density of such material is used to power the majority of appliances including automobiles. Engines help convert chemical energy of fuel to thermal energy needed to run vehicles.

iii) **Electric Battery:** The electric vehicles get energy from the battery pack which stores electricity powered through the local grid. The electrode and electrolyte store the electricity in the form of chemical energy. On the basis of chemical composition and physical features there are mainly four types of batteries that are used for powering EVs. The lead-acid, nickel cadmium, nickel metal hybrid and lithium-ion are different battery technologies. The energy density of battery cells, energy efficiency, and weight of the battery pack determines the vehicle's overall range. Lithium-ion batteries, the latest battery technology is the preferred choice among the manufacturers owing to its higher energy efficiency and better temperature resistance.

iv) **Electric motor:** The function of the electric motor is rotation at a faster pace to generate mechanical energy for the motion of the vehicle. The motor uses the electrical energy stored in the battery pack. The two physical units of the motor: stator – fixed part, uses the electricity to generate a magnetic field and its displacement leads to the faster rotation of the rotor – the rotating part of the motor. The rotations per minute (RPM) in an electric car are more than engine-based counterparts, providing a light driving experience. Most of the electric motors come with the regenerative function – that restore the energy when brakes are imposed, and vehicles are in stationary position. Therefore, the electric vehicle efficiency does not decline in traffic congestion, which has adverse impact on the ICE-vehicles.

Consumer Behavior: Car drivers are known to have set driving behavior which significantly affects that performance of vehicles, fuel efficiency and vehicle maintenance. For the sake of ease, this study does not consider the behavioral pattern of Indian drivers. It is assumed that such factors have negligible impacts on product life and hence is not part of the scope of this study. Also, the difference in driving behavior between ICE and EV drivers, if any, is not part of the scope of this study as it would complicate the study further.

Other factors: Other factors like road conditions, charging infrastructure, driving range and timings are assumed to have negligible impacts on total impacts of the product. Also, impacts associated with both vehicle technologies are assumed to cancel out one another.

4.1.3 Functional Unit

A functional unit provides a reference to which the inputs and outputs are related/converted and is necessary to ensure comparability of results. The functional unit of this study is taken to be 1,60,000 kilometres of vehicle run for 4Ws and 1,00,000 for 3Ws which is considered to be the life time of the vehicles respectively.

4.1.4 System Boundary

The system under consideration is a cradle-to-cradle system—starting from raw material extraction to end-of-life. The system boundary of both types of vehicle technologies for 3 and 4 wheelers is given in Figure 4 and 5.

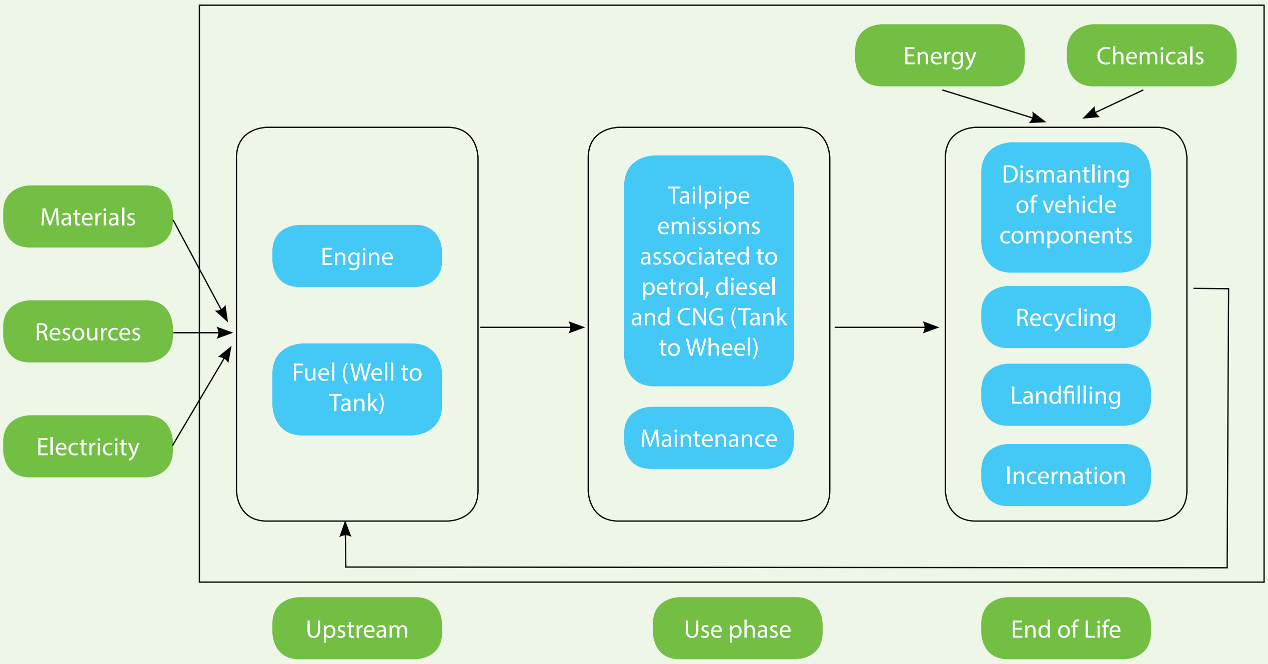


Figure 4: System boundary of 3 and 4-wheeler Internal Combustion Engine (ICE) vehicles

The upstream materials for ICE vehicles are considered such that they comprise 80% of the ICE engine weight. The upstream stream fuel cycle considers extraction, transportation of different types of fuel into India and that data is procured from secondary sources. The energy requirement for refining/processing crude oil and Liquified natural gas is taken from secondary sources. The data is provided in the Annexure. For the end-of-life phase, three processes are considered namely: Recycling, Incineration and Landfilling. The emissions associated with the latter two will be part of the LCA while credits will be provided for recycling of upstream materials that are replacing virgin materials in the economy. In the India case, there is hardly any recycled content in making of vehicle components and hence recycled content credit isn't applied.

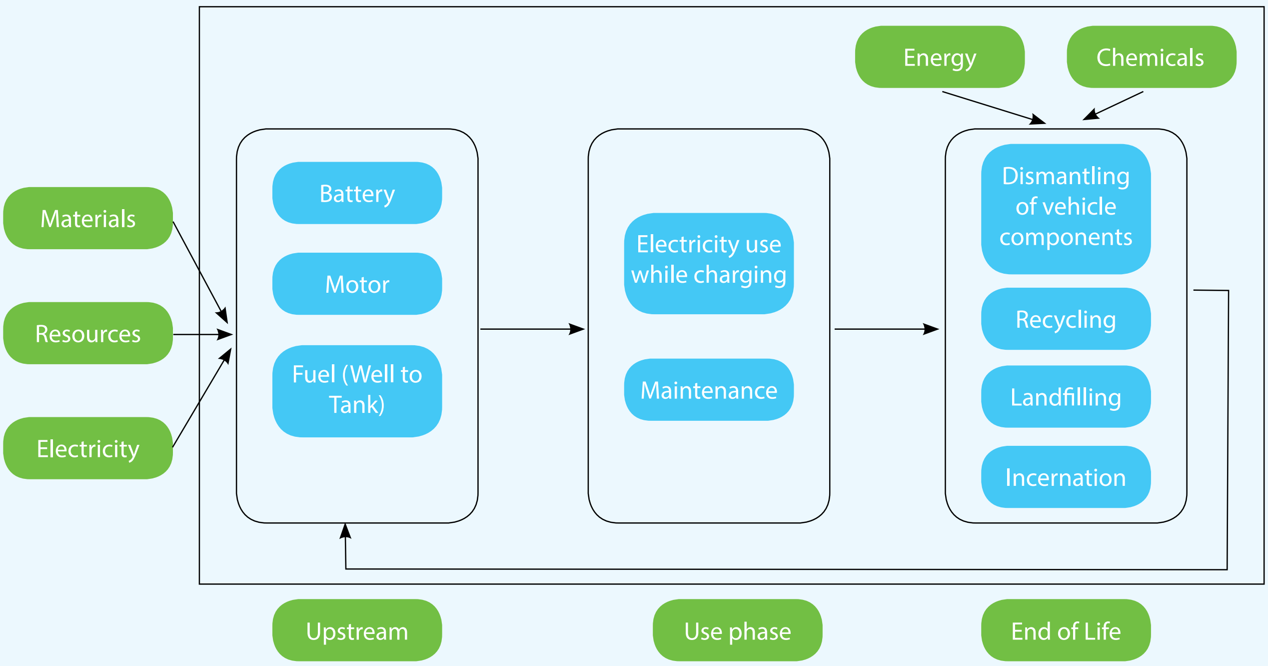
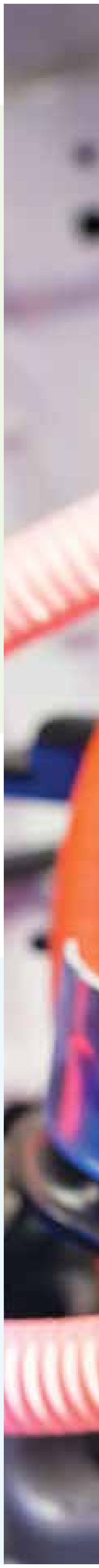


Figure 5: System boundary of 3 and 4-wheeler Electric Vehicle (EV)



Similar to ICE vehicles, the upstream materials for Electric Vehicles are considered by assessing the active weight of the motor which comes around 60-80% of the total motor weight, depending on the peak power requirement. The battery materials are also considered alike. The upstream phase for EVs included extraction, processing, refining and transportation of different materials from source to component manufacturing facilities. The relevant data on energy consumption in due course is taken from secondary sources. The data is provided in Annexure. At the end-of use of vehicles, three procedures are found: Recycling, Incineration and Landfilling. The emissions levels in the latter two procedures are quite high for EV's motor and battery and thus become part of the LCA. Whereas recycling and reuse of essential components in the same or another sector fulfils the dimension of the circular economy and provides emissions credits to EVs. From an Indian perspective, the reuse and recycling of batteries is available to a limited commercial extent. And technological availability to extract materials from motors is limited to recover high value metals of permanent magnets, whereas steel, aluminium and copper scrap are recycled in the economy with certain efficiency. Hence, the emission credits of electric motor recycling are considered accordingly.

The system description of the assessed powertrain component is presented in the Inventory chapter. The stages which are included are concisely presented in Table 3.

Table 3: Stages included in the system boundary

Internal Combustion Engine vehicles		Electric vehicles	
Vehicle Cycle	Fuel Cycle	Vehicle Cycle	Fuel Cycle
Raw material extraction	Fuel extraction	Raw materials mining and processing	Electricity generation in India
Transportation	Oversea transportation	Transportation	Battery charging
Manufacturing	Refining/ Reprocessing	Manufacturing	
Assembly	Domestic transportation	Assembly	
Component End of life		Component End of life	

The system boundary excludes the following: Capital goods used in component manufacturing and assembly, packaging materials of components, fuel filling process into vehicles, evaporation losses at fuel stations during filling.

4.1.5 Selection of LCIA Methodology and Impact Categories

The scope of the study covers the Indian market, the scientific community in India uses ReCiPe LCIA methodology. The methodology is selected in consultation with Advisory

Committee Experts. This method translates emissions and resource extractions into a limited number of environmental impact scores by means of characterisation factors. Two prime ways of deriving characterisation factors are at mid-point and end-point levels. As per ReCiPe, there are

- 18 mid-point indicators
- 3 end-point indicators

Mid-point indicators focus on single environmental problem, for example, global warming potential, acidification or water footprint. The indicators are presented in Figure 2. End-point indicators show environmental impacts on three higher aggregation levels: (1) effect on human health, (2) biodiversity, and (3) resource scarcity. Converting midpoints to end-points simplifies the interpretation of LCIA results.

Figure 6: Some impact categories presented under ReCiPe

Not all impact categories will be included in the main report. Only those categories that are relevant to the goals of the study will be demonstrated. However, the results of all the categories for all product categories can be found in the Annexure 5 and 7. Table 4 below gives a description of ReCiPe impact categories and applicable references for each of the impact categories.

Table 4: ReCiPe impact categories

Impact Category	Description	Unit	Main report	Annexure
Global Warming Potential (GWP)	Amount of energy absorbed by certain mass of greenhouse gas in comparison to amount of energy absorbed by equivalent amount of CO2	kg CO2 eq.	✓	✓
Stratospheric ozone depletion	Ozone Depletion Potential (ODP) calculating destructive effects of stratospheric ozone layer over time horizon of 100 years	kg CFC-11 eq.		✓
Ionizing radiation	Absorbed dose increase	kBq Co-60 eq.		✓
Ozone formation	Terrestrial/Tropospheric ozone formation	kg NOx eq.		✓
Fine particulate matter	PM2.5 population intake increase	kg PM2.5 eq.	✓	✓
Terrestrial acidification	Ability of certain substances to build and release H+ ions	kg SO2 eq.		✓
Freshwater Eutrophication	Phosphorous increase in freshwater	kg P eq.		✓
Terrestrial eco toxicity	Hazard weighted increase in natural soils	kg 1,4-DCB eq.		✓
Marine eco toxicity	Hazard weighted increase in marine waters	kg 1,4-DCB eq.		✓
Freshwater eco toxicity	Hazard weighted increase in fresh waters	kg 1,4-DCB eq.		✓
Land use	Occupation and time integrated transformation	M2a crop eq.		✓
Mineral Resource Scarcity	Surplus Ore potential	kg Cu eq.	✓	✓
Fossil Resource Scarcity	Fossil Fuel Potential	kg oil eq.	✓	✓
Water Consumption	Fresh water use	M 3	✓	✓

4.1.6 Interpretation

The interpretation of the results largely relies upon the goal and scope of the study. The interpretation addresses the following aspects:

- Identification of main processes, inputs (material and energy), outputs (waste and emissions) which contribute to overall results
- Evaluate sensitivity, consistency to make results more robust as to justify usage of proxy data to fill data gaps
- Conclusion, limitations, and recommendations

4.1.7 Type and Format of the report

As per requirements of ISO (ISO, 2006) this document reports the results and conclusion of the study without any bias to the intended audience. The results, data, methods, assumptions, limitations, and recommendations are presented in a detailed and transparent manner to convey the prime message very clearly to the reader. This allows the results to be interpreted and used in a manner consistent with goals of the study.

4.1.8 Software and Database

The LCA models were created using the SimaPro 9.3.0.3 software system for life cycle engineering, developed by PRé Sustainability. The ecoinvent 3.8 (2020) Database provided the upstream life cycle inventory data for the background process.

05 Life Cycle Inventory

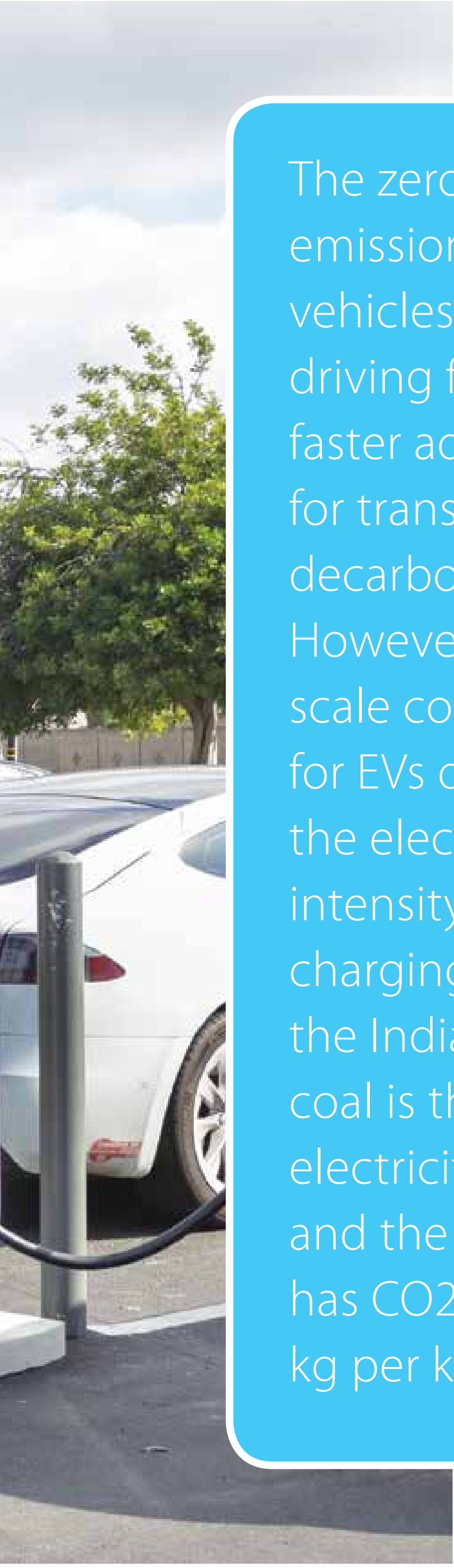
The life cycle inventory (LCI) provides a detailed account of all the flows entering and leaving the studied product system. It consists of all the inputs such as raw materials, energy, water, chemicals, and others required for the production of powertrain components and fuel (conventional fuel and electricity) so as to fulfil the functional unit (that is, 1 vehicle kilometre travel) and the outputs associated with each of these stages—emissions, waste and final products leaving the system.

Overview of product systems

ICE Vehicle Cycle: The data for the product type and material composition of components used in the vehicle is collected considering the approximate weight vehicle engine, from OEM manuals and other well-recognised secondary literature including journal papers and academic notes. Different OEMs' product brochures were revised and analyzed in concurrence to powertrain specifications of selected models. From OEMs consultation and several studies, it was found that a generic Internal Combustion Engine of a four-wheeler fuelled by gasoline, displacement 1199cc with 3 cylinders weighs approximately 87 kg, whereas a diesel fuelled engine of 1497cc displacement with 4 cylinders weighs approximately 170 kg. The details of the inventory for both 3 and 4 wheelers ICE are given in Annexure 1.

ICE Fuel Cycle: India imports 82% of its oil needs and 45% of its gas needs (MoPNG). The shipment of these petroleum and liquefied natural gas happens through oceanic tankers from sea ports major export partners of India. The environmental impact associated with such transoceanic shipment, oceanic distances, and energy requirement during refining is considered in the upstream stage of ICE fuel cycle. When it comes to use phase of vehicles, several primary data points on Tata Nexon petrol and diesel were collected through questionnaire surveys and the average mileage of both types of fuels is calculated. For 3-wheeler section, information is obtained from ARAI's existing database. The emission factors associated with diesel and petrol is 2.6 kg CO_2 and 2.3 kg CO_2 per litre of fuel while it is 0.107 kg CO_2 per km of 3-wheeler CNG.

EV Vehicle Cycle: The data for the product type and material composition of components used in both 3 and 4-wheeler vehicle models is collected from well-recognised secondary sources. The details of upstream segment of EV motor and battery is given below:



The zero-tailpipe emission from electric vehicles is the key driving force in their faster adoption for transportation decarbonisation. However, the emission scale could be positive for EVs depending on the electricity's emission intensity used for the charging purposes. In the Indian scenario, coal is the major fuel for electricity generation and the nation's grid mix has CO2 emission of 0.79 kg per kWh.

- EV Motor: The specifics of motor type, peak power and maximum torque are considered to determine the material intensity in its production. Due to the least indigenous production capability of permanent magnets and high performing motors, the design and material specifications adopted by motor manufacturers, and which is published in international reports are taken for this study. The active material intensity is measured in terms of the kW/kg (peak power-to-weight ratio). Similar to ICE vehicles, the material composition of the electric powertrain components, performance specification of motor such as peak power, peak torque, and motor battery was studied and literature related to motor design and specification was reviewed (Nordelof, 2018). After OEM's consultation and product reviews, the approximate range of motor weight was identified. For an electric 4-wheeler with peak power of 94.8 kW in our case, offered by TATA Nexon EV, a motor should weigh 38-43 kg, out of which active weight (including rotor core, stator core, stator windings, and magnets) comes around 33 kg [AMES paper]. The active weight of the motor measures the mass of the stator, rotor, copper windings and magnets. Whereas for an electric 3-wheeler with peak power of 5.44 kW @ 3500 rpm, the motor weight should be around 6-8kg [Mahle, Golden Motor]. Considering the selected vehicles payload capacity and kerb weight, it was assumed that the motor weight is 6.5 kg. The approach for identifying the minerals and metals used in motor production is similar to the 4-wheeler vehicle. Detailed data inventory of an electric motor is given in Annexure 2.

- EV Battery: The battery type and its charging capacity along with the weight has provided insights for the electrochemistry used in the battery pack. The material composition of the battery core parts has been measured in the terms of kg/kWh. The imported product availability and comparative price has a dominant role in their market penetration. Also, OEM's collaboration with the Chinese company in battery assembly is regarded as the determining factor to calculate emission levels involved in the manufacturing processes. To ascertain the material composition of an electric battery, it is essential to understand the cathode chemistry. The battery capacity, energy efficiency, the offered driving range, and charging efficiency are some parameters that help in narrowing down the chemistry. Apart from that, several literatures related to different cathode chemistries among the lithium-ion batteries were reviewed. The recent trend of battery applications highlights that the manufacturers prefer NCM (Nickel, Cobalt, Manganese) chemistry over others (such as LFP, NCA, LMO) for higher capacity vehicles, to provide improved driving range while simultaneously reducing the vehicle kerb weight. Therefore, it was assumed that our 4-wheeler model TATA Nexon EV has NCM Li-ion battery. Whereas, for the 3-wheeler vehicle, Ape E-city, the assumed battery chemistry is LFP (Lithium-Iron-Phosphate), considering its higher market proliferation among public vehicles, low-cost intensive (cobalt absence), longer life cycle, and more suitability for logistics and low speed vehicles. After careful analysis of battery chemistry and reviewing landmark literature, it was assumed that the battery weight of a LFP Li-ion battery of 7.5 kWh would be around 68 kg [Felicity Battery], and a NCM Li-ion battery of 30.2 kWh would be around 210 kg. The minerals composition of these batteries' chemistry is adopted from Linda Gaines et. Al. (2011), Ellingsen et. Al. (2014), Emilsson et. Al. (2019), TRAN Committee Report (2018), etc. Detailed data inventory of an electric battery is given in Annexure 3.

- Transportation: The materials availability is geographically diverse, and few countries hold major reserves and dominant supply share in the global market. This geographic factor has been used to assess the emission released in the transportation of raw materials from one mining site to a manufacturing facility. Major materials suppliers and major component manufacturers are regarded as the start point and end point in the production line.

EV Fuel Cycle: The zero-tailpipe emission from electric vehicles is the key driving force in their faster adoption for transportation decarbonisation. However, the emission scale could be positive for EVs depending on the electricity's emission intensity used for the charging purposes. In the Indian scenario, coal is the major fuel for electricity generation and the nation's grid mix has CO2 emission of 0.79 kg per kWh.

The survey covered 33 electric vehicles, and their driving range (distance covered in 1 charge) was from 155 km to 230 km. The average distance covered by TATA Nexon EV with the battery capacity of 30.2 kWh was observed as 200 km. The use phase analysis shows that an electric vehicle contributes to 0.12 kg of CO2 per km due to its charging operations of a 4-wheeler EV. For the 3-wheeler section, several primary data points have been obtained from ARAI database. The use phase calculations have been done using an excel based model using the standard emission factors.

Data Collection Procedure

This section presents a structure of data inventory and the list of sources that are used for collecting product related information. In the selected product system, there are two sub-products outlined as vehicle technology – Internal Combustion Engine based vehicles, and Electric motor-based vehicles; and their fuels technology – Petrol, Diesel, CNG, and Electricity. And the life cycle covers three stages upstream, use phase and end-of-life. Table 5 summarize the list of processes considered in this analysis and the data sources used for life cycle inventory preparation.

Table 5: Generic List of processes considered for building life cycle inventory with their data sources

Product- Life Cycle Stage	Internal Combustion Engine Based Vehicles	Electric Vehicle
Engine/Motor & Battery - Upstream	• Minerals and Metals Mining/ Extraction (Secondary Sources) • Metals sheets/ blocks production (established database)	• Minerals and Metals Mining/ Extraction (Secondary Sources) • Metals sheets/ blocks and Magnet alloys production (established database)
Fuels / Electricity – Upstream	• Mining/Extraction (Secondary sources)) • Transportation (Secondary sources) • Port to refinery (established database) • Refining (Secondary) • Engine oil (established database) • Ethanol production for Blending (Secondary)	• Coal Mining/Extraction (Secondary) • Coal Transportation (Secondary) • Electricity Generation (Secondary) • Sensitivity Analysis: Increased renewable source based electricity generation – 50% installed capacity (Secondary sources)

Product- Life Cycle Stage	Internal Combustion Engine Based Vehicles	Electric Vehicle
Engine/Motor – Use phase	• Normal component Wear and Tear (not considered) • Engine Life (secondary sources)	• Normal component Wear and Tear (not considered) • Motor Life (secondary sources)
Fuels / Electricity – Use Phase	• Tail pipe emissions (with 5% ethanol blending in petrol) (ARAI, Secondary) • Fuel Efficiency (OEM's consultation, secondary) • Vehicle kilometers (Primary) • Sensitivity Analysis – 20% ethanol	• Transmission and distribution (Secondary, LCA Database) • Charging efficiency (Secondary, Primary) • Battery efficiency degradation (Secondary, OEM's consultation)
Engine/ Motor – End-of-Life	• Scrap Engine recycling – metals recovery (Secondary sources)	• Scrap Motor Recycling – magnets and metals recovery (Secondary sources)
Fuels – End-of-Life	• No recycling	• Spent Battery Recycling – (Secondary Sources)

Life Cycle Assessment Datasets Used

This section discusses in detail regarding the datasets which were used to model the inventory for different vehicle technologies. Most of the datasets were not readily available in the Eco invent database. To enhance the representativeness of the study, India specific data from literature was plugged into best available data from Eco invent for other regions. In some case, global (GLO) and rest-of-world (RoW) datasets were used.

5.1.1 Electric vehicles

Upstream: The datasets used for mapping the vehicle cycle of upstream EVs is primarily as per global production standards of individual material. The Eco invent datasets do not have India specific mineral extraction and processing burden. The impact associated with component manufacturing, processing and assembly is measured primarily in terms of energy used, which is India specific data. All transportation impacts are included as the market category of process is chosen. Minor domestic transportation during mineral manufacturing, processing and assembly is missed out due to lack of data on the same. For the fuel cycle, the impact burden of electricity generation in India is part of the upstream stage for which the process is self-created based on emission factors of Indian electricity grid mix given by Govt. of India.

Use phase: Some amount of electricity is lost during battery charging. The process is self-created based on emission factors of Indian electricity grid mix given by Govt. of India.

End of Life: Two end of life streams were considered i.e., recycling and landfilling which is as per secondary literature. The datasets used to assess impact of inputs used during recycling is as per global standards. The datasets used for landfilling is as per impact associated with unsanitary landfills of developing world.



Table 6: Datasets used to model powertrain of electric vehicles running on Indian roads

Material/Process		Eco invent database	Reference Year
Upstream	Vehicle Cycle		
	Aluminium	market for aluminium, primary, cast alloy slab from continuous casting GLO	2018
	Boron		2018
	Electrolyte solvent	market for lithium brine, 6.7 % Li GLO	2018
	Cables	market for cable, unspecified GLO	2018
	Carbon		2018
	Chromium steel	market for steel, chromium steel 18/8, hot rolled GLO	2018
	Cobalt	market for cobalt GLO	2018
	Copper	market for copper GLO	2018
	Electrical steel	market for steel, low-alloyed, hot rolled GLO	2018
	Electronics	market for battery, Li-ion, rechargeable, prismatic GLO	2018
	Electricity	market for electricity, high voltage IN-	2018
	Ferrite (Iron)	market for ferrite GLO	2018
	Graphite	market for graphite, battery grade GLO	2018
	Lithium	market for lithium GLO	2018
	Lithium salts	market for lithium brine, 6.7 % Li GLO	2018
	Low alloyed carbon steel	market for aluminium, primary, cast alloy slab from continuous casting GLO	2018
	Manganese	market for manganese GLO	2018
	Nickel	market for nickel, 99.5% GLO	2018
	Oxygen		2018
	Phosphorous		2018
	Plastics	market for polypropylene, granulate GLO market for polyethylene, high density, granulate, recycled RoW	2018
	Rare Earths	market for rare earth concentrate, 70% REO, from bastnäsite GLO	2018

Material/Process		Eco invent database	Reference Year
Upstream	Stainless steel	Steel, stainless 304, scrap/kg/GLO	2018
	Fuel Cycle		2018
Use phase	Electricity generation		
	Charging losses		
End of Life	**Recycling**		2018
	Electricity for recycling	market for electricity, high voltage IN-Northern grid	2018
	Decarbonised water	market for water, decarbonised, at user GLO	2018
	Sulphuric acid	market for sulfuric acid RoW	2018
	Lime	market for lime, hydrated, lose weight RoW	2018
	Low alloyed steel	market for steel, low-alloyed GLO	2018
	Copper	market for copper GLO	2018
	Rare earth concentrates	market for rare earth concentrate, 70% REO, from bastnäsite GLO	2018
	Landfilling	Municipal solid waste (waste scenario) {RoW}| Treatment of municipal solid waste, landfill | Cut-off, U	2018

5.1.2 Internal Combustion Engine Vehicles

Upstream: The datasets used for mapping the vehicle cycle of upstream ICE vehicles is primarily as per global production standards of individual material. The Eco invent datasets do not have India specific mineral extraction and processing burden. The impact associated with component manufacturing, processing and assembly is measured primarily in terms of energy used, which is India specific data. All transportation impacts are included as the market category of process is chosen. Minor domestic transportation during mineral manufacturing, processing and assembly is missed out due to lack of data on the same. For the fuel cycle, the production and refining of three types of fuel is as per global standards. The transportation distances are included as per major production and import sites which largely coincides the Indian situation.

Use Phase: The emission factors associated with three types of fuel i.e., Petrol, diesel and CNG is taken as per Automotive Research Association of India (ARAI) data. Use phase processes have been built using this secondary data.

End of Life: Two end of life streams were considered i.e., recycling and landfilling which is as per secondary literature. The datasets used to assess impact of inputs used during recycling is as per global standards. The datasets used for landfilling is as per impact associated with unsanitary landfills of developing world.

Table 7: Datasets used to model powertrain of internal combustion engine vehicles running on Indian roads

Material/Process		Eco invent database	Documentation	Reference Year
Upstream	Vehicle Cycle			
	Aluminium	market for aluminium, primary, cast alloy slab from continuous casting GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/609191E8-EF71-4A7A-BDB2-123697E379F8/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Copper	market for copper GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/C23CAA32-1B86-48D3-A735-069AF81F60A1/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Engine oil	market for lubricating oil RoW	https://v35.ecoquery.ecoinvent.org/Details/PDF/09D7DA3F-B98F-43B5-9293-D9FA468AD4DA/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Iron	market for cast iron GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/24F92BFC-DE45-4F24-8215-591EFB16F1E6/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Manganese	market for manganese GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/18BFD945-9658-486F-8FC2-5189A725819D/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Nickel	market for nickel, 99.5% GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/3C61E3BB-E6FF-4904-BBC0-CA26218E017D/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Plastics	market for polypropylene, granulate GLO market for polyethylene, high density, granulate, recycled RoW	https://v35.ecoquery.ecoinvent.org/Details/PDF/5549CCBA-EC59-4FA8-BD1C-E6FBC927283B/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE https://v35.ecoquery.ecoinvent.org/Details/PDF/994AE6DD-59A9-47C0-8925-205AE37BC70D/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Rubber	market for synthetic rubber GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/DC6D4A2C-FCBB-4796-837F-6F5DC2FCD84B/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Stainless steel	Steel, stainless 304, scrap/kg/GLO		2018
	Sulphur			2018
	Electricity	market for electricity, high voltage IN-	https://v35.ecoquery.ecoinvent.org/Details/PDF/81CFA9D4-63B9-411F-A5EE-CFBF7DB07B02/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018

Material/Process		Eco invent database	Documentation	Reference Year
Upstream	**Fuel Cycle**			
	Diesel	market group for diesel GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/1E30D0FE-009A-4F09-971F-0CD25A28BB25/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Petrol	market for petrol, 5% ethanol by volume from biomass GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/3E82D82A-A1B2-4AC8-837C-14C8EDDD5AB1/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Ethanol for ethanol blending	market for ethanol, without water, in 99.7% solution state, from fermentation GL	https://v35.ecoquery.ecoinvent.org/Details/PDF/25913F3D-14B4-46D0-A67A-7C379169EBD2/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	CNG	market for natural gas, from high pressure network (1-5 bar), at service station	https://v35.ecoquery.ecoinvent.org/Details/PDF/75264B85-988A-469C-8609-DE6AE230C36E/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
Use Phase	Emission factors for fuels			
End-of-Life	**Recycling**			2018
	Electricity for recycling	market for electricity, high voltage IN-Northern grid	https://v35.ecoquery.ecoinvent.org/Details/PDF/81CFA9D4-63B9-411F-A5EE-CFBF7DB07B02/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Decarbonised water	market for water, decarbonised, at user GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/E9F3F079-2767-47CE-8A34-4FF90014AE87/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Aluminium scrap	aluminium scrap, post-consumer, prepared for melting, Recycled Content cut-off G	https://v35.ecoquery.ecoinvent.org/Details/PDF/978C9064-8A2B-43C3-8138-9BC35BB13185/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Manganese	market for manganese GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/18BFD945-9658-486F-8FC2-5189A725819D/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Nickel	market for nickel, 99.5% GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/3C61E3BB-E6FF-4904-BBC0-CA26218E017D/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Copper	market for copper GLO	https://v35.ecoquery.ecoinvent.org/Details/PDF/C23CAA32-1B86-48D3-A735-069AF81F60A1/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE	2018
	Landfilling	Municipal solid waste (waste scenario) {RoW}| Treatment of municipal solid waste, landfill | Cut-off, U		2018

Additional Data Points

Some additional data points used in the study along with the sources are tabulated below:

Table 8: Additional data points used in the study

Item	Data Points	Source
Emission factor of petrol	2.3 kg CO2/liter	ARAI
Emission factor of diesel	2.6 kg CO2/liter	ARAI
Emission factor of CNG	0.107 kg CO2/km of 3W CNG run	ARAI
Grid emission factor (CO2)	0.79 kg CO2/kWh	CEA
Grid emission factor (PM)	0.00019 kg/kWh	CEA
Grid emission factor (SOx)	0.00468 kg/kWh	CEA
Grid emission factor (NOx)	0.00391 kg/kWh	CEA
Grid emission factor (Hg)	0.000000008 kg/kWh	CEA
Vehicle lifetime (4Ws)	1,60,000 kms	Tata Nexon manual
Vehicle lifetime (3Ws)	1,00,000 kms	Secondary Literature
Battery degradation factor	34%	Secondary Literature
Vehicle recycling rate	70-80% (We have considered 75%)	Automobile Recycling Association
Reduced fuel efficiency with ethanol blending	4-5% decrease foe E20	CRISIL Research

The Life Cycle Inventory Analysis Results

ISO 14044 defines life cycle inventory (LCI) analysis results as "outcomes of the life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment."

06 Life Cycle Impact Assessment

This chapter contains the description of results for the major impact categories as presented under ReCiPe. These results are presented for various powertrain components and fuel types as per the scope of this study. The method has been given the name ReCiPe as it provides a 'recipe' to calculate life cycle impact category indicators. It is important to mention here that the reported impact categories represent impact potentials. In other words, they are approximations of environmental impacts that could occur if emissions would follow: (a) the underlying pathway; and (b) meet certain conditions in the receiving environment while doing so.

LCIA results are therefore relative expressions and do not depict actual impacts, the exceeding thresholds, safety margins, and risks.

The results presented in this report also have contribution analyses, which split the numbers according to the life cycle stages upstream, use phase, and end-of-life. This will help in understanding the influence on the GWP of each stage on overall environmental impact. This also enables hotspot identification.

The chapter on life cycle assessment is divided into (i) comparative baseline analysis and (ii) sensitivity analysis

Comparative Baseline Analysis

This section depicts the performance of the two vehicle technologies each for 3 and 4-wheeler section with respect to key relevant environmental impact categories. The analysis is done using substitution method where a value of scrap burden associated with input amount of scrap content is calculated as well as credits for recycling are earned for the product.

The baseline assessment presents results for following impact categories (i) GWP, (ii) Fine particulate matter formation (iii) Mineral resource scarcity (iv) Fossil resource scarcity and (v) Water consumption. However, detailed results for all impact categories for different products assessed are presented in the Annexure.

6.1.1 Global Warming Potential (GWP)

GWP is the most used parameter to assess the climate change potential of emissions. The GWP refers to the amount of energy that 1 tonne of gas will absorb over a given period of time, relative to the emissions of carbon dioxide (CO_2). Most common greenhouse gases (GHGs) responsible for climate change are carbon dioxide, methane, and nitrous oxide. In this study, all these gases are not marked individually but are represented as CO_2 equivalent.

The GWP impact is presented for the entire lifetime of the vehicles which is considered to be 1,60,000 kms for 4-wheelers and 1,00,000 kms for 3-wheelers. From the results of the 4-wheeler category, it is found that EVs are best performing when it comes to Global warming impact with an emission intensity of 0.15 kg CO_2 eq./km while it is 0.17kg CO_2 eq./km and 0.19 kg CO_2 eq./km for diesel and petrol respectively. The GWP impacts of three stages of different vehicle technologies of 4-wheeler is presented in Figure 7.

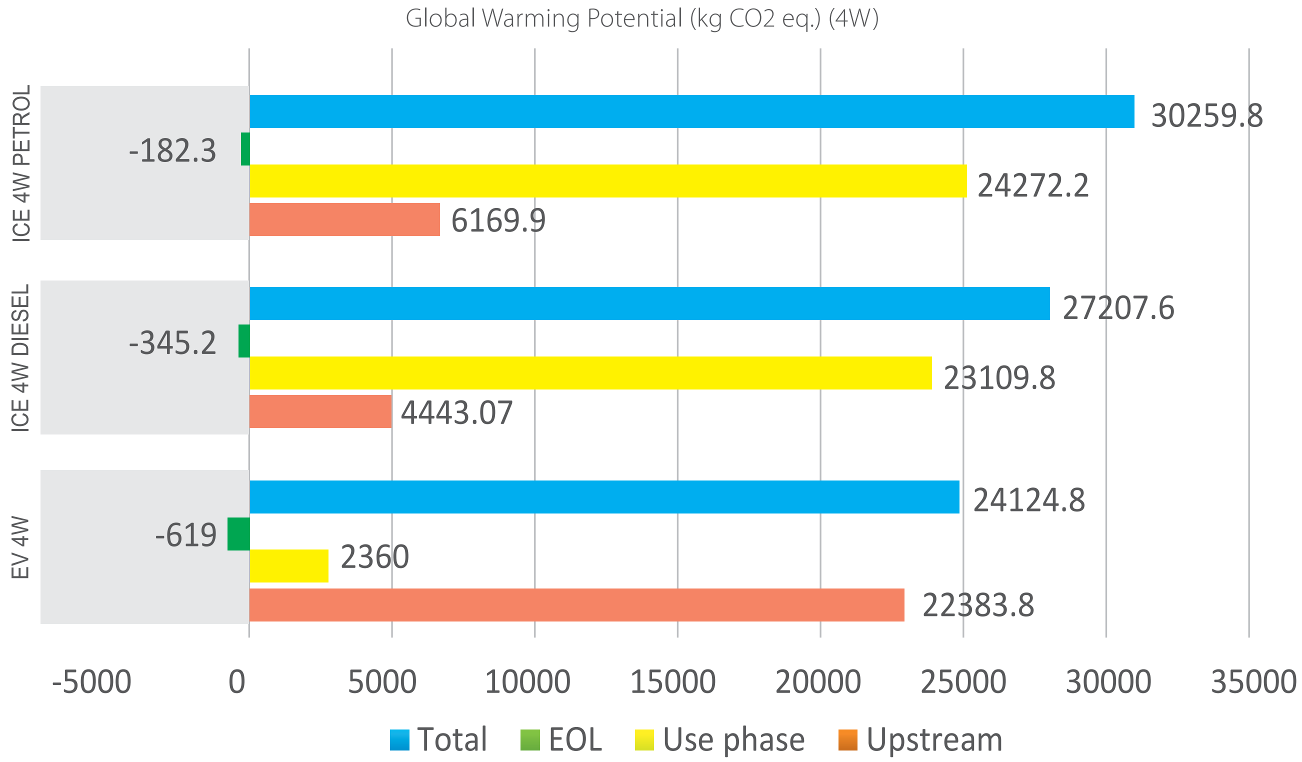


Figure 7: GWP impact of 4-wheeler ICE versus EV segregated into 3 life cycle stages

The weight of the Tata Nexon 4-wheeler petrol and diesel engine is considered to be 87 and 170 kgs respectively and composition of all materials considered, makes up to 80-85% of this weight. The upstream GWP impacts associated with Tata Nexon petrol and diesel vehicles are 4443 and 6169.9 kg CO2 eq. This includes impacts associated with engine manufacturing and Well to Tank (WTT) emissions of fuel at 335 and 5834 kg CO2 eq. for petrol and 430 and 4012 kg CO2 eq. for diesel respectively. The upstream GWP impact of EVs is 22383.8 kg of CO2 eq. which is primarily contributed by electricity generation in India at 21424.8 kg of CO2 eq. at an emission intensity of 0.79 kg of CO2 per kWh of electricity. Rest of the upstream emissions is from engine, battery and motor manufacturing. The weight of the Tata Nexon EV motor is much smaller at 32.09 kg and the material composition makes up to 80% of the motor. The motor has the least upstream GWP impact of 110 kg CO2 eq. among the powertrain components. However, the Tata Nexon EV battery has the highest GWP impact of 849 kg CO2 eq. considering its heavy weight of 210 kg which is significantly composed of large amounts of aluminium and a variety of steel types like chromium and electrical steels. Additionally, the cathode materials used in batteries are extracted and processed through very energy and emission intensive procedures. The upstream and use phase impacts of all vehicle technologies in 4-wheeler category is presented in Figure 8.

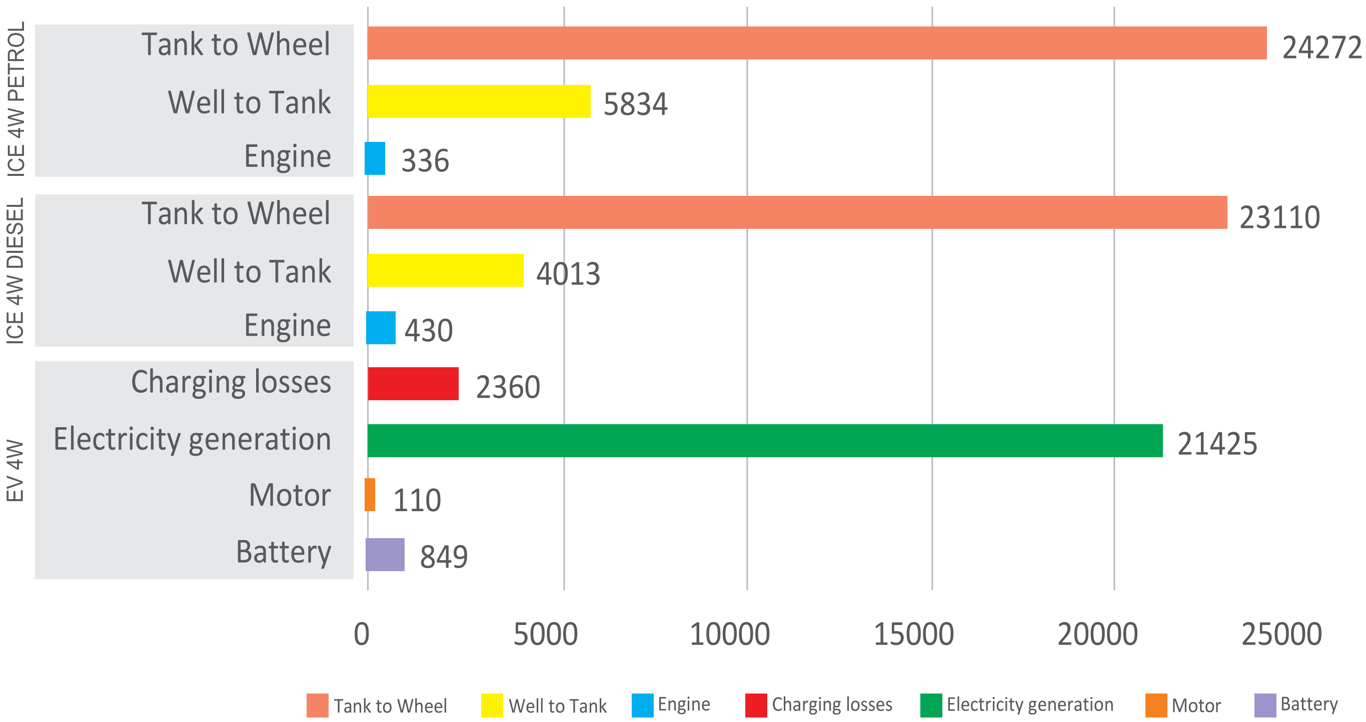


Figure 8: Breakdown of GWP impact (kg CO2 eq.) of upstream and use phase of 4-wheeler ICE vehicle versus EV

The use phase emissions of 4-wheeler EV are associated with electricity losses incurred during charging which amounts to 2360 kg CO2 eq. While for ICE, it is 23109.8 and 24272.2 for diesel and petrol, and the emission intensity is at 2.667 kg CO2/litre and 2.311 kg CO2/litre of diesel and petrol respectively. Increased fuel efficiency of the diesel engine gives higher mileage and total amount of diesel required for the vehicle lifetime is 8,665.1 litres while it is higher for petrol at 10,502.9 litres causing higher use phase impact for petrol despite lower emission intensity.

The End-of-life emissions (EOL) has given higher benefits to EV than ICE vehicles. Virgin materials that go into making EV components have higher resource and energy intensity and hence replacing them with recycled materials is likely to benefit the environment more.

In the 3-wheeler category, EVs are best performing with emission of 0.063 kg CO2/km while it is 0.13 kg CO2/km for CNG vehicle. The GWP impacts of three stages of two technologies of 3-wheeler are presented in Figure 9.

The weight of the Piaggio Ape 3-wheeler CNG engine is considered to be 43 kgs and the material composition considered, makes up to 85-90% of this weight. The upstream GWP impacts associated with Piaggio Ape CNG is 2902.2 kg CO2 eq. This includes impacts associated with engine manufacturing and Well to Tank (WTT) emissions of fuel at 343.5 and 2558.7 kg CO2 eq. respectively. The upstream GWP impact of the 3-wheeler EV is 6162.7 kg of CO2 eq. which is primarily contributed by electricity generation in India at 5943.9 kg of CO2 eq. at an emission intensity of 0.79 kg of CO2 per kWh of electricity. Rest of the upstream emissions is from engine, motor and battery manufacturing. The weight of the Piaggio Ape EV motor is much smaller at 6.5 kg and the material composition makes up to 90-95% of the motor. The motor has the least upstream GWP impact of 19.4 kg CO2 eq. among the powertrain components. However, the Piaggio Ape EV battery has the high GWP

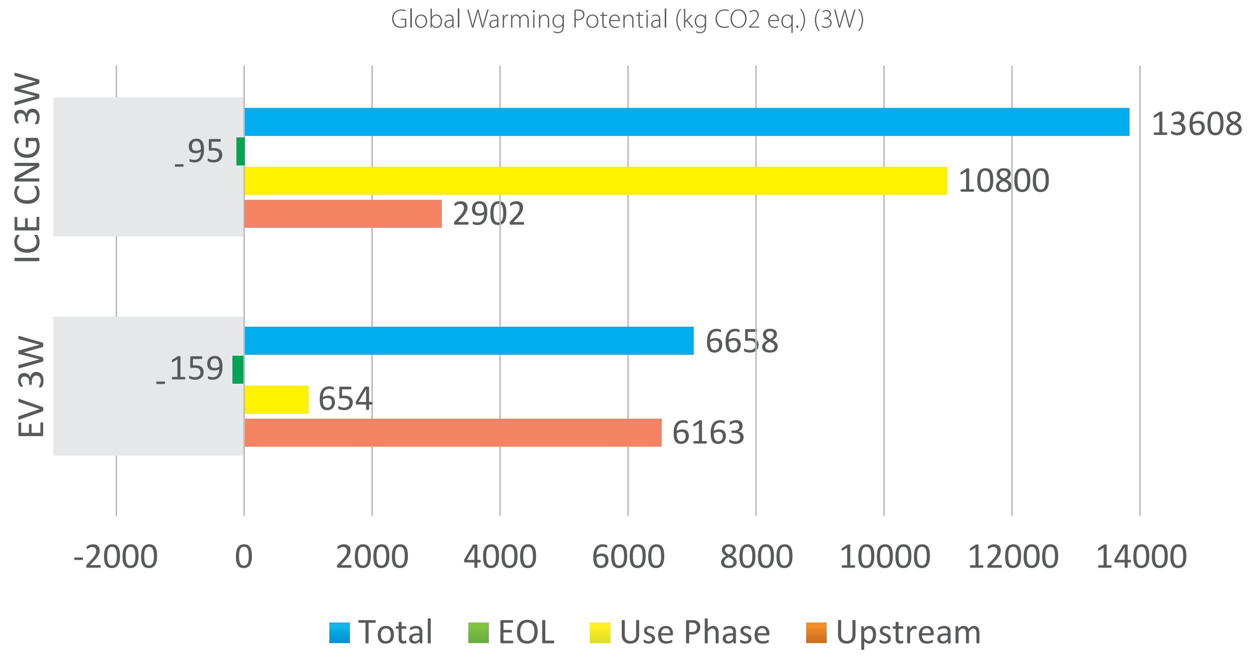


Figure 9: GWP impact of 3-wheeler ICE versus EV segregated into 3 life cycle stages

impact of 199.4 kg CO2 eq. considering its heavy weight of 68 kg which is significantly composed of large amounts of aluminium, copper, and iron. Additionally, the cathode materials used in batteries are extracted and processed through very energy and emission intensive procedures. The upstream and use phase impacts of all vehicle technologies in 3-wheeler category is presented in Figure 10.

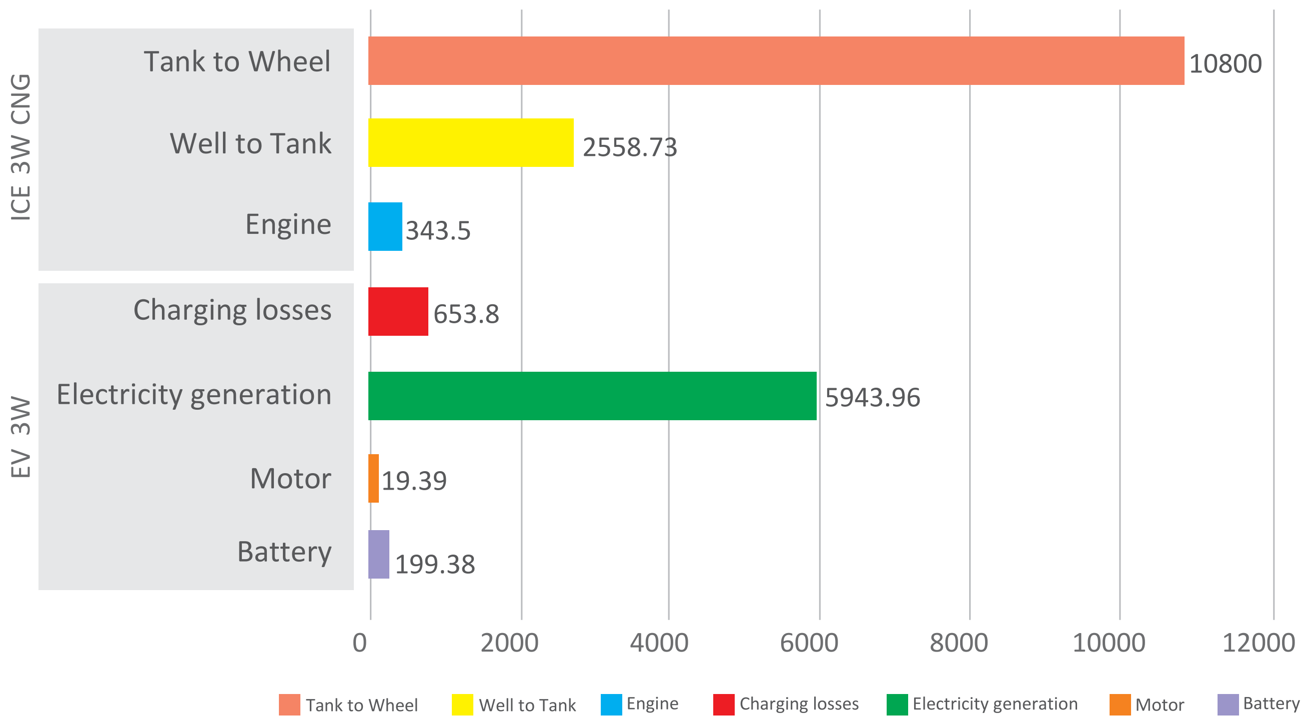


Figure 10: Breakdown of GWP impact (kg CO2 eq.) of upstream and use phase of 3-wheeler ICE versus EV

The use phase emissions of 3-wheeler EV are associated with electricity losses incurred during charging which amounts to 653.8 kg CO2 eq. While for 3-wheeler ICE, it is 10800 for CNG, at an emission intensity of 0.10768 kg CO2/km of 3-wheeler vehicle run with CNG (India GHG Program).

In the End of Life stage, a substitution approach was adopted where the benefits and burden of recycling the materials are given to the product itself. The End of Life emissions of EVs is more negative than ICE vehicles because the benefits of avoiding critical materials and rare earths that goes into making EVs is much higher than avoiding just the ferrous and nonferrous metals used in ICE vehicles. A vehicle recycling rate of 75% is considered as per the information received from Automobile Recycling Association while the rest is assumed to be landfilled.

For ICE vehicles the amount of output materials from recycling process which also serve as virgin materials avoided is multiplication of total amount of material recycled with the recycling yield of each material which is assumed to be 95% for all for the sake of simplicity. The recycling yield of most metals like aluminium, steel, cast iron, copper, manganese ranges between 90%-100% in standard recycling processes.

Avoided materials = Recycled amount* Recycling yield

For EVs, a detailed analysis was done to understand the material recovery intensity of used battery and electric motor. As per data found in Mohr M et. al. (2020), the critical minerals used in lithium-ion battery, such as lithium, nickel, manganese, cobalt, copper and aluminium, can be recovered up to 93%. Whereas, for electric motor, the NdFeB magnet recovery rate of 75% has been assumed on the basis of studies by Yang, et al. (2017) and Elwert et al. (2016). The input and output amounts of the lithium-ion battery in respect of per kg of spent-battery for 3W EV and 4W EV powertrain is given in Annexure 4. The outputs serve as avoided virgin materials whose benefit is given to the product itself under the substitution method.

6.1.2 Fine Particulate Matter Formation

Particulate matter (PM) is a complex mixture of small liquid droplets and solid particles suspended in air. These can be from natural as well as man-made sources. PM is a massive environmental pollutant and a health hazard owing to its very small size which allows it to travel deep into the respiratory tract and reach the lungs. Figure 11 presented below shows the PM emissions associated with different 4-wheeler vehicle technologies segregated into three life cycle stages.

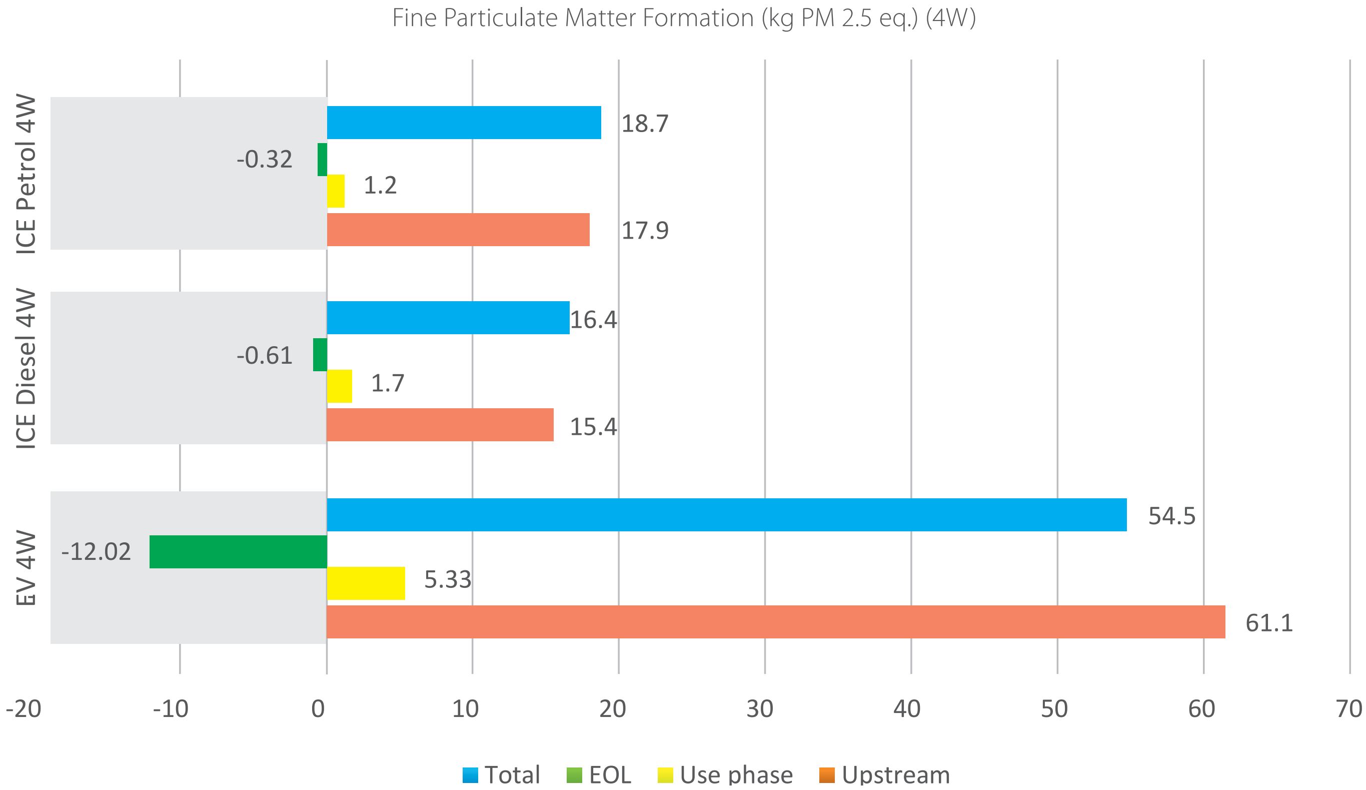


Figure 11: Fine PM formation impact of 4-wheeler ICE versus EV segregated into 3 life cycle stages

The total PM emissions are highest for EVs due to high upstream emissions contributed by electricity generation in India. The PM intensity of Indian thermal power plants is 0.00019 kg/kWh. (CEA, 2021) Figure 12 below further breaks up PM emissions of 4 wheelers into different segment of individual life cycle stages for better understanding.

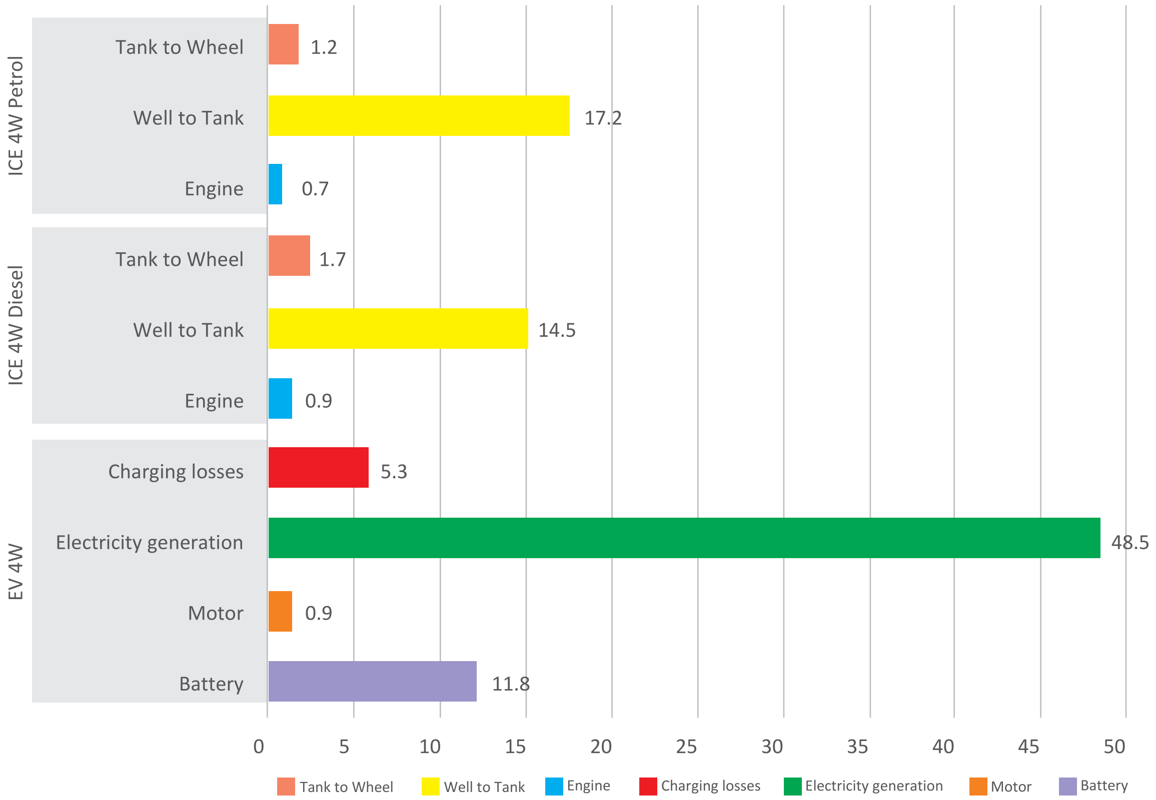


Figure 12: Breakdown of Fine PM formation (kg PM 2.5 eq.) impact of upstream and use phase of 4-wheeler ICE versus EV

Among 4-wheeler ICE vehicles, the PM emissions are high for diesel than petrol in the use phase (Tank to Wheel). However total PM emissions is higher for petrol owing to the higher Well to Tank emissions of the fuel.

Significant EOL benefits are obtained only in case of EVs because of the PM emissions saved during battery manufacturing process.

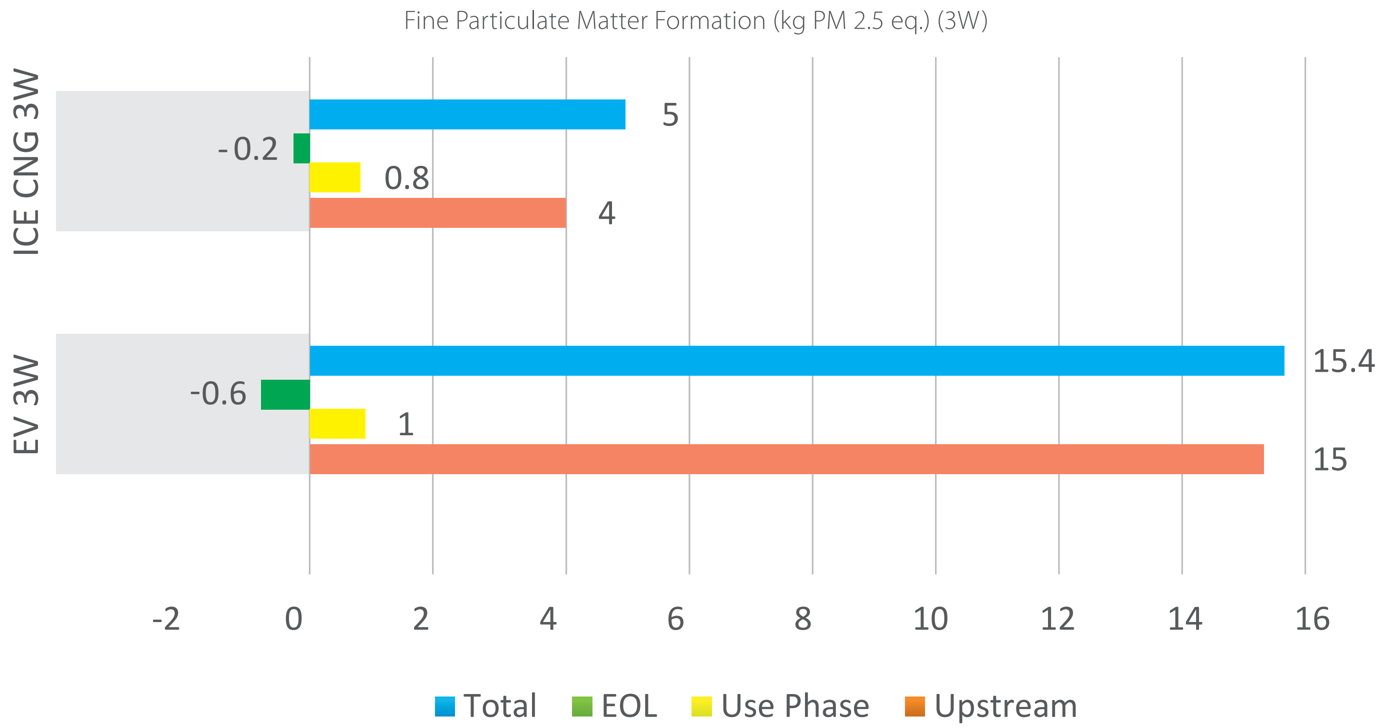


Figure 13: Fine PM formation impact of 3-wheeler ICE versus EV segregated into 3 life cycle stage

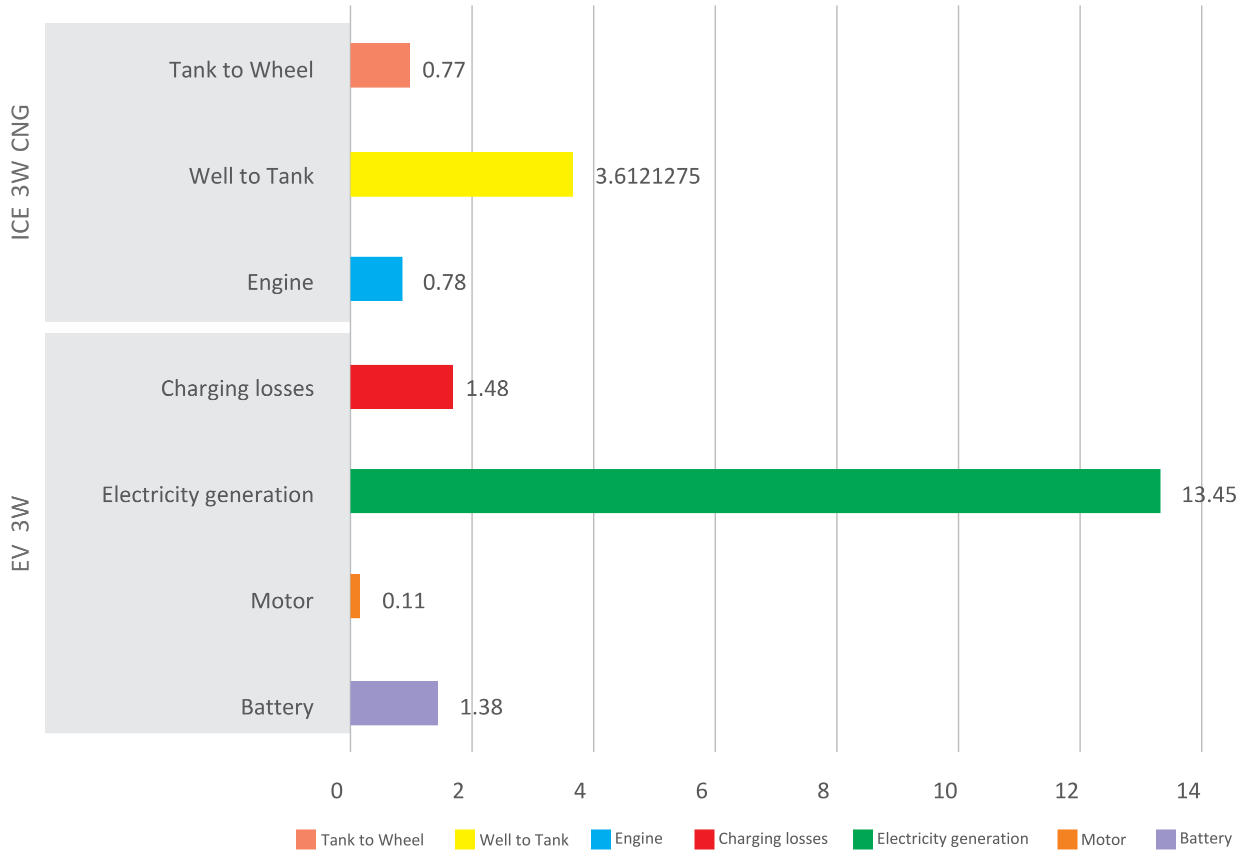


Figure 14: Breakdown of Fine PM formation (kg PM 2.5 eq.) impact of upstream and use phase of 3-wheeler ICE versus EV

For 3-wheelers, EVs have higher PM emissions at 12.7 kg PM eq. than ICE CNG variants, which is significantly contributed by electricity generation (Figure 14). Figure 13 presented below shows the PM emissions associated with two 3-wheeler vehicle technologies segregated into three life cycle stages.

For both 3 and 4-wheeler vehicles, PM emissions during the manufacture of an EV battery are significantly higher than any other powertrain component manufacturing. (Figure 12 and 14) This can be largely attributed to the lithium battery manufacturing process which is a long process with numerous inputs like electrolyte solvents, additives and salts.

The use phase emissions of EVs for both 3 and 4-wheelers at 1.48 kg PM eq. and 5.33 kg PM eq. respectively are not tailpipe emissions unlike ICE vehicles but are non-localized emissions released at the power plant station. There is no doubt that replacing ICE vehicles with EVs significantly reduces air pollution inside cities as localized emission of EVs is almost nil. However, high levels of PM released during EV battery manufacturing as well as massive release of PM during electricity generation suggests that the pollution is getting transferred elsewhere. (Vidhi R., 2018) In case of India which has some of the world's top polluted cities such an option may be a temporary solution.

6.1.3 Mineral Resource Scarcity

The life cycle impact assesses the minerals scarcity in future, by modelling the amount and grade of material used. It is an indicator of the abiotic resources' depletion. Considering the operational essence of a product, the material composition and its grade get determined. The higher grade of materials needs to be produced by larger amounts of ore extraction. The total mineral resource scarcity of different vehicle technologies for the 4-wheeler and 3-wheeler segment is presented in Figure 15 and 16 respectively.

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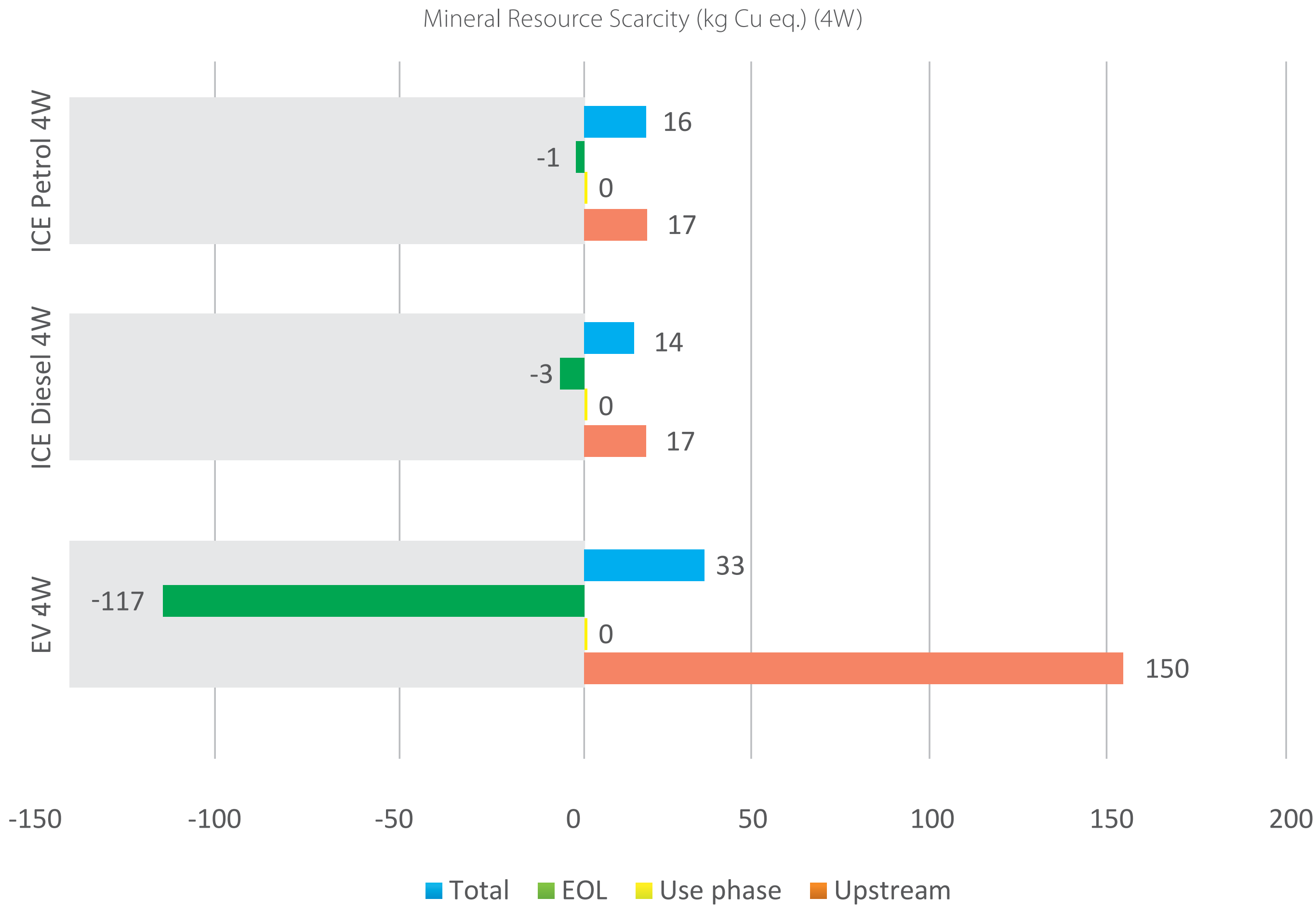

Figure 15: Mineral resource scarcity impact of 4-wheeler ICE versus EV segregated into 3 life cycle stages

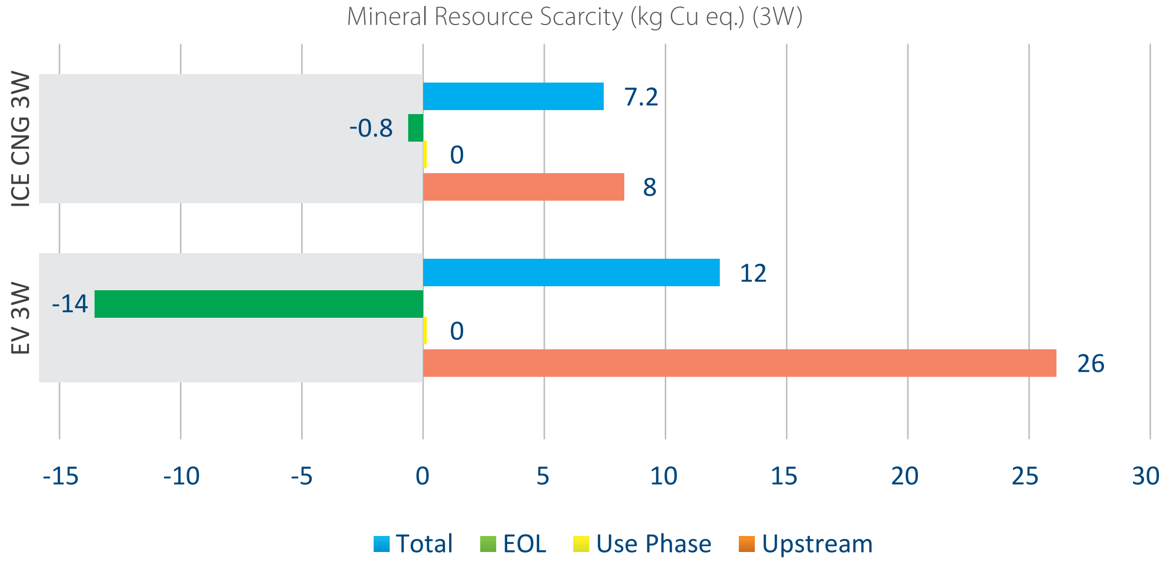

Figure 16: Mineral resource scarcity impact of 3-wheeler ICE versus EV segregated into 3 life cycle stages

Both for 3 and 4-wheeler engines, the materials used in are majorly steel, aluminium, and plastics. Ferrous material is not naturally scarce and available in crust around the depth of 250-300m, thereby having comparatively lesser impact. It should be noted that the impact is comparatively higher for diesel engine than petrol and CNG engine, because of change in component weight and material composition. The increased share of steel and other materials in diesel engines has resulted in higher impact. Meanwhile, in the case of EV motors steel and copper requirement in motor architecture is lesser than the IC engine, but scarce materials such as rare earth metals, cobalt, boron, etc. results in higher impact compared to ICE engines. The battery materials are scarcer and more non-ferrous, thus, extracted from more depths of around 1500m and more, causing the situation of higher scarcity in future. It is the battery associated impact that contributed to the significantly high burden of impact for EVs, and it is at 93% for 4 wheelers (i.e., 140 kg CO eq. out of 150.43 kg CO2 eq.) and 94% for 3-wheelers (i.e., 24.1 kg CO2 eq. out of 25.8 kg CO2 eq.)

The materials considered for recycling for EOL calculations are given in table below. The EOL emissions show a similar situation as described in the above segment. The replacement of rare materials used for battery manufacturing is likely to give higher benefit to total impacts as it does in the case of EVs.

6.1.4 Fossil Resource Scarcity

This impact indicates the extent of fossil resources depletion caused by a product during its life cycle. The analysis quantifies the required raw materials and their withdrawals from nature. The mining of materials requires energy which is fulfilled by fossil fuels combustion in the earlier stage. The fossil resource scarcity impact associated with different 4-wheeler vehicle technologies is given in Figure 17.

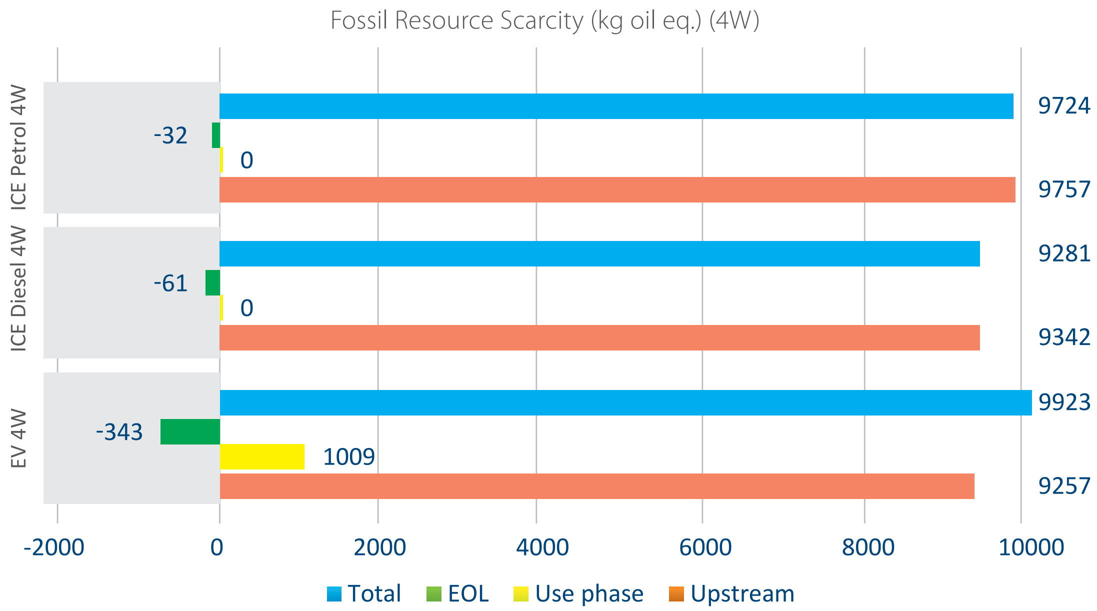

Figure 17: Fossil resource scarcity impact of 4-wheeler ICE versus EV segregated into 3 life cycle stages

4-wheeler EVs have the highest fossil resource depletion in the upstream contributed significantly by coal depletion required for electricity generation in India. A small portion is also contributed by electricity requirements associated with component manufacturing of EVs. For 4-wheeler ICE vehicles the upstream value is largely contributed by Well to Tank emissions. The use phase emissions of 4-wheeler EV are from electricity loss during charging which is absent in case of ICE vehicles. Further breakup of the upstream and use phase impact is shown in the Figure 18. Coal consumption for production of electricity in the Indian grid is reflected in the electricity generation column while fuel production is reflected in the Well to Tank (WTT) column for diesel and petrol. The Tank to Wheel impacts of 4-wheeler ICE vehicles is part of the use phase where there is no additional consumption of fossil resources and hence is zero.

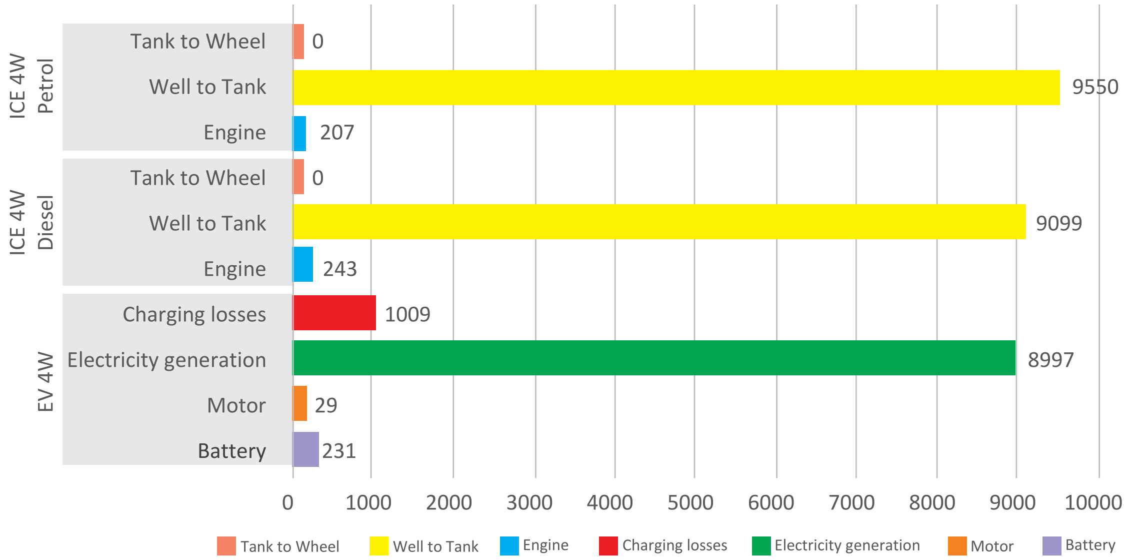

Figure 18: Breakdown of Fossil resource scarcity (kg oil eq.) impact of upstream and use phase of 4-wheeler ICE versus EV

For 3-wheeler segment, the trend of total fossil resource scarcity changes with respect to 4-wheeler counterparts. (Figure 19) The range of Piaggio Ape considered for the 3-wheeler segment is 110 km/charge with a battery capacity of 7.5 kWh. This is significantly better than range of 200.6 km/charge for Tata Nexon considering it has a battery capacity of 30.2 kWh. This could probably be the reason of high corresponding electricity consumption in case of 4-wheeler EVs compared to 3-wheeler EVs, leading to high fossil resource scarcity in the former, relative to their ICE counterparts. For ICE vehicles the impact of 3-wheelers is approximately half of 4-wheelers; while it is one third for EVs.

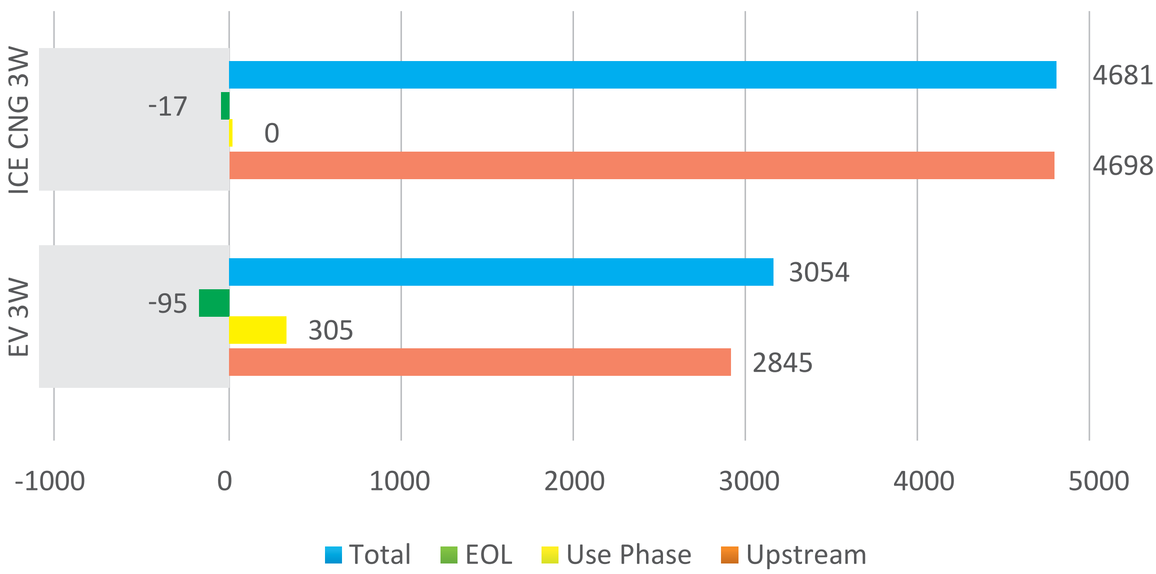

Figure 19: Fossil resource scarcity impact of 3-wheeler ICE versus EV segregated into 3 life cycle stages

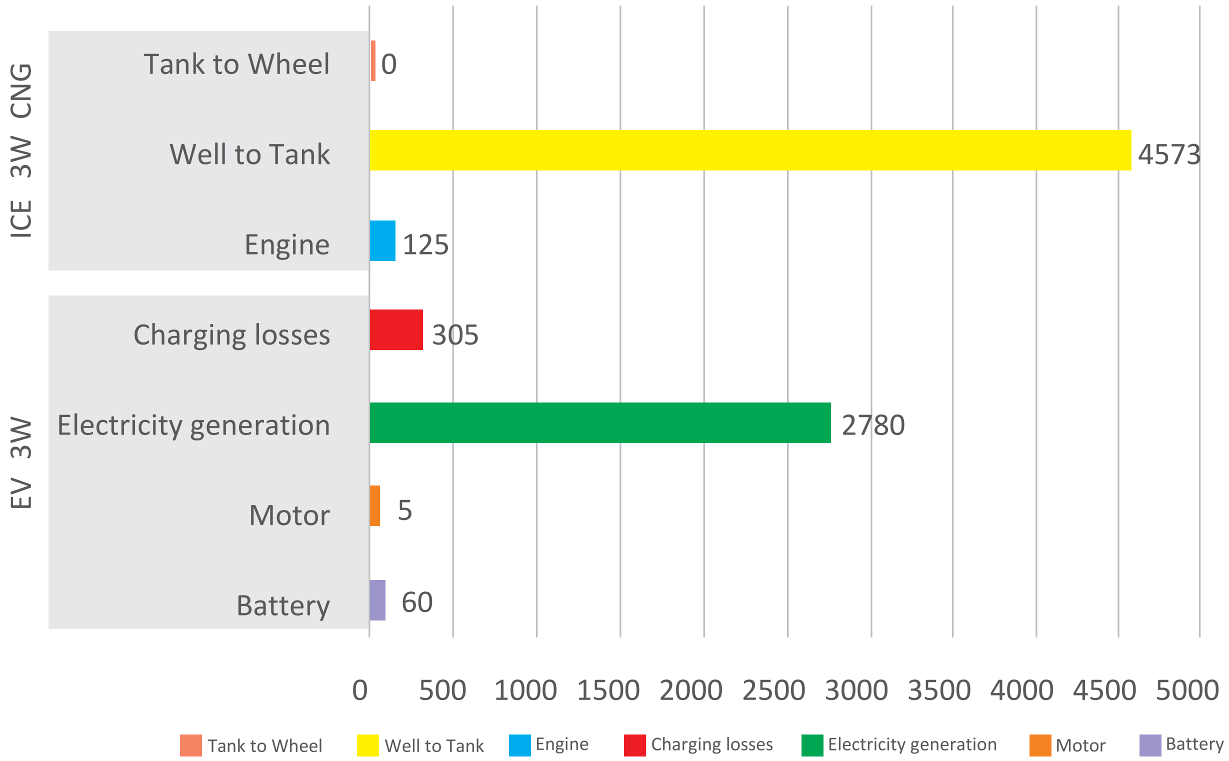

Figure 20: Breakdown of Fossil resource scarcity (kg oil eq.) impact of upstream and use phase of 3-wheeler ICE versus EV

Among powertrain components of both 3W and 4-wheelers, diesel engines have highest impact as steel manufactured through energy intensive processes is required in higher quantities in IC engines and thus their potential threat to fossil scarcity is higher. Petrol and CNG engines show lesser impact due to corresponding low weight and material requirement. (Figure 18 and 20) EV batteries also have high impact on fossil resource availability. The cathode materials used in batteries are extracted and manufactured through rigorous energy involved procedures. Further, drying of cathode materials to make them accidental proof demands high temperature for longer duration.

In the EOL, for both the vehicle segment 3W and 4W across the fuel type, a benefit is observed. This benefit can be attributed to electricity saved in manufacturing of materials which have now been avoided due to recycling. The benefit is high for EVs because of larger weight of EV powertrain and higher use of energy intensive materials in EVs.

6.1.5 Water Consumption

Water consumption is the use of water in such a way that the water is evaporated, incorporated into products, transferred to other watersheds or disposed of. (Falkenmark et al. 2004). Water being a scarce resource, it is imperative to understand the potential impacts of various vehicle technologies on water consumption during their lifetime. Such knowledge is especially relevant in a water stressed country like India. The water consumption impact of the 4-wheeler segment of different vehicle technologies is given in Figure 21.

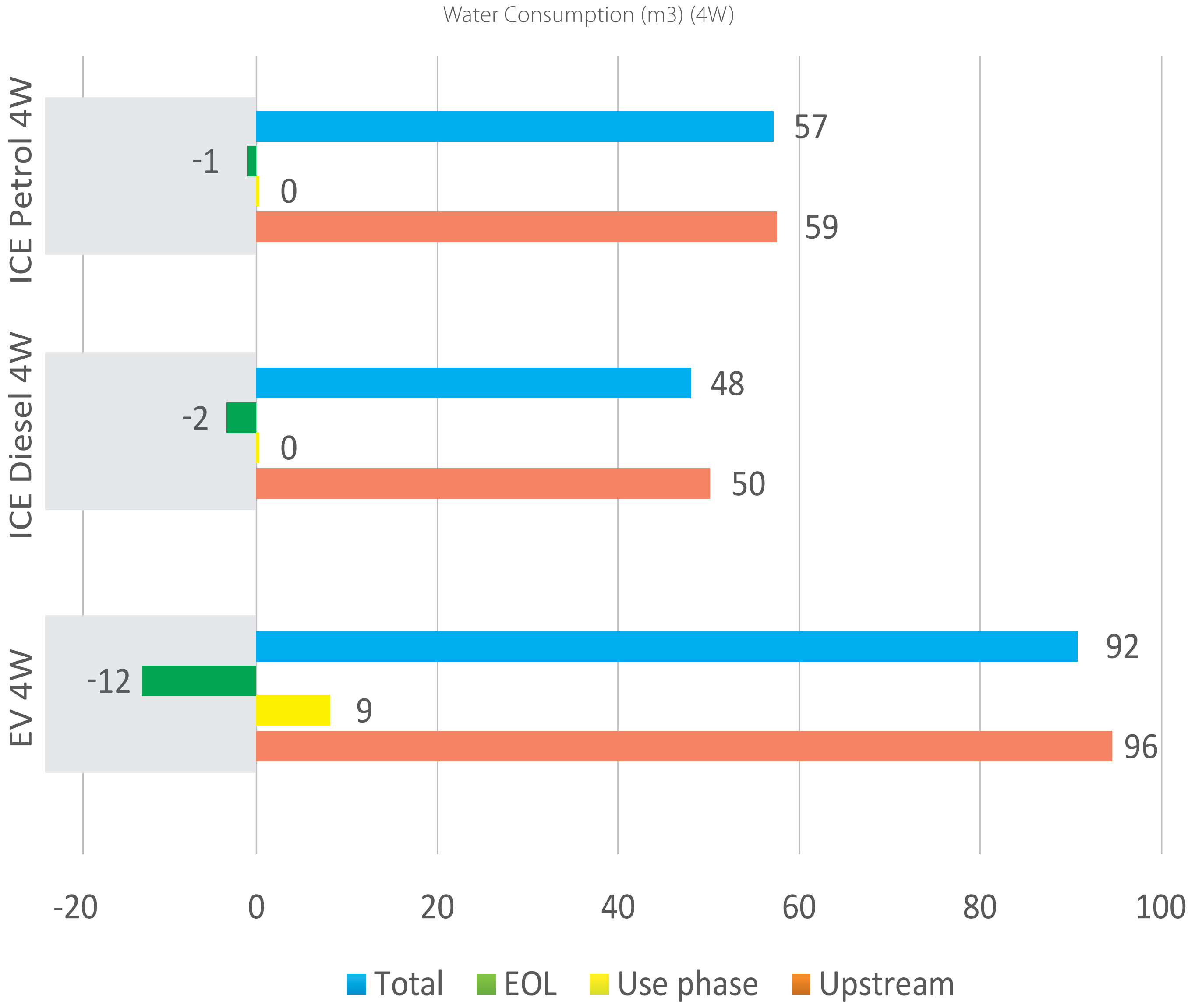

Figure 21: Water consumption impact of 4-wheeler ICE versus EV segregated into 3 life cycle stages

The total water consumption of EVs is higher than ICE vehicles mainly contributed by the water requirement during electricity production, which is reflected as a significant proportion in the upstream phase. Most water requirement for ICE vehicles comes from the fuel production stage i.e. Well to Tank requirement, which is again reflected in the upstream stage. Further break up of water requirement for 4-wheeler segment is shown in Figure 22.

Water usage for EVs during the use phase is accounted for by the charging loss. Water is utilised to produce energy and charging loss would indicate that the electricity was not used. This accounts for the use phase water consumption of EVs which is absent for ICE vehicles.

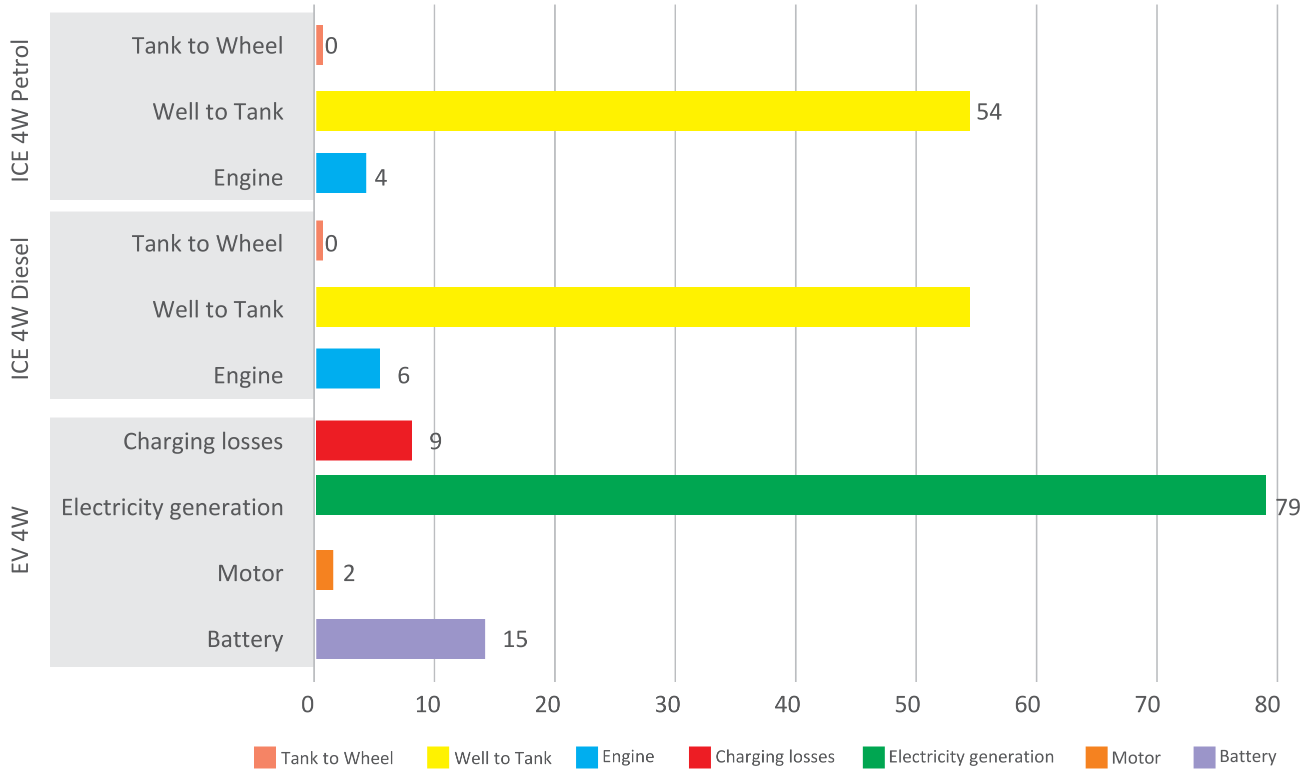

Figure 22: Breakdown of Water consumption (m3) impact of upstream and use phase of 4-wheeler ICE versus EV

For 3-wheeler segment, water consumption is high for EVs again largely contributed by electricity generation in India. For 3-wheeler ICE vehicles, fuel production i.e., Well to Tank impact is the significant contributor to the upstream impact. (Figure 23 and 24)

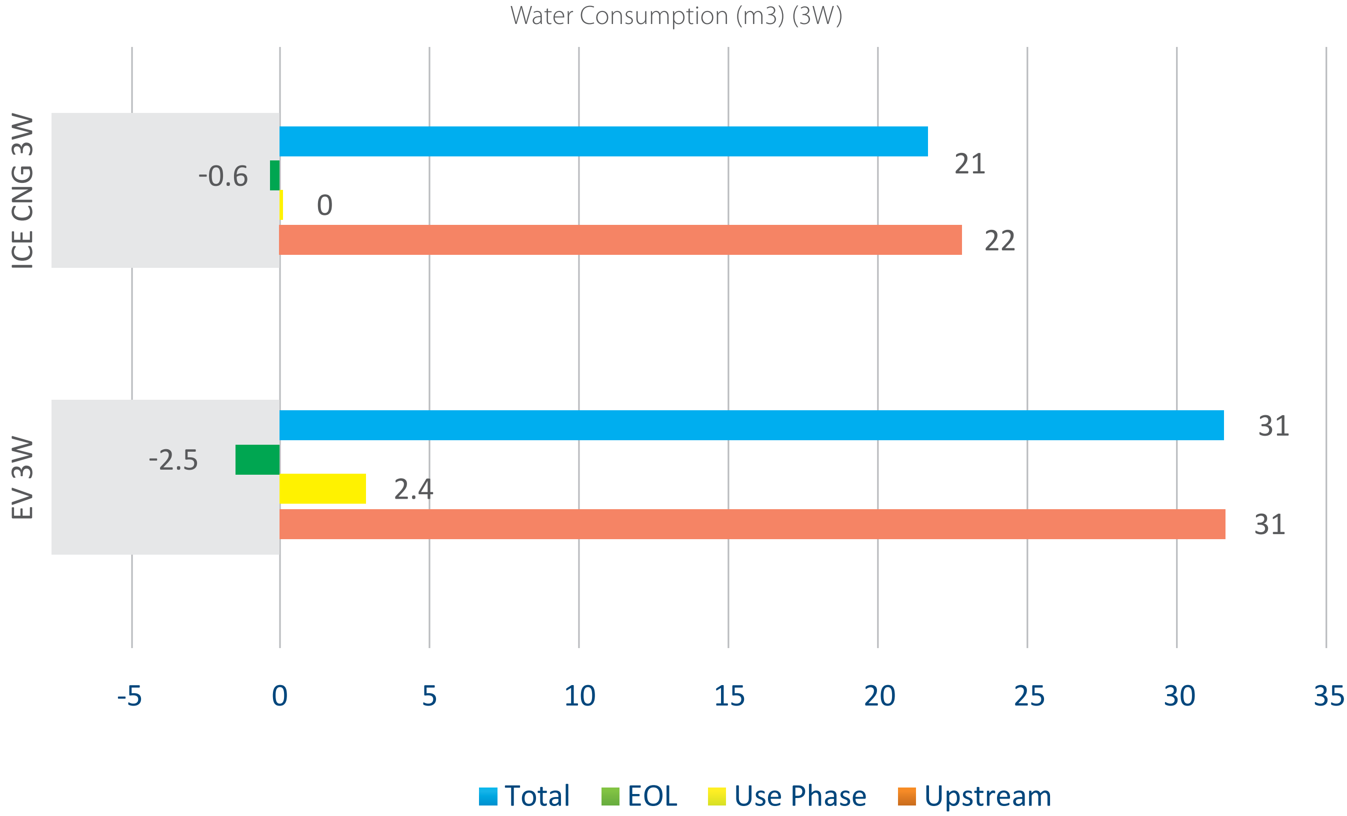

Figure 23: Water consumption impact of 3-wheeler ICE versus EV segregated into 3 life cycle stages

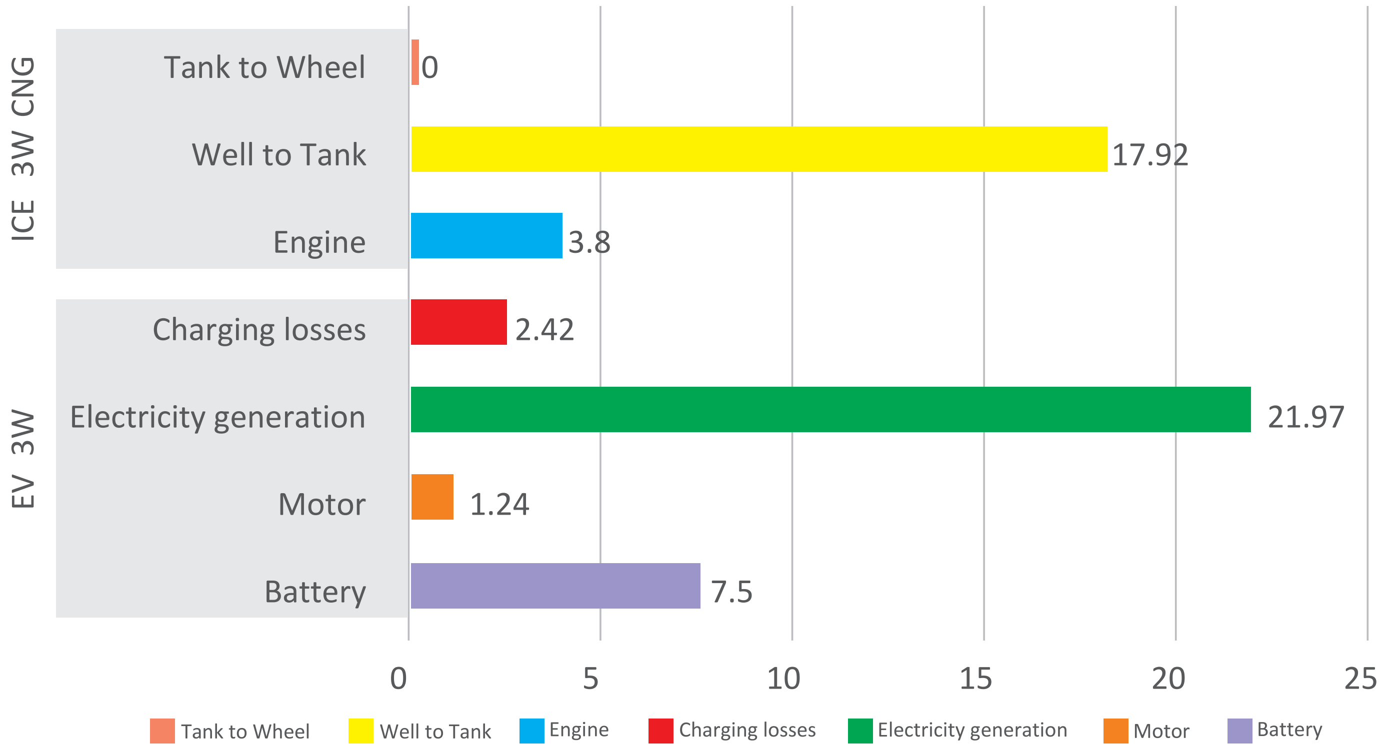

Figure 24: Breakdown of Water consumption (m3) impact of upstream and use phase of 3-wheeler ICE versus EV

Water consumption of an ICE diesel engine is larger than petrol and CNG due to the larger weight of the former owing to more requirements of materials for its manufacturing. The EV motor involves mining of several rare earths like neodymium, dysprosium, and praseodymium during manufacturing but due to very small quantities the impact is not significant. Water is at the heart of current lithium extraction technology where the mineral is found dissolved in salt flats and needs evaporation for separation. Accordingly, among powertrain components, the EV battery has the highest water consumption of 14.8 m3 and 7.5 m3 for 4-wheeler and 3-wheeler respectively.

The water intensity of the Indian grid is significantly high because Indian thermal power plants still don't have a closed loop water recycling. The water intensity of Indian grid is taken from Eco Invent database. Thus, the electricity generation process has the largest water consumption causing a higher water burden for EVs. The trend of water consumption for the Well to Tank section is consistent with the energy intensity of the processes. Petrol production is one of the largest waters consuming processes out of all refinery products due to the energy intensive nature of the processes involved like alkylation, and fluid catalytic cracking. While natural gas extraction is also water intensive over all higher mileage of gas-based vehicles keeps the Well to Tank emissions of 3-wheelers lower than 4-wheelers.

6.1.6 End point impact categories' results

The end-point impact categories in the ReCiPe methodology serve as a composite score for all mid-point impact categories and present them in a format most relevant to humans. The impacts can be understood by referring to the damage pathways as per ReCiPe given in Figure 2. Figure 25 and 26 demonstrates the impacts of assessed products across parameters of human health, ecosystem and resource utilisation for 4-wheeler and 3-wheeler vehicles respectively.

For the sake of convenience percentage comparison is presented between EV versus ICE diesel versus ICE petrol for 4-wheelers and between EV versus ICE CNG for 3-wheelers, instead of absolute values. This is to improve the readability of the graph. The impact of EVs is fixed at 100% for all three end-point categories and the impact of ICE diesel, petrol and CNG is given with reference to their corresponding EVs.

The water intensity of the Indian grid is significantly high because Indian thermal power plants still don't have a closed loop water recycling.

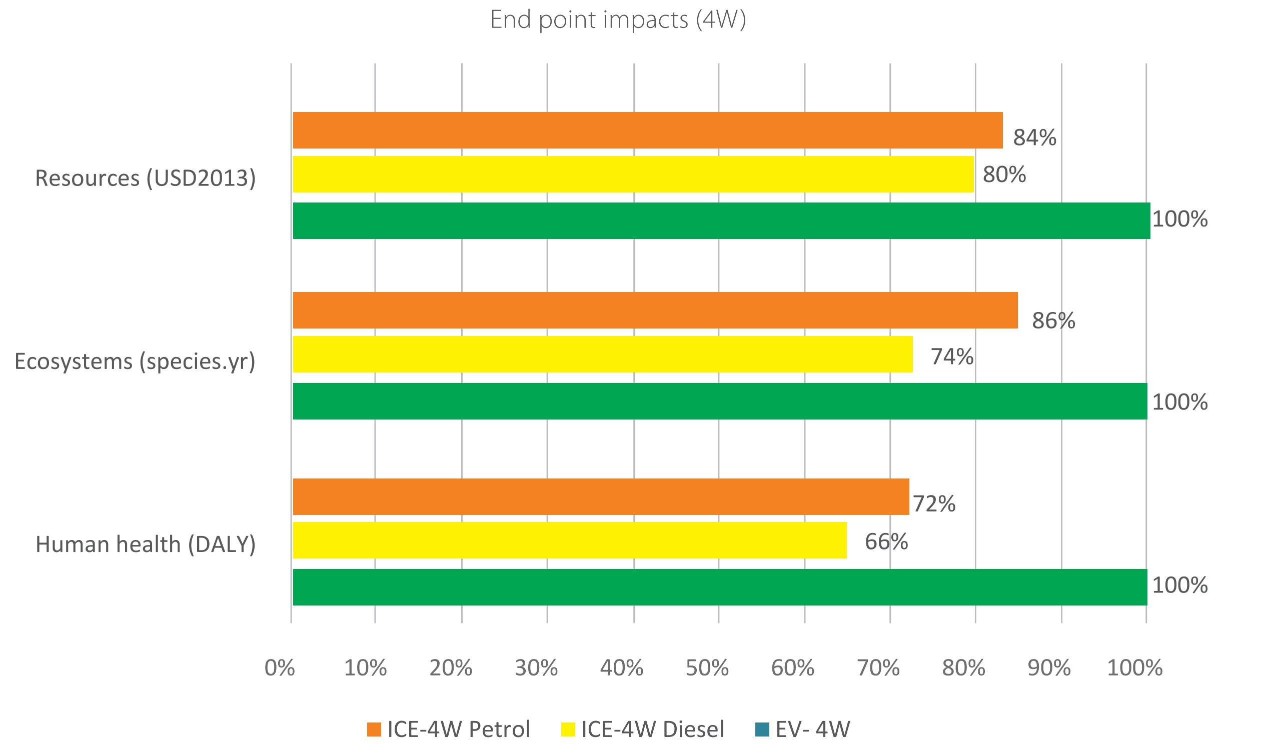

Figure 25: End point impact results for 4-wheeler ICE vehicle versus EV

For 4-wheeler segment, EVs has the highest impact in all end point impact categories owing to its higher burden is most mid-point impact categories barring a few namely GWP, Stratospheric ozone depletion, Ionizing radiation and Land use.

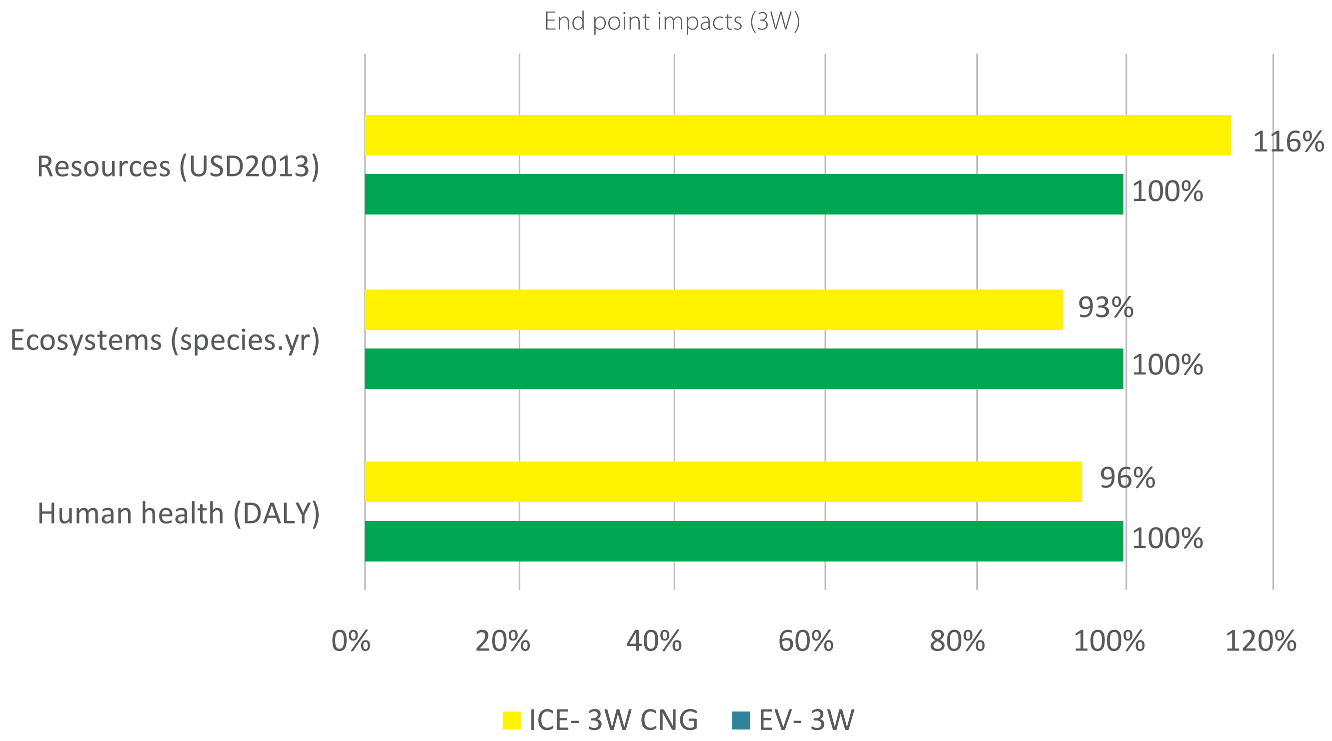

Figure 26: End point impact results for 3-wheeler ICE vehicle versus EV

Human health measured in Disability Adjusted Life Years (DALY) is assessed through impact categories of GWP, PM formation, tropospheric ozone formation, ionizing radiation, water consumption, human toxicity (refer to Figure 2). Both 4-wheeler and 3-wheeler EV's performance is worse than ICE vehicles in most of these categories except ionizing radiation and human toxicity.

The contrast is more for 4-wheelers compared to 3-wheelers resulting is larger difference in impact for the former. (See Annexure for reference)

Ecosystems measured in species.yr are assessed through impact categories of water consumption, eco toxicity, eutrophication, tropospheric ozone formation, acidification, land use (refer to Figure 2). 4-wheeler EVs have higher impact than its ICE counterparts in almost all of the categories. Again, the difference is not as high for 3-wheelers owing to less contrast of numbers in case of 3-wheelers (See Annexure for reference)

Resource utilization measured in USD 2013 are assessed through impact categories of mineral and fossil resource scarcity (refer to Figure 2). 4-wheelers EVs have higher impact in both these categories compared to ICE vehicles while in case of 3-wheelers ICE has higher impact. This can be attributed to higher fossil resource scarcity impact of 3W ICE CNG. (See Annexure for reference)

Sensitivity Analysis

Sensitivity analysis is a model that assesses how target variables are affected based on changes in other variables known as input variables. It helps to predict outcome of a decision within a certain range of variables. Thus, sensitivity analysis can help to make predictions about future course of action needed in order to promote a particular product or service over others.

Sensitivity analysis serves as a viable tool for studying the robustness of results and their sensitivity to uncertainty factors in life cycle assessment (LCA). It also highlights an important set of model parameters to determine whether data quality needs to be improved, and to enhance interpretation of results. For the purpose of this study, sensitivity analysis has been done with respect to two parameters:

1) Use of E20 fuel instead of current 5% blending
2) 50% renewable installed capacity in Indian grid instead of current 38% renewable installed capacity including large hydro.

6.1.7 Ethanol blending to petrol (E5 versus E20 fuel)

Under the Govt. of India's Ethanol Blending programme (EBP), it is aimed to achieve a 20% ethanol blending to petrol by 2025. Most states in India are currently selling E5 petrol while E10 petrol is available mostly in Maharashtra. Among vehicle companies, only Honda has confirmed that its engine is suitable for usage of E10 petrol. As this study is specific to Delhi, the sensitivity compares reduction of environmental impact on switching to E20 fuel from current E5 as aimed under EBP.

Ethanol has low calorific value than petrol hence blended petrol has lower calorific value than pure petrol. However blended petrol also has higher Research Octane Number (RON) which reduces knocking tendency of fuel. There is a general understanding that usage of E20 reduces mileage of a spark engine. Due to lack of accurate numbers we have considered a negative impact on fuel economy of E20 by 5%. This decreases average mileage of the E20 fuel to 14.06 km/l from 14.5 km/l of E5 fuel. Accordingly, the total amount of E20 fuel required for vehicle lifetime is higher than E5 fuel required. Therefore, the change in environmental impact associated with change is blending proportion depends on a multiplicity of factors including source of feedstock, energy and emission intensity of ethanol versus petrol and amount of fuel required. Figure 27, 28 and 29 below gives results for a comparative impact assessment for EV, E5 and E20 petrol for three different environmental impact categories.

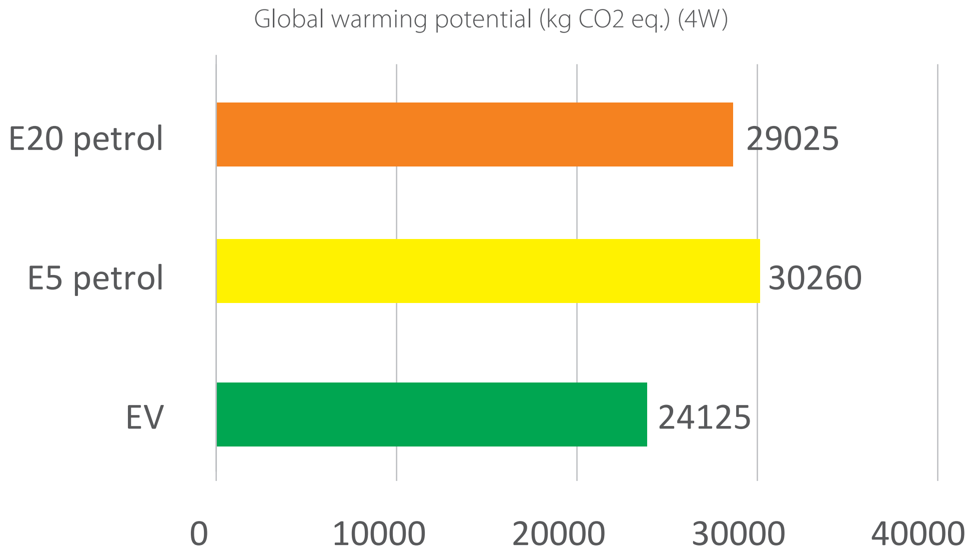

Figure 27: Comparative GWP impact of EV versus E5 and E20 petrol

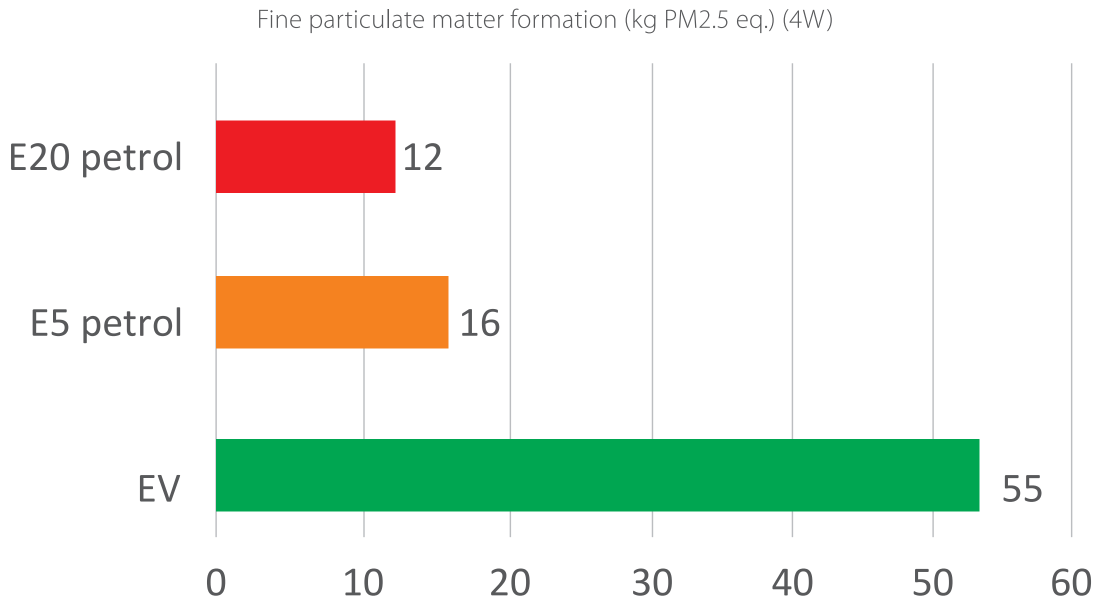

Figure 28: Comparative PM Formation impact of EV versus E5 and E20 petrol

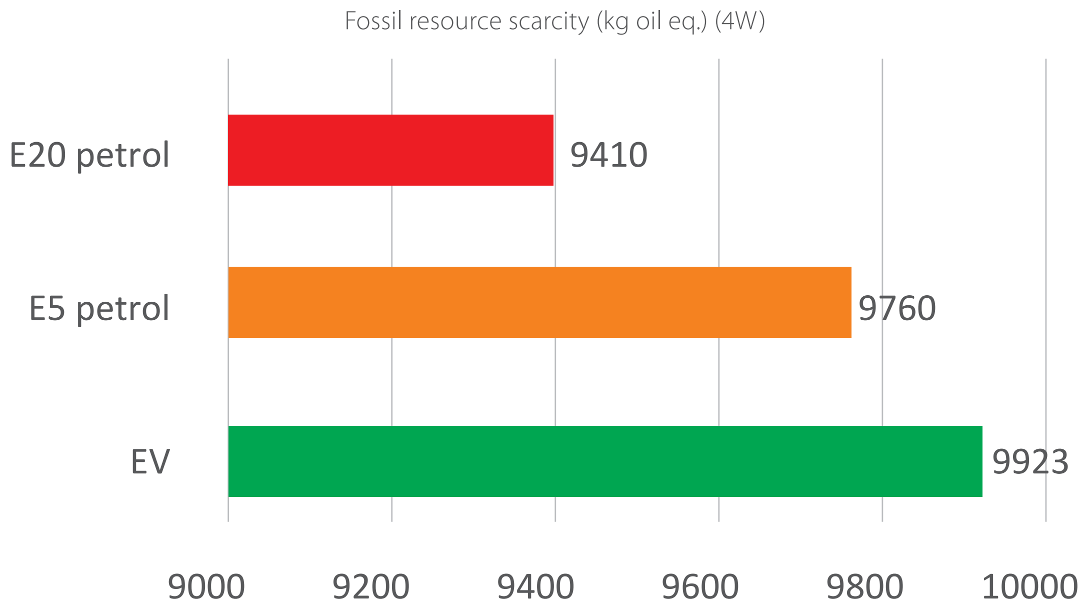

Figure 29: Comparative Fossil resource scarcity impact of EV versus E5 and E20 petrol

6.1.8 Renewable installed capacity in India

The environmental burden of EVs is most intricately linked to the type of grid mix. Quick transition to EVs is sensible only after the Indian grid has significant renewable contribution to itself. Currently the installed capacity of renewables is 38% of the grid including large hydro. In this sensitivity analysis, a 50% installed capacity of renewable is assessed with effective reduction in emissions for 4W and 3W respectively.

Figure 30 and 31 depicts the decrease in GWP burden with increased renewable installed capacity to 50% from current levels for 4-wheelers and 3-wheelers respectively .

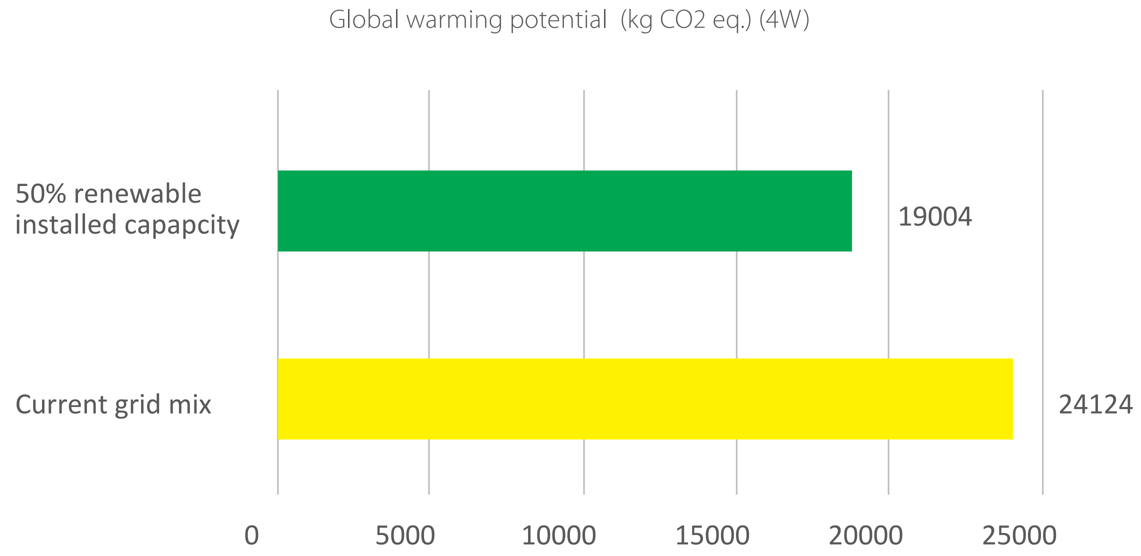

Figure 30: Change in GWP impact (kg CO2 eq.) in 4 wheelers with increased renewable installed capacity

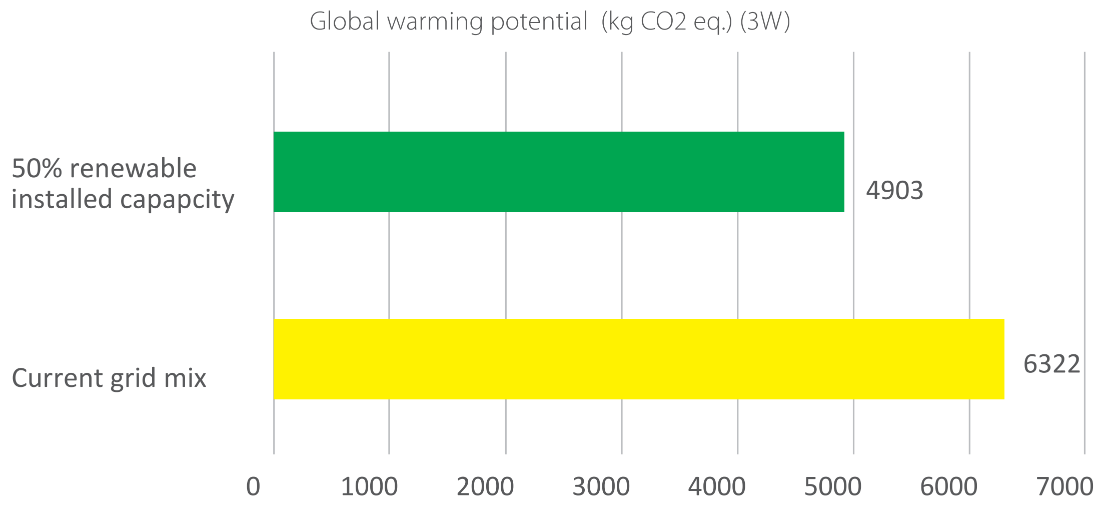

Figure 31: Change in GWP impact (kg CO2 eq.) in 3 wheelers with increased renewable installed capacity

07 Limitations

- A key limitation of this study is data quality difference between different stages of the vehicle life.
- Most data for upstream and end of life is secondary while it is primary for use phase.
- The results described in this report are valid only within specified scope of the study, i.e., EVs and ICE vehicles running on Indian roads particularly the National Capital Territory of Delhi (NCT)
- Results may vary in comparing similar technologies that may have used more region-specific data or regional use phase data.
- The assumption related to switching rate of 1:1 is key the limitation of the study, results might vary if the recycled material is used in other industries.
- Even though chemical and material production processes are standardised across the world, the use of proxy datasets might vary the results from region specific datasets.
- There was no data for transportation distances in upstream processes hence it was avoided. Any change in transportation distance, location, and so on will affect the results.
- The material assembly impacts are only measured in terms of energy used due to lack of extensive data.
- As stated by ISO 14040, LCA shall not be the sole basis of comparative assertions. Other social, economic, and environmental aspects should also be considered. However behavioural and infrastructural dimensions like driving behaviour and road conditions were not part of the scope of this study.

08 Conclusion and Recommendations

From the above analysis it is observed that EVs score significantly better over ICE in impact categories of GWP, Ozone depletion, Ionizing radiation, marine and freshwater eco toxicity. The GHG emission for four-wheeler EVs have been found to be 24.8 tons during the entire product life cycle, followed by diesel 27.2 tons for ICE diesel and 30.2 tons ICE petrol. Similar trend is observed for 3 wheelers EV, followed by CNG fuelled 3 wheelers.

However, EVs performance is found to be weak when compared with ICE counterparts in categories of Water consumption, Particulate Matter formation, Eutrophication, Ozone formation, Acidification and Resource utilization. Water Consumption for EVs more than 1.5 times than ICEs. Further, particulate emissions for EVs along the life cycle assessments are higher compared to others due power generations attributable to coal.

With a 50% renewable grid, GHG emissions reduces by 22% further increasing competitiveness of EVs over ICE vehicles.

Coal tends to be the critical factor. At least 20% reduction in overall GHGs of EVs is observed, if the carbon intensity of electricity is brough down to 500 gCO2eq/kWh, compared to 790 gCO2/kWh at current levels. A 50% reduction in GHG emission of EV is observed from the reference emission if the emission factor is brought to 300 gCO2eq/kWh. This means 46% and 62% below the current electricity carbon intensity level.

Like many other batteries, the lithium-ion cells that power most electric vehicles rely on raw materials — like cobalt, lithium and rare earth elements — that have been linked to environmental and human rights concerns. Cobalt has been especially problematic (70% DRC and artisanal mining) (hazardous tailings and slags that can leach into the environment).

Based on the conclusions derived from the results, the following recommendations can be suggested for improved sustainability of transportation in India:

- Reduction of coal intensity of the Indian grid not only from the GHG perspective, but also the PM emission perspective. India currently has 174 GW of renewable installed capacity including large hydro and aims to achieve a 500 GW target by 2030 as per the updated NDCs. While the Government of India is aggressively pushing for policy measures for promotion of renewables particularly solar; the focus needs to be well balanced including addressing existing challenges. The gaps in state and union level renewable energy policies must be filled. Promotion of solar PV comes with other set of challenges like need for procuring solar cells from China, USA, Taiwan and high anti-dumping duties imposed on these imports. The reality is a major segment of solar project introduced recently is built on imported solar cells.
- The primary factor of poor performance of EVs on several impact categories is due to upstream environmental burden of the product which is largely due to coal based electricity generation in India. As already mentioned, solar has additional challenges for India, hence focus is needed on other renewable source like hydro. Water surplus regions of the country like the North eastern part are still untapped for electricity generation. For more efficient and effective roll out of schemes like FAME, they must be clubbed with associated policy of renewable electricity generation. The advantage of such group schemes can be high penetration of EVs, and rapid rise of EV based capital infrastructure through investments flowing into regions that are usually unreached.
- The need is to focus not just on the end product but each stage of the supply chain. Under the Production Linked Incentive (PLI) scheme, the government has recently earmarked significant amount of funding for domestic manufacture of polysilicon cells, ingots, wafers and panels for PV modules. However, the drawback remains that funds are disbursed only after setting up of plant. This may discourage small businesses into the same. The focus must be on advance funding for critical sector like solar.
- Switching to renewable electricity generation will automatically help in improving EV's performance in categories of GWP, fossil resource scarcity which will improve the end point impact categories. Improving EV's performance in water consumption, eutrophication, mineral resource scarcity needs global collaboration and application of R&D rather than isolated national initiatives. Lithium is imported into India and its mining is highly water intensive. Several other critical minerals used in EV motor are also imported into India. Thus, it can be concluded that these impacts are source impacts and are not directly linked to country of EV use.
- Special attention must be given to R&D for reduced initial installation cost. While a coal-based power plant has an initial cost of Rs. 4 crores/MW; the same for a wind plant running at 25% and 80% capacity utilisation is Rs. 6 crores and Rs. 18 crores/MW respectively. For a solar plant running at 15% and 80% capacity utilisation the cost is Rs. 18 crores and 98 crores/MW respectively. A

comprehensive policy framework for price control via indigenisation of technology and production can help address the scenario.

- In the power sector, opportunities exist in improving electricity distribution business and its operations for increased energy resilience, incorporation of renewables and effective energy storage technologies.
- The private sector and civil society can deliver on ambitious national goals and further the ambitions of the ecosystem through new technologies, business models and ideas.
- Augmentation of other battery chemistries and increasing recycling efficiency will help improve some of the hazardous environmental impacts associated to battery raw materials like lithium, cobalt, and rare earths. Increasing battery recycling efficiency, benchmarking and commercialization of technologies will support in improving some of the low performance parameters. Increasing recycling content in new batteries as mandated in Battery Waste Management Rules of 2022 will be a game changer. However, the need is for promoting recycling units and putting in place a standard compliance mechanism for the same.
- Promotion of second life, through stationary application is another sustainable option that needs faster adoption. This will also help to improve EV performance in category of mineral resources. There are several pilots where use of old electric vehicle batteries for grid storage is being currently tested. Reusing lithium-ion batteries will require extensive testing and upgrades to make sure they perform reliably and warrant standards for testing and identification of agencies and successful business model. The government must bring guidelines to encompass innovative measure like these for quick.
- A sustainable transport policy has to incentivise the right technology mix at the right time and in the right location for providing clear signals to all stakeholders.
- A modal shift to Non-motorized transportation is a much desired option that can come with infrastructure development like cycling tracks, pavements; and policies like congestion and parking fees.

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Annexure

Annexure 1: The data inventory for engine and fuel of ICE vehicles for both 3-wheeler and 4-wheeler.

Process/Materials	Fuel Cycle Fuel			Vehicle Cycle (Engine)	
Raw materials	CNG	Petrol	Diesel	Petrol (1199 cc, 3 cylinders) -87kgs	Diesel (1497 cc, 4 cylinders)- 170 kgs
Energy for refining/processing					
West Asia (Port of Basra, Iraq to Kandla port) (83.5%)		2891 kms			
Africa (Port of Lagos to Paradeep) (10.36%)		17262 kms			
USA (Gulf coast to Paradeep) (6.1%)		19518 kms			
Middle East (56%)	2020 kms				
West Africa (23%)	12229 kms				
USA (8%)	17888 kms				
Australia (4%)	7741 kms				
Steel				28.6	40.8
Rubber				1.3	2
Plastics				27.1	38.7
Alloyed steel				3.7	5.5
Manganese				0.006	0.008
Copper				0.52	0.7
Aluminium				27.8	39.7

Annexure 2: Data inventory for electric motor of both 3-wheeler and 4-wheeler

Material	Electric Motor	
(Quantity in kg)	Three-Wheeler Vehicle	Four-Wheeler
Cobalt	0.0018	0.018
Nickel	0.002	
Copper	0.71	6.65
Aluminium	2.09	
Low-alloy medium Carbon Steel	0.31	
Plastics	0.04	
Cables		
Stainless Steel	0.08	
Rare earths	0.0576	0.573
Boron	0.0018	0.018
Iron (Ferrite)	0.118	1.18
Electrical steel	2.95	23.71
Total Weight (approx.)	6.5	32.9

Annexure 3: Data inventory for electric battery for both 3-wheeler and 4-wheeler

Material	Electric Li-ion Battery	
(Quantity in kg)	Three-Wheeler (LFP chemistry)	Four-Wheeler (NCM622 Chemistry)
Lithium	0.75	4.2
Graphite	10.40	
Cobalt		4.2
Nickel		10.5
Manganese		4.2
Copper	9.38	19.32
Aluminium	15.44	72.5
Chromium Steel	0.07	18.9
Plastics	3.13	23.1
Cables/ Electronic Parts	0.20	4.83
Oxygen	6.12	10.08
Phosphorus	2.99	
Iron (Ferrite)	5.30	
Thermal insulation	0.88	
Carbon	1.43	
Binder	2.31	
Electrolyte Solvent	9.66	
Total Weight (approx.)	68	210

Annexure 4: Input output table for recycling process of 3W and 4W EVs.

		3W (LFP)	4W (NMC)
Inputs	Reagents	0.025	0.025
Inputs	Electricity	0.14	0.14
Inputs	Water	0.72	0.72
Inputs	H2SO4	0.213	0.213
Inputs	Lime	0.116	0.116
Outputs	Lithium compound	0.098385	0.082046
Outputs	Al+Cu	0.081963	0.266989
Outputs	Al	0.028621	0.053845
Outputs	Cu	0.053343	0.213143
Outputs	Cobalt Compound	-	0.172527
Outputs	Nickel Compound	-	0.172266
Outputs	Manganese Compound	-	0.168095

Annexure 5: Mid-point impact results for 4-wheelers

		Electric vehicles						ICE Diesel vehicles					ICE Petrol vehicles				
		Upstream			Usage Phase	EOL	Total	Upstream		Usage Phase	EOL	Total	Upstream		Usage Phase	EOL	Total
Impact category	Unit	Battery	Motor	Electricity generation	Charging losses	EOL	Total	Engine	Well to Tank	Tank to Wheel			Engine	Well to Tank	Tank to Wheel		
Global warming	kg CO2 eq	848.8399	110.114	21424.8	2360	-619	24124.75000	430.104	4012.964	23109.76	-345.227	27207.6	335.538	5834.411	24272.2	-182.334	30259.81
Stratospheric ozone depletion	kg CFC11 eq	0.000857	0.000128	0	0	-0.00086	0.00012	0.0002	6.64E-03	0.00E+00	-7.86E-05	0.006766	0.00016	9.83E-03	0	-4.14E-05	0.009947
Ionizing radiation	kBq Co-60 eq	6.744951	1.039239	0	0	-6.90316	0.88103	3.59295	203.7279	0	-0.82984	206.491	3.210612	217.5236	0	-0.42951	220.3047
Ozone formation, Human health	kg NOx eq	3.684729	0.48876	106.0392		-5.17431	105.03838	1.47566	14.31332	15.20269	-0.87485	30.11682	1.208485	19.11196	11.200282	-0.46064	31.06009
Fine particulate matter formation	kg PM2.5 eq	11.84276	0.864238	48.471576	5.3	-12.0296	54.44896	0.86765	14.51915	1.671996	-0.60931	16.44948	0.661302	17.17243	1.232	-0.31779	18.74794
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.785835	0.503257	106.0392	11.66	-5.23213	105.09616	1.75216	15.22067	15.20436	-0.87816	31.29903	1.469113	20.21191	11.200454	-0.46221	32.41927
Terrestrial acidification	kg SO2 eq	36.68391	2.345924	165.09571	18.1605	-36.2775	167.84806	2.00771	33.51724	5.471985	-1.629	39.36794	1.51228	43.85049	4.032	-0.85706	48.5377
Freshwater eutrophication	kg P eq	0.960717	0.222802	2.33997	0.2574	-0.73261	2.79088	0.06684	0.065149	0	-0.0085	0.123483	0.040449	0.132364	0	-0.00454	0.168274
Marine eutrophication	kg N eq	0.045027	0.008066	0.357245	0.0392964	-0.03096	0.37937	0.0072	0.035075	0	-0.00164	0.04063	0.004232	0.62608	0	-0.00087	0.629447
Terrestrial ecotoxicity	kg 1,4-DCB	59262.58	14051.24	299.4048	32.9345	-43557.7	30055.54980	3156.71	5330.947	0.59158	-35.6247	8452.625	1901.04	9619.211	0.35024277	45.30766	11565.91
Freshwater ecotoxicity	kg 1,4-DCB	2.919771	0.452517	0.00021913	0.0000241	-2.58495	0.78755	0.47693	8.627628	0.003474	-0.21689	8.89115	0.344809	9.869732	0.002184956	-0.11054	10.10618

		Electric vehicles						ICE Diesel vehicles					ICE Petrol vehicles				
		Upstream			Usage Phase	EOL	Total	Upstream		Usage Phase	EOL	Total	Upstream		Usage Phase	EOL	Total
Impact category	Unit	Battery	Motor	Electricity generation	Charging losses	EOL	Total	Engine	Well to Tank	Tank to Wheel			Engine	Well to Tank	Tank to Wheel		
Marine ecotoxicity	kg 1,4-DCB	30.30304	6.691979	0.0520704	0.0057277	-22.6376	14.40953	2.41581	26.58533	0.137177	-0.38017	28.75816	1.588594	30.55876	0.0917739	-0.16239	32.07674
Human carcinogenic toxicity	kg 1,4-DCB	76.94892	15.51534	0.015100416	0.001661	-91.0879	1.39149	9.69973	18.77234	0.952751	-14.134	15.29081	6.859756	24.26565	0.37867898	-6.87646	24.62763
Human non-carcinogenic toxicity	kg 1,4-DCB	1294.016	293.1604	5.380608	0.59186	-919.466	673.09107	102.738	471.0326	0.162948	-5.92349	568.0102	63.18846	550.2329	0.07182688	-1.69953	611.7936
Land use	m2a crop eq	42.05697	6.530191	0	0	-40.7242	7.86301	8.04205	48.54929	0	-4.47083	52.12051	5.744875	56.95705	0	-2.28951	60.41242
Mineral resource scarcity	kg Cu eq	140.0732	10.35721	0	0	-117.152	33.27848	10.1735	6.67891	0	-3.25402	13.5984	6.738285	10.64361	0	-1.35641	16.02549
Fossil resource scarcity	kg oil eq	230.7024	28.8712	8997.08	1009	-343.099	9922.55476	242.863	9098.746	0	-61.1436	9280.465	207.0227	9549.584	0	-32.4403	9724.166
Water consumption	m3	14.8038	1.498243	79.1904	8.7	-12.4469	91.74549	6.04414	44.37799	0	-2.28025	48.14188	4.152883	54.34143	0	-1.12393	57.37039

Annexure 6: End-point impact results for 4-wheelers

Damage category	Unit	EV-4W	ICE-4W Diesel	ICE-4W Petrol
Human health	DALY	2.5253582	1.4642135	1.6296714
Ecosystems	Species. yr	0.00171511	0.001275005	0.001476028
Resources	USD 2013	0.038806231	0.030922914	0.032517423

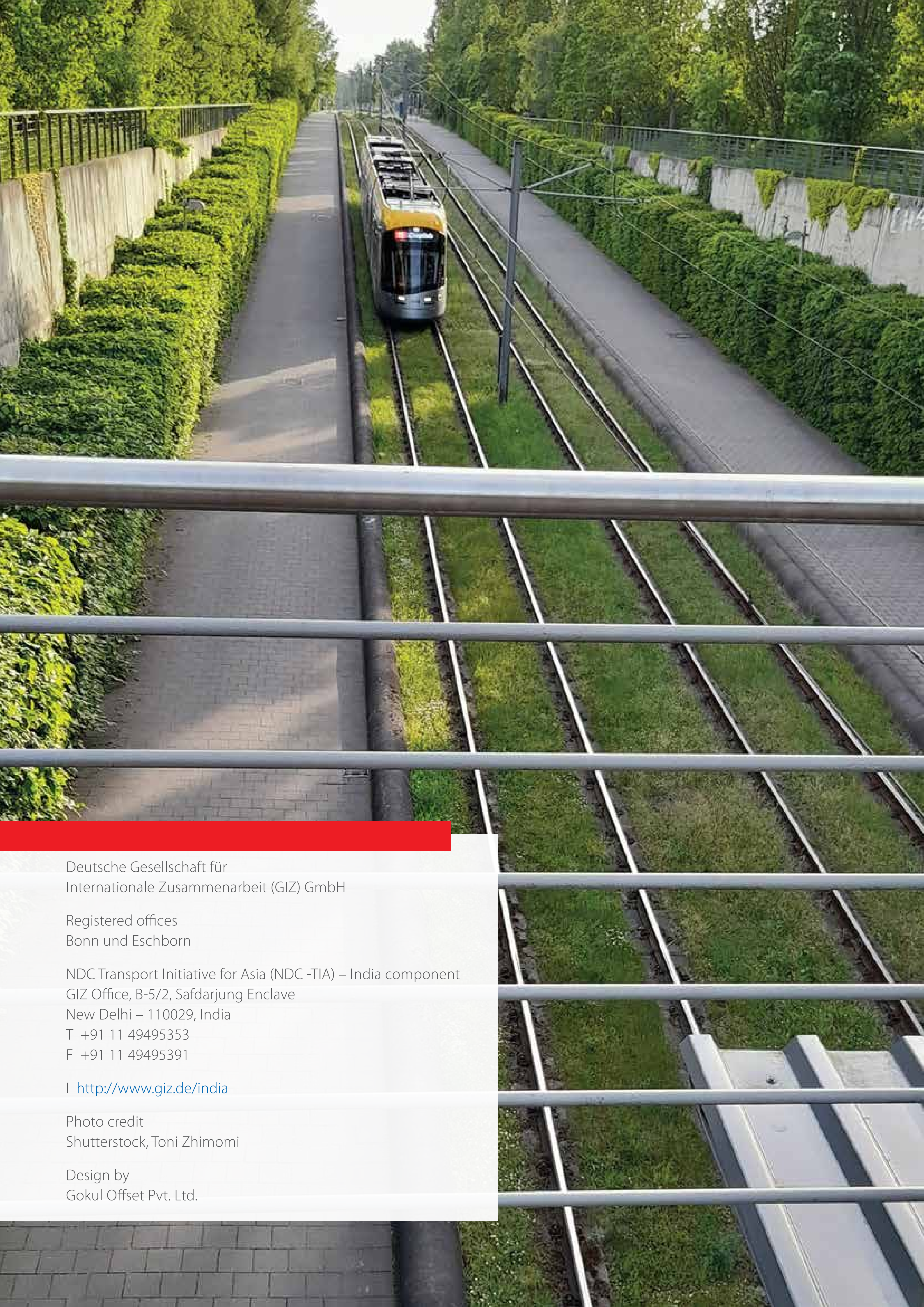
Annexure 7: Mid-point impact results for 3-wheelers

		Electric vehicles						ICE CNG vehicles				
		Upstream			Usage Phase	EOL	Total	Upstream		Usage Phase	EOL	Total
Impact category	Unit	Battery	Motor	Electricity generation	Charging losses	EOL	Total	Engine	Well to Tank	Tank to Wheel		
Global warming	kg CO2 eq	199.38263	19.386192	5943.96	653.804	-493.96053	6322.572292	343.49628	2558.7257	10800	-94.6211	13607.6
Stratospheric ozone depletion	kg CFC11 eq	0.000215872	1.77856E-05	0	0	-0.000116595	0.000117063	0.000166532	0.001858719	0	-2.15E-05	0.002004
Ionizing radiation	kBq Co-60 eq	2.7195548	0.11863548	0	0	-2.1331624	0.70502788	3.031834	9.4795429	0	-0.22395	12.28742
Ozone formation, Human health	kg NOx eq	0.86823524	0.075977408	29.41884	3.235916	-1.598097	32.00087165	0.96544635	4.8643821	7.00E+00	-0.23918	12.59083
Fine particulate matter formation	kg PM2.5 eq	1.3794293	0.11295382	13.447645	1.4791695	-3.7009393	12.71825832	0.77504072	3.61	0.77	-0.16585	4.99132
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.90090743	0.078706047	29.41884	3.235916	-1.6159575	32.01841198	1.0850709	5.3127774	7.0002838	-0.24002	13.15811
Terrestrial acidification	kg SO2 eq	3.6932579	0.29827346	45.803102	5.0380978	-11.1546	43.67813116	1.5418173	8.8704859	2.52	-0.44537	12.48693
Freshwater eutrophication	kg P eq	0.32468501	0.026050673	0	0	-0.22733534	0.123400343	0.057145726	0.052635047	0	-0.00236	0.107423
Marine eutrophication	kg N eq	0.015222772	0.00118182	0	0	-0.009602792	0.0068018	0.003525628	0.014079645	0	-0.00045	0.017157
Terrestrial ecotoxicity	kg 1,4-DCB	20458.666	1584.5162	83.06496	9.136704	-13528.005	8607.378864	2789.6891	911.31072	0.21890173	15.0357	3716.254
Freshwater ecotoxicity	kg 1,4-DCB	0.68815848	0.064555606	6.08E-05	6.69E-06	-0.09735817	0.655423397	0.25223115	6.8935852	0.001365598	-0.05775	7.089436
Marine ecotoxicity	kg 1,4-DCB	9.8694279	0.78669415	0.01444608	0.001588992	-7.0219522	3.650204922	1.7121498	13.770464	0.057358687	-0.08911	15.45087
Human carcinogenic toxicity	kg 1,4-DCB	21.279525	2.1003866	0.004189363	0.000460808	-22.08897	1.295591771	4.6241322	10.390893	0.23667436	-3.63418	11.61752

		Electric vehicles						ICE CNG vehicles				
		Upstream			Usage Phase	EOL	Total	Upstream		Usage Phase	EOL	Total
Impact category	Unit	Battery	Motor	Electricity generation	Charging losses	EOL	Total	Engine	Well to Tank	Tank to Wheel		
Human non-carcinogenic toxicity	kg 1,4-DCB	433.48739	34.829026	1.4927616	0.16419584	-285.51253	184.4608434	71.563988	176.12319	0.0448918	-1.06901	246.6631
Land use	m2a crop eq	11.665026	0.93764742	0	0	-1.592695	11.00997842	7.7772149	13.895777	0	-1.19696	20.47603
Mineral resource scarcity	kg Cu eq	24.140889	1.6144569	0	0	-16.06395	9.6913959	5.3061603	2.9509691	0	-0.75013	7.507001
Fossil resource scarcity	kg oil eq	59.541512	5.0063567	2780	305	-105.97166	3043.576209	125.37592	4572.9482	0	-16.8426	4681.482
Water consumption	m3	7.4966633	1.2439598	21.97008	2.416592	-3.843795	29.2835001	3.817933	17.9299515	0	-0.58379	21.1641

Annexure 8: End-point impact results for 3-wheelers

Damage category	Unit	EV- 4W	ICE-4W CNG
Human health	DALY	0.01686005	0.01614553
Ecosystems	Species. yr	3.58388E-05	3.35E-05
Resources	USD 2013	0.023298335	3.10E-02



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