LIFE CYCLE ASSESSMENT OF ELECTRIC AND COMBUSTION VEHICLES IN INDIA

by

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Abstract

This study assesses the life cycle greenhouse gas emissions of electric and conventional vehicles in the context of India, a country which still relies on a coal-fired power grid. It assesses the emissions of electric and conventional vehicles under three different scenarios for the development of the electricity grid between now and 2030. These three scenarios are the Current Trends Scenario (CTS), which is a business-as-usual scenario, the Current Policies Scenario (CPS), under which extant renewable energy policies are fully implemented, and a High Renewable Energy Scenario (HRES), under which additional renewable energy is added to the grid. In the HRES, this work incorporates the benefits of utilizing the battery for grid energy storage after the life of the vehicle is over, because high penetrations of renewable energy will also require grid-level energy storage.

This study finds that, even with a carbon-intensive power grid, electrification of vehicles confers a reduction in greenhouse gas emissions. In a business-as-usual CTS scenario for the power grid's evolution, an average electric vehicle (EV) has life cycle GHG emissions 23% below the equivalent combustion vehicle's (ICEVs) in 2030. This benefit greatly increases in a HRES scenario when the batteries are utilized for energy storage after the life in a battery. In this case, an average EV has life cycle GHG emissions 60% below equivalent combustion vehicles.

In addition, this study conducted uncertainty analysis to assess the impact of uncertainty in the fleet averages for various input variables. It used a Monte Carlo analysis to assess the life cycle GHG emissions of conventional and combustion vehicles under a range of values for seven to eight key variables (depending on the scenario). It found that under the HRES, all simulation runs resulted in lower emissions with the EV, and in the CPS, almost all simulation runs resulted in lower emissions with the EV. In the CTS, 95% of simulation runs indicated that EVs have lower life cycle emissions.

Lay Summary

This study assesses the life cycle greenhouse gas emissions of electric and conventional vehicles in the context of India, a country which still relies on a coal-fired power grid. It assesses the emissions of electric and conventional vehicles under different scenarios for the development of the electricity grid between now and 2030. It incorporates the benefits of utilizing the battery for grid energy storage after the life of the vehicle is over. It found that, even with a carbon-intensive power grid, electrification of vehicles confers a reduction in greenhouse gas emissions. However, the benefit is blunted by the carbon-intensive sources electricity. As such, India should move forward with policies to electrify its vehicle fleet, but it should also take additional steps to reduce the carbon intensity of the power grid.

Preface

This thesis is original, unpublished work by the author, Narayan Gopinathan. It did not require any ethics clearance from BREB because it did not require fieldwork or research conducted upon humans or animals.

The calculations and analysis were conducted by Narayan Gopinathan, with guidance from Karthik Ganesan and Abhinav Soman at the Council on Energy, Environment, and Water in New Delhi, and assistance and data from Thirtha Biswas and Harsimran Kaur at the same institution; in addition to his advisor at UBC, Milind Kandlikar and his committee member, Amanda Giang.

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List of Abbreviations

CO_2e – Carbon dioxide equivalent

CPS – Current Policies Scenario

CTS – Current Trends Scenario

g – grams

GHG – Greenhouse Gas Emissions

HRES – High Renewable Energy Scenario

kg – kilograms

$kgCO_2e$ – kilograms of carbon dioxide equivalent

$kgCO_2e/kWh$ – kilograms of carbon dioxide equivalent per kilowatt-hour

kWh – kilowatt-hour

tCO_2e – metric tons of carbon dioxide equivalent

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Chapter 1: Introduction and background

In order to prevent the drastic consequences of a warming beyond 2 degrees Celsius above preindustrial levels, global civilization must virtually eliminate its usage of fossil fuels, over the coming decades. Emissions of carbon dioxide and other greenhouse gases must decrease to net-zero in order to stabilize the climate at any level of warming (IPCC, 2018). In order to accomplish this, electricity generation must be decarbonized and end uses of energy must be electrified, as there is a growing consensus for environmentally beneficial electrification (Dennis, Colburn and Lazar, 2016). For this reason, renewable energy and electric vehicles are being promoted as solutions to the climate crisis. However, in a situation where the electricity generation comes from carbon-intensive sources, such as coal, it remains an open question whether electrification is optimal. In such cases, the climate-based rationale for electrification would depend on specifics of the use; it is important to consider under what circumstances electrification of end uses of energy is truly environmentally beneficial, and under what circumstances electrification might not be beneficial.

India is a country where this consideration is more important than most. India has been only a minor contributor to past emissions, but will likely be a major contributor to future emissions, on an overall but not on a per-capita basis (Dubash, Khosla, Kelkar, *et al.*, 2018). India has low per-capita emissions, on the order of 3 tCO2e/person per year. However, the country has a high population that is likely to overtake China as the world's most populous country within the coming decade. Consequently, it has the world's third largest carbon footprint at a national level after China and the U.S. (Timperley, 2019). In its 2018 submission to the United Nations Framework Convention on Climate Change, the Government of India emphasized that solutions to climate change rest on the principle of common but differentiated responsibility in light of different national circumstances, and that these circumstances in India include low per capita emissions and income, the “overriding priority” of poverty eradication, and the fact that India’s natural resource endowment includes large quantities of coal (MoEFCC, 2018). These factors mean that, despite a temporary slowdown due to the COVID-19 pandemic, India’s greenhouse gas emissions are likely to rise again in the near future (Rajshekhar, 2020). Conversely, if a low-emissions growth trajectory is followed, impacts on the global climate can be avoided (Dubash, Khosla, Rao, *et al.*, 2018).

India has made commitments to reduce its emissions trajectory, as part of its nationally determined contribution to the Paris Agreement. The independent Climate Action Tracker rates India’s pledges as 2°C compatible (*Pledges And Targets | Climate Action Tracker*, 2018). Its pledges include reducing GHG intensity of the economy by 33 to 35% below 2005 levels by 2030, and to build a cumulative carbon sink in forests of 2.5 to 3.0 gigatons of carbon dioxide equivalent (CO2e) by 2030. Another target is to increase the share of non-fossil electrical generating capacity to 40% of its total generating capacity by 2030 (*Pledges And Targets | Climate Action Tracker*, 2018). As of 2020, low-carbon non-fossil sources, such as nuclear, hydropower, and renewable energy, make up 38% of its generating capacity,[1] putting it very close to achieving this benchmark, so India is likely to achieve this goal well in advance of the 2030 deadline (Government of India, Central Eectricity Authority, 2020). However, despite this success, the majority of the country’s electrical energy continues to be from coal.

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[1] Renewable energy has a lower capacity factor, since it cannot produce energy when the sun does not shine or the wind does not blow. This means that its generating capacity is higher than the amount of electricity generated.

For this reason, renewable energy needs storage to fully meets its potential. This is particularly crucial in India, as in other places where the peak electricity demand occurs in the evening, a trend that will only increase as the climate warms, and as more Indians buy air conditioners. Solar energy is available during daylight hours, but when the sun sets then other sources of energy need to ramp up to compensate for the drop in solar energy generation, resulting in a 'duck curve' of solar PV generation (Jones-Albertus, 2017). Thus, in order for the electricity sector to optimize the use of solar PV, and to fully wean itself off of fossil fuels, energy storage is necessary (Tongia and Parray, 2019; Ershad *et al.*, 2020). Potential solutions for energy storage include compressed air, pumped hydropower, and battery storage built for that purpose. Another possibility for cost-effective grid storage is the used batteries from electric vehicles – once they are not used in the vehicle anymore, they could be repurposed for grid storage (Ahmadi *et al.*, 2014, 2017). Given the fact that "million-mile" batteries are likely to become available, the EV batteries could outlast the vehicles that they power, providing an opportunity for them to be used again for energy storage on the grid (Stone, 2020).

1.1 Electrification of transportation in India

India has increasing demand for mobility and transportation services, and members of its rising middle class are buying 4-wheeler vehicles, many for the first time. As of 2017, nearly 50,000 new motor vehicles were registered every day in India, and for the decade up through 2017, the country's total number of vehicles registered increased by 10% every year (Newcomb *et al.*, 2017). Registration of new vehicles slowed in 2019 and 2020 as a result of an economic slowdown and the COVID-19 pandemic, and auto sales may take three to four years to recover (Shah and Monnappa, 2020; Sharma, 2020b). However, the economic recession induced by the

COVID-19 pandemic may cause investment plans towards the electrification of vehicles in India to be delayed by 12 to 18 months (Sharma, 2020a).

If consumers' first cars can be electric, then a degree of fossil fuel lock-in can be prevented, as unlike combustion-powered vehicles, electric vehicles can get cleaner over time as the power grid gets cleaner. This will enable the country to leapfrog past dirtier forms of development, and achieve savings in oil imports and emissions of air pollution and greenhouse gases (Ghate *et al.*, 2019). If the opportunity is seized before the vehicle sales recover to their previous level, then this benefit will be maximized, and the polluted air of India and the country's contribution to global warming will be mitigated.

Large segments of India's national rail network are already electrically powered, and the country has pledged to complete electrification of its national rail network by 2023, and for the railway network to achieve net-zero carbon emissions by 2030 (Cuenca, 2020). In addition, the electric three-wheeler autorickshaws have become common on the streets of Indian cities (Harding and Kandlikar, 2017). However, among four-wheeler cars, electric vehicles are a rare and new technology in India (Del Bello, 2020; Slater, 2020).

In fact, electric cars are a new technology everywhere. Only in the past decade have electric vehicles (EVs) come of age and to become a viable competitor to internal combustion engine (ICE) vehicles. The International Energy Agency projects that in a "stated policies scenario" with no additional policies, the sales of EVs are likely to rise from 2.2 million in 2019 to 25 million in 2030 (IEA, 2020). Several countries, including India, have set deadlines for the complete or partial phaseout of combustion vehicles in favor of electric vehicles (Burch and Gilchrist, 2018). In 2018, the Government of India set a target for 100% of new vehicle sales to be electric by 2030. This target was rolled back to 30% the following year (Arora, 2018). The

Indian government has ambition to electrify its transportation sector, but this dramatic shift in its target shows that it needs more detailed information on the effects of the scenarios for electrification that it is considering.

India has other policies to foster electrification of road vehicles as well. Its FAME-2 program provides incentives for electrification of certain vehicle classes. These include electric buses, three-wheelers, two-wheelers, and passenger cars (*National Automotive Board (NAB)*, no date). The FAME-2 scheme plans to fund the purchase of 1 million electric two-wheelers, 500,000 electric three-wheelers, 55,000 electric four-wheelers, and 7,000 electric buses, and ensure that these vehicles are deployed by 2022. NITI Aayog and the Rocky Mountain Institute, two leading think tanks, have estimated that the electric vehicles purchased through FAME-2 will collectively save 5.4 million tons of oil equivalent, which would save 170 petajoules of energy and 7.4 million tons of carbon dioxide equivalent over the vehicles' lifetimes (Ghate *et al.*, 2019). The number of vehicles of each type that are eligible for subsidies under FAME-2 indicate that the main focus of the policy will be electrification of two-wheelers and three-wheelers, and that private four-wheeler cars are a lower priority for electrification. Given that private vehicles are a lower priority, their emissions benefit from electrification should be used to determine whether the electrification of private cars is an appropriate target for electrification at all, or whether it should be postponed until the power grid reduces its carbon intensity.

1.2 Health Benefits of electrification

India's cities suffer from high rates of ambient air pollution, and one of the biggest health hazards is the fine particulate matter ($PM_{2.5}$) pollution. A major source of this pollution is tailpipe emissions from cars: a 2018 survey found that in New Delhi, around 28% of the ambient $PM_{2.5}$ in winter comes from vehicular tailpipe emissions (Sharma and Saraf, 2018; Pujari, 2019).

Though this is hardly the only source of air pollution, eliminating tailpipe emissions would make a difference to air quality. If the cars are electrified, then the tailpipe emissions will stop, though particulate matter from road dust and tires may still be produced (Timmers and Achten, 2016). Vehicle electrification could bring a net health benefit, and this might be the case even if it causes a net increase in particulate and other pollutant emissions. Unlike with greenhouse gas emissions, particulate matter has a short lifetime in the atmosphere. Power plants can be located far from cities, so that people are *exposed* to less particulate matter that they produce, relative to that produced in closer proximity. In the EV case, a net health benefit could be achieved, because people could be exposed to lower levels of air pollution. Cumulative health impacts of particulate matter depend on the location of the source of pollution and the number of people who experience direct exposure to it (Nopmongcol *et al.*, 2017; Schnell *et al.*, 2019).

1.3 Potential synergies

There are potential synergies between electric vehicles, renewable energy, and energy storage. Renewable electricity decreases the carbon footprint of electric vehicle operations, because of the reduced carbon intensity of electricity. This matters not only for the vehicle's operation, but also for the manufacture of the battery, as electricity is a major input for the manufacture of lithium-ion batteries. Battery manufacture is energy-intensive and can have a substantial impact on the life cycle emissions of the electric vehicle. Batteries manufactured using coal based electricity have a much higher carbon footprint from manufacturing than batteries made with renewable energy (Hausfather, 2019).

To enable a stable grid to function with high volumes of variable renewable energy, energy storage is necessary, on the order of 22% of the overall grid's average daily power and energy demand (Solomon, Kammen and Callaway, 2014). In particular, the period after sunset is a major challenge for power grids with a high portion of solar PV, because power demand typically remains high or even increases in the evening, as workers return home, while supply of solar power drops. This phenomenon is sometimes known as the ‘duck curve’ due to the shape of the graph of the load profile (Jones-Albertus, 2017). In India, the peak demand is in the evening, which means that variable renewable energy cannot reliably meet this demand without energy storage (Tongia and Parray, 2019).

Vehicle electrification presents more than one opportunity for energy storage to stabilize the grid. One possibility is vehicle to grid integration. This means that the batteries in the vehicles would serve as energy storage for the power grid while the vehicle are parked. Vehicle to grid integration could effectively turn electric vehicles into a distributed energy resource. (Coignard et al., 2018; IEA, 2020). In addition, once the vehicle retires, then the lithium ion battery could be repurposed for grid storage. In this case, the battery would have a second life of grid storage after its first life in a vehicle is complete. This has been described as a “cascaded life cycle” (Ahmadi *et al.*, 2017; Hossain *et al.*, 2019).

Together these factors enable multiple synergies to arise between the use of renewable energy and electric vehicles. Renewable energy enhances the benefit of vehicle electrification, by reducing the greenhouse gas emissions throughout the supply chain; while vehicle electrification can enable the success of renewable energy through energy storage – both during the vehicles’ life through the use of vehicle to grid integration, and after the vehicle’s life through the use of second-life batteries for grid storage.

1.4 Research Objectives

The remainder of the thesis is an assessment of the life cycle GHG emissions of EVs and ICEVs in the context of India. Chapter 2 examines the extant literature available on this topic.

Chapter 3 explains the methodology of this assessment. There is a parallel structure which assesses the GHG emissions from manufacture, operation, and disposal of ICEVs and EVs in India. Chapter 4 will present the results of this assessment, Chapter 5 will discuss limitations and opportunities for future work, and Chapter 6 will provide an overview, discussion, and conclusion.

This study provides an overview of the comparative life cycle greenhouse gas emissions of ICEVs relative to EVs in India. The study conducts a cradle to grave assessment of the combustion and electric vehicles. In assessing the life cycle GHG emissions of EVs, this study incorporates three different scenarios for the evolution of the country's power grid, and how they would affect the life cycle greenhouse gas emissions of electric vehicles in India. In assessing the life cycle GHG emissions of ICEVs, the study estimates 'well to wheel' upstream carbon emissions from extracting, transporting, and refining oil for combustion vehicles, as part of a cradle to grave assessment of ICEVs.

Where applicable the study incorporates the potential reduction in emissions that arises when electric vehicle batteries are repurposed for grid storage after their life in a vehicle, thus displacing the manufacture of a new battery, as well as the benefit of recycling the battery after that. However, the analysis does not endeavor to quantify the potential benefits of vehicle to grid integration, which would accrue on top of the benefits of electrification if properly managed.

This study focuses only on greenhouse gas emissions,[2] not other pollutants, and it compares the life cycle emissions of fleet averages for combustion and electric vehicles assumed to be manufactured in India, over the course of the decade from 2019 to 2030. In addition, for the

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[2] This assumption enables a consistent comparison across the different scenarios, because the impacts of greenhouse gas emissions do not depend on the location

sake of simplicity, this study assumes that the vehicle's production takes place entirely within India, including the manufacture of the battery and the vehicle. This assumption is consistent with the Indian government's stated preference for making lithium ion batteries in India (Nandi, 2020).

The purpose of this study is to estimate the net difference in greenhouse gas emissions over the life cycles of combustion vehicles and electric vehicles, as represented by the average vehicle, in India. The carbon intensity of the power grid has a large impact on the electric vehicle's emissions profile, but this study found that despite the high carbon intensity of India's electric grid, electrification of vehicles still reduces the life cycle greenhouse gas emissions of cars in India, even in a business-as-usual scenario for the power grid's development. Not surprisingly, the benefit of electrification is maximized in a scenario with a higher portion of renewable energy on the power grid.

Chapter 2: Literature Review

The literature on the topic of vehicle electrification in India is in its nascent phases, and is not as comprehensive as the corresponding literature globally. However, there is hope that electrification of vehicles in India can achieve multiple co-benefits, including energy security through reduced reliance on imported oil, mitigation of climate change, and reduction in air pollution (Abhyankar *et al.*, 2017).

2.1.1 India's Electricity Sector

Due to India's overwhelmingly coal-powered electricity grid, there is concern that electrification could have a net effect of increasing GHG emissions. Even if tailpipe emissions are eliminated, the benefit could be overwhelmed by a corresponding increase in coal burned at power plants. Following this line of logic, Doucette and McCulloch (2011) argued that "for China and India, and other countries with a similarly high CO_2 intensity of grid electricity, unless power generation becomes dramatically less CO_2 intensive, BEVs will not be able to deliver a meaningful decrease in CO_2 emissions and an increase in the penetration of BEVs could actually lead to higher CO_2 emissions." (Doucette and McCulloch, 2011) Similarly, Woo, Choi, and Ahn (2017) found that in countries with electricity dominated by coal, including India, some electric vehicles can emit more GHG/km than equivalent gasoline or diesel vehicles (Woo, Choi and Ahn, 2017). This was a well-to-wheel analysis which did not consider the implications of vehicle or battery manufacturing or disposal.

India's power grid has changed dramatically in the past few years, and is expected to continue to do so. Renewable energy has become less expensive and more prevalent around the world, including in India. In its Nationally Determined Contribution (NDC) to the Paris Agreement, the country made a commitment to have 40% of its grid's installed generating capacity from non-fossil sources by 2030, a move which would dramatically reduce the carbon intensity of its grid. India is on track to achieve this target ahead of schedule (“Pledges And Targets” 2018).

There is much more to be done to reduce carbon emissions from the country’s transportation sector. A 2017 analysis found that to meet either the 2°C or the 1.5°C targets for global climate stabilization, India would have to enact significant new measures to reduce emissions action than it has previously outlined in its NDC. These measures include clean vehicle technologies, such as electric vehicles, as well as clean electricity, and investments in urban mass transit (Dhar, Pathak and Shukla, 2017). Many of these measures, such as electrification, are of great interest to Indian policymakers, not only due to their climate benefits but also due to their co-benefits, such as improved energy security and air quality (Dhar and Shukla, 2015). Electric vehicles in particular have attracted attention from Indian policymakers because of their potential to achieve multiple co-benefits related to air quality, energy security, and greenhouse gas emissions (Dhar, Pathak and Shukla, 2017) in addition to supporting a new sector for India’s manufacturing economy.

Despite concerns that electrification could increase the use of coal on India’s power grid, more recent analysis has found that large-scale electrification of vehicles is a feasible option for India, and that the co-benefits and synergies would likely outweigh the trade-offs. Abhyankar and Sheppard (2017) found that electric vehicles’ costs are lower than comparable costs for combustion vehicles, that transitioning the country’s entire vehicle fleet to battery electric vehicles would add only 6% to peak power demand, and that BEVs would significantly lower the country’s CO2 emissions as well as oil imports (Abhyankar and Sheppard, 2017). They found that even if India engages in aggressive electrification, only 3.3% of the country’s power demand would come from electric vehicles. This is for three reasons: the growth in electric demand from vehicles is overwhelmed by the growth in electric demand from other appliances, notably air conditioners; vehicle penetration in India is dominated by two-wheelers, which use less energy than cars; and overall vehicle penetration is expected to be significantly lower than in other countries. This study projected India's overall peak load from battery electric vehicle charging in 2030 to be 23 GW, which is about 6% of the country's overall peak load in that year.

2.2 Life Cycle Assessment of Electric Vehicles

Life cycle assessment of electric and conventional vehicles in the context of other countries has been completed. Nealer, et al. (2015) found that in the context of the United States, EVs almost always have lower life cycle GHG emissions than ICEVs. This benefit is even more pronounced when the proportion of renewable energy on the power grid increases, and when the proportion of coal decreases (Nealer, Reichmuth and Anair, 2015).

Huo, et al. (2015), compared the life cycle impacts of EVs and ICEVs in the US and China, and found that EVs reduce all forms of pollution in areas like California which have a low proportion of coal on their power grid, but that in regions that use coal power, electrification of vehicles has mixed effects, depending on which type of pollutant is considered. Depending on specific circumstances, the electrification of vehicles could increase or decrease the net GHG emissions from the vehicle. In addition, electrification changes the location of the pollution, because it eliminates tailpipe emissions but increases the fuel burned at power plants. This can bring a net health benefit if the power plant is located in a sparsely populated region (Huo *et al.*, 2015). These results suggest that there may be a trade-off between emissions of greenhouse gases and the air pollution that directly affects human health.

Life cycle analysis of electric vehicles in India is still in its nascent phases. Upadhyayula, et al., (2019) compared the emissions of combustion and electric vehicles in India between now and 2030. They found that electrification is beneficial for small vehicles but not large ones, and argued that the "lightweighting" – reducing the weight of vehicles - is the best strategy for reducing emissions from vehicles in India (Upadhyayula *et al.*, 2019). However, no study thus far has considered the impacts of battery recycling and reuse for grid storage as part of the life cycle of an electric vehicle in the context of developing countries like India.

Knobloch, et al. (2020) assessed the possibility of electrifying indoor heating through heat pumps and vehicles with EVs. They found that electrification of both of these end uses of energy has a net effect of decreasing GHG emissions in most countries, and in a scenario consistent with limiting the global warming to 2°C, electrification decreases GHG emissions in all countries. They found that electrification of vehicle in India would have an effect of increasing GHG emissions in 2015, due to the carbon-intensive power grid, but that by 2030, the grid's carbon intensity will decrease enough that electrification will almost always decrease emissions, if it remains on its current trajectory (Knobloch *et al.*, 2020).

Thus far, few assessments have done a full 'cradle to grave' life cycle assessment for EVs, because few EVs have completed a full life cycle. For that reason, many of the life cycle assessments have not fully considered the end of life for the electric vehicle. There remains an open question about the lifetime impacts of electric and combustion-powered vehicles in the context of India, which has a unique mix of vehicles on its roads and power on its grid. Since India has more than 1.3 billion people (World Bank, 2019), and increasing demand for energy and transportation services (Pathak and Shukla, 2016), this question matters greatly not only for the future of India, but for that of the entire global climate. This is especially pertinent in light of the gap in the literature related to battery disposal.

For that reason, we conducted a new life cycle analysis of electric vehicles and combustion vehicles in the context of India. This study incorporates newly available data on the impacts of EV battery recycling and reuse (Ciez and Whitacre, 2019a; Ambrose, 2020), which enables us to estimate the benefit of EV recycling and battery reuse. The rest of the thesis explains the methodology, results, and conclusions of this study.

Chapter 3: Methodology

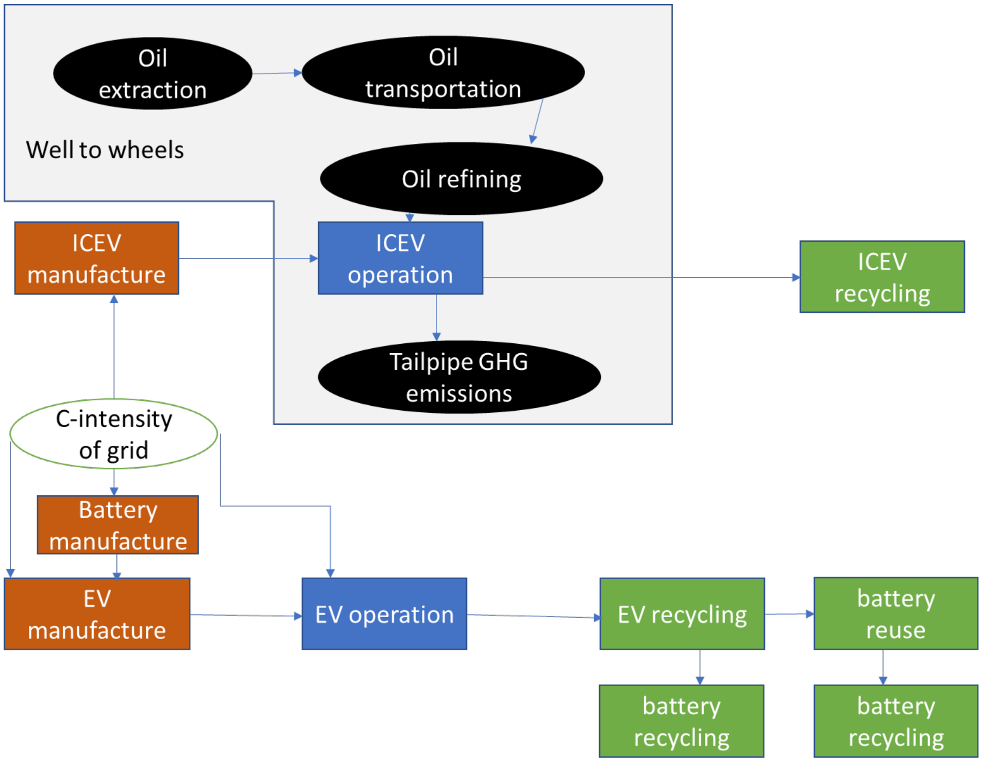

Figure 1-System Diagram

In conducting this analysis, the emissions from vehicle, manufacture, operations, and recycling were combined using a “base case”. The base case refers to the estimate in which fixed central estimates were selected for each of the key input parameters. In addition, given the uncertainty in these parameter values, a Monte Carlo analysis was conducted, in which probability distributions for all key input parameters were developed and used as inputs.

A system diagram is shown above in Figure 1. The system diagram shows how the carbon intensity of the grid is an input for the manufacture of the EV battery, the bodies of the EV and ICEV, and the operation of the EV. The emissions from the operation of the ICEV are determined by the emissions from crude oil extraction, refining, and transportation, and the tailpipe emissions of the ICEV. The emissions from the end of life are determined by the processes for recycling the vehicle body, and for the recycling and reuse of the EV battery.

Three scenarios were assessed for the carbon intensity of India's power grid. Pachouri et al., of The Energy and Resources Institute (TERI), wrote a report on the scenarios for India's power grid between 2018 and 2030. This paper was developed for the Energy Transitions Commission India, which is an initiative of TERI in collaboration with the Climate Policy Institute and National Renewable Energy Laboratory to facilitate the government of India's energy goals, by assessing power demand and supply scenarios. They developed these three scenarios for the evolution of the country's power grid between 2018 and 2030. The first two scenarios can be characterized as variations of a business-as-usual (BAU) trajectory. The Current Trends Scenario (CTS) assumes that current trends in the power sector continue, and that no additional renewable energy investments are made. The Current Policies Scenario (CPS) assumes that current policies related to renewable energy, such as the commitments in India's Nationally Determined Contribution to the Paris Agreement, will be fully implemented, but that no additional investments are made. The CPS has a lower carbon intensity than the CTS, implying that there are extant policies which are not being fully implemented. The High Renewable Scenario (HRES), on the other hand, is one under which substantial additional renewable energy investments are made. However, in all three of the scenarios, coal remains the major source of energy on India's power grid; even in the HRES, coal accounts for an outright majority of India's power generation through the year 2030 (Pachouri, Spencer and Renjith, 2018). The carbon intensity numbers for the electricity generation were not in the report, but were obtained privately from the authors (Pachouri, personal correspondence).

Table 1-Projected grid emissions factors by Pachouri, et al.

Grid Emissions Factor (gCO2/kWh)	2019	2022	2027	2030
CPS	744	659	589	596
CTS	748	698	648	671
HRES	733	655	584	556

In addition to the base case, an uncertainty analysis using Monte Carlo simulations was also performed. using the @Risk software. Monte Carlo simulations assess the ranges of possible values for seven to eight key inputs. In the CTS and CPS, there were seven key inputs, but in the HRES, there were eight key inputs because the lifespan of the battery in its second life for grid storage was an additional input for the Monte Carlo analysis. Input values are shown in Table 1. Probability distributions are triangular, with minimum and maximum bounds, with the mode as the base value. Other probability distributions without minimum or maximum boundaries were considered, but were rejected because of unrealistically long statistical tails. These values will be discussed in more detail below. The values for these parameters come from many sources including Ambrose, 2020; Ellingsen et al., 2014; NITI Aayog and Rocky Mountain Institute, 2017; Romare & Dahllöf, 2017; Saxena, Gopal, & Phadke, 2014; Tata Power Delhi Distribution Limited, 2019; World Bank, n.d.; and Yang, 2018.

Table 2 - Inputs for specifications

Specification	**Base/Mode**	**Min**	**Max**
Vehicle kilometers traveled (VKT) per year	15000	12,000	18,000
Vehicle lifespan (years)	9.6	7.6	11.6
Battery capacity (kWh)	26.6	20	60
Emissions from producing battery (kgCO$_2$e/kWh)	172	150	200
T&D Loss (%)	10.82	6	20
Efficiency of average EV (Wh/km)	101.28	92.72	126
ICEV tailpipe emissions per km in 2030 (gCO$_2$/km)	112	99	121
Second life of battery (years)	6.5	5	8

The analysis assumes that, for both electric and combustion vehicles, the fleet is composed of 80% privately operated vehicles and 20% commercial vehicles. The private cars have a lifetime of 8 to 12 years, with a base case value of 10 years, and drives 10,000 to 15,000 km per year, with a base case value of 12,500 km per year. The commercial vehicles have a lifetime of 6 to 10 years, with a base case value of 8 years, and drive 20,000 to 30,000 km per year, with a base case value of 25,000 km per year. This means that in the base case, the combined fleet average vehicle drives 15,000 km per year, for 9.6 years, while the range for the fleet average goes from 12,000 to 18,000 km per year, for 7.9 to 11.6 years.

For the Monte Carlo analysis, the triangular distributions were chosen to represent the distribution of possible values. This means that there were upper and lower boundaries for the distributions. This was selected to avoid outliers in the results.

3.1 Electric vehicle operations

The emissions from operations of electric vehicles depend on two primary factors: The greenhouse gas intensity of the electricity generation and the electrical efficiency of the vehicle. The numbers for vehicle efficiency were drawn from Saxena, et al. (Saxena, Gopal and Phadke, 2014), who estimated power consumption for electric vehicles in India. Table 3 gives their estimates for power consumption in Wh/km.

Table 3 - Values for EV efficiency given by Saxena, et al. (Wh/km)

Vehicle class	Average in City	Average in Hwy	Range
Low-power EV	84	133	70-192
High-power EV	123	164	101-224

This study assumes that 80% of vehicles will be low-powered, because small vehicles are more prevalent in India. In addition, this study assumes that 80% of driving happens in city conditions, due to the high prevalence of traffic congestion in India. As such, the assumed fleet average for electric vehicle efficiency in India is 101.28 Wh/km.

As part of the Monte Carlo assessment, a range of potential values for the fleet average was assessed. The lower end of the range assumes that 90% of driving happens in low-powered electric vehicles under city conditions, leading to a fleet average of 92.72 Wh/km. The upper end of the range assumes that low-powered and high-powered electric vehicles are equally prevalent, and that city and highway driving is equally prevalent, leading to a fleet average of 126 Wh/km.

Electric vehicles, unlike combustion vehicles, have an advantage in that they can decrease the carbon intensity per km travelled over time, as the grid decreases in carbon intensity. Electric vehicles do not only use electricity in the year that they are made. For that reason, this study extrapolated the carbon intensity for fifteen years after 2030. For the two BAU scenarios, this study assumes that the carbon intensity stays the same as its 2030 value for all years thereafter. For the HRES, this study assumes a linear extrapolation. In this case, the carbon intensity decreases by 4.8% every three years, just as it does from 2027 to 2030, and the carbon intensity of the grid in 2045 is 435 gCO_2e/kWh. A rolling average was taken of the grid's carbon intensity for the fifteen years after the car's manufacture.

Table 4 - Extrapolated emissions factor for power grid for years after 2030

Grid Emissions Factor(gCO2/kWh)	2033	2036	2039	2042	2045
CPS	596	596	596	596	596
CTS	671	671	671	671	671
HRES	529	504	480	457	435

Table 5- Rolling average of grid emissions factors for 15 years after vehicle manufacture

Rolling 15-year average of grid emissions factor (gCO2/kWh)	2019	2022	2027	2030
CPS	637	607	595	596
CTS	687	672	666	671
HRES	611	566	531	493

3.2 Electric Grid Losses

This study also considers the impact of transmission and distribution (T&D) losses, which are the losses of energy that occur between the power generation and the final use of energy, on the transmission and distribution wires. The true rate of T&D losses in India is hard to quantify, because of the high prevalence of electricity theft, colloquially known as *katiya* in Hindi-Urdu speaking regions. This occurs when individuals illegally connect their own wires to the T&D lines, to steal electricity. The true prevalence of this practice is unknown, and this theft gets counted as T&D losses in official statistics. However, to consider theft as T&D losses would be improper accounting, because stolen electricity gets used for some other purpose and should be assigned to that other purpose (Ganesan, Bharadwaj and Balani, 2019).

For this reason, this study took the official T&D loss value from the distribution company that operates in New Delhi (Tata Power Delhi Distribution Limited, 2019). The assumption is that the theft of electricity is less prevalent in a developed city, and that over the coming decade, the rest of the country will converge to the level of T&D losses seen in New Delhi.

For the Monte Carlo analysis, a range of true values for the T&D losses was considered. The low value is 6%, which is the value reported in the United States. The high value is 20%, which is the official statistic for the T&D losses that India reported to the World Bank. This is the maximum because it may include the theft of electricity as T&D losses.

If the electricity consumption of the vehicle, in kilowatt-hours per kilometer (kWh/km), is defined to be a, and the transmission and distribution losses are defined to be t, then the upstream consumption of electricity at the power plant (Uc), in kWh/km, is equal to

$$Uc = \frac{a}{(1-t)} \tag{1}$$

If the emissions factors of the power grid, in gCO_2e/kWh, are *e*, then the emissions from operating the vehicle 1 km are equal to the product of the upstream consumption and the emission factor. If V is the emissions per kilometer travelled,

$$V = U_C e = e * \frac{a}{1-t} \tag{2}$$

3.3 ICEV operations

The emissions from the operations of ICEVs depend on two primary factors: the tailpipe emissions and the upstream emissions from the fuel supply chain. Yang (2018) found that the Indian four-wheeler vehicular fleet average for tailpipe emissions were 121 g of CO_2 per kilometer. In addition, for the fiscal year 2022-2023, there is a legal limit for the fleet average tailpipe emissions to be 112.1 gCO_2/km, which is set by the Government of India (Yang, 2018). The base case in this study assumed that the tailpipe emissions remain at this legal limit for all years thereafter. For the Monte Carlo analysis, we assume a triangular distribution, with a defined minimum and maximum, for each input parameter. The mode for this distribution, for each input parameter, is the same as the value for the base case. A minimum value of 99 gCO_2/km assumes that the tailpipe emissions continuously improve through 2030 at the same rate that they do from 2018 to 2022. The maximum value of 121 gCO_2/km assumes that the tailpipe emissions completely fail to improve or meet their target for 2022. The total emissions from operating a combustion vehicle were estimated as such:

$$(X + Y) * (1 + M_C + M_S + M_R) \tag{3}$$

Where

X is defined to be the average tailpipe emissions of an Indian vehicle, in gCO_2e/km.

Y is defined to be the emissions per km from refining the fuel, in gCO_2e/km.

M_C is a derived multiplier to estimate emissions from crude oil extraction

M_S is a derived multiplier to estimate emissions from shipping oil by sea

M_R is a derived multiplier to estimate emissions from shipping oil by rail

The fleet average well-to-wheel emissions for ICEVS was determined to be 149 gCO_2e/km.

The upstream emissions from the supply chain are partitioned into emissions from crude oil refining (3.3.1), extraction (3.3.2), and transportation, which in turn is partitioned into international sea transportation (3.3.3) and domestic rail (3.3.4) transportation.

3.3.1 Refining emissions

The emissions from refining were assessed based on the emissions from refineries. To estimate emissions from refining crude oil into automotive fuel in India, the following method was used. If we define the following variables:

R is defined to be the GHG emissions, in kg of CO_2e per kg of refined fuel in India,

D is defined to be the density of average fuel in kg/L. Then we find the following equations.

The stoichiometric CO_2 emissions from burning 1 L average automotive fuel are defined as s.

$\frac{X}{s}$ = the average fuel consumption in L/km. (4)

RD = emissions in $kgCO_2e$ per liter of fuel, so thus (5)

$$Y = \frac{(rd\frac{X}{s})}{1000} = 8 \text{ gCO2e/km} \tag{6}$$

The emissions from operating a vehicle 1 km, if only the tailpipe and refining emissions are included, is thus equal to

$$X + Y = X + \frac{(rd\frac{X}{s})}{1000} = 129 \text{ gCO2e/km.} \tag{7}$$

3.3.2 Emissions from extraction of oil

Masnadi, et al. (2018), found the upstream GHG emissions associated with crude oil extraction in each oil-extracting country of the world (Masnadi *et al.*, 2018). A global trade database contained information on the countries that export oil to India (Chatham House, 2017), and the Indian government had data on the total volume of oil that was imported.

We calculate a weighted average of the GHG intensity of crude oil production in all of these countries that export oil to India. It found that the production of 1 ton of oil exported to India causes the emissions of .48235 tons of CO2e upstream at the extraction sites. Combustion of one ton of oil causes the emissions of 3.0667 tons of CO2e directly. Thus, a multiplier can be derived to estimate upstream emissions from fuel used in India:

$$M_c = \frac{.48325}{3.0667} = .1573 \tag{8}$$

3.3.3 Emissions from international shipping of oil

This study also calculated the emissions from shipping this oil to India. It calculated the nautical distance from the predominant oil export terminal in each oil exporting country to the port of Kandla, which is India’s primary oil import terminal. The volume of crude oil shipped from each country exporting to India was multiplied by the distance and the average GHG emissions factors of shipping cargo by sea; division by the total mass of oil consumed in India helps obtain the average shipping emissions per ton of oil. Shipping 1 ton of oil causes .03 tons of CO2e to be emitted in the process of shipping oil to India. From this number, a multiplier can be obtained to estimate emissions from shipping oil, as with the upstream crude oil emissions.

$$M_s = \frac{.03}{3.0667} = .0098 \tag{9}$$

3.3.4 Emissions from domestic rail transportation of oil

In the most recent year for which data is available, 43,110,000 tons of oil were transported by rail in India, for an average of 642 km (Ministry of Petroleum & Natural Gas Economics & Statistics Division, 2019), and that to move one ton of cargo 1 km on Indian Railways emits .009594 kg of CO2 (Gajjar and Sheikh, 2015). Thus, the total emissions from shipping oil by rail in India can be calculated, and this number can be divided it by the total volume of oil used in the country to get a figure per ton. Using one ton of crude oil in India emits .0012 tons of CO2 from transporting oil by rail within India. The same multiplier strategy used for crude emissions and shipping emissions was used to estimated emissions from moving oil by rail in India.

$$M_R = \frac{.0012}{3.0667} = .000389 \tag{10}$$

3.4 Vehicle Manufacturing

The vehicle can be partitioned into two portions: the glider and the drivetrain. The glider is the entire vehicle minus the drive train. The glider includes the body, the interior, and the wheels, and is common to electric and combustion vehicles, while the drivetrain includes the combustion engine and transmission for combustion vehicles, and the battery and electric motors for electric vehicles.

EcoInvent, a database used for life cycle analysis, has data on the mass of materials that go into all the components of a vehicle glider, and a combustion engine (*ecoinvent*, no date). EcoInvent data was not specific to India, so the global average value for mass of each material component was used. The data taken from EcoInvent includes the vehicle glider, the combustion engine, and the electric vehicle motor. Since the EcoInvent database does not provide data on the combustion vehicle transmission, data for ICEV transmission was obtained from Sullivan, Kelly, & Elgowainy, (2018).

EcoInvent provided data on the materials that go into the vehicle glider and combustion engine, but it did not provide data on their embodied emissions. That data was obtained from the India Construction Materials Database of Embodied Energy and Global Warming Potential, which is published by The World Bank's International Finance Corporation. This database includes data on the embodied emissions of carbon dioxide equivalent that occur when materials such as steel, aluminum, and glass are manufactured in India. For the purposes of this study, a simplifying assumption was made that the materials and the vehicle were manufactured in India. The embodied energy and greenhouse gas footprint from the materials were multiplied by the quantity of each material that is in each component. This is consistent with the Government of India's Make in India initiative (NITI Aayog and Rocky Mountain Institute, 2017).

EcoInvent includes the amount of electrical energy that was an input for the manufacture of vehicle gliders and internal combustion engines. In order to estimate the embodied GHG emissions from the energy used to manufacture the vehicle, the quantity of electrical energy was multiplied by the carbon intensity of the grid in each year for each scenario. In addition, EcoInvent provides the amount of natural gas, in megajoules, that was used for heat as input for the manufacture of a vehicle glider and combustion engine. This was multiplied by the stoichiometric amount of CO2 emissions that result from the combustion of natural gas, under the assumption of complete combustion.

3.4.1 Manufacture of batteries

Emilsson and Dahllöff (2019) found that the production of lithium ion batteries causes emissions of around 610 to 106 kilograms of CO_2e per kilowatt-hour ($kgCO_2e/kWh$) of battery capacity, and that this scales linearly with battery size, in proportion to battery capacity (Emilsson and Dahllöf, 2019). This is lower than their previous estimate of 150 to 200 $kgCO_2e/kWh$, but the estimate was updated because newer and more accurate production data has become available. Here we use a base value of 83.5 $kgCO_2e/kWh$, which is the middle of that range; for the Monte Carlo analysis, we use a range from 61 to 106 $kgCO_2e/kWh$. This value will be defined as P.

Ellingsen et al. found that 51% of the battery's carbon dioxide equivalent emissions came from the fossil fuels at electrical power plants, the remaining 49% attributed to manufacturing processes. Manufacturing of one kWh of battery capacity used 586 megajoules (MJ) of energy; to estimate the emissions from electricity from manufacturing the battery in each scenario and each year, this value (586 MJ) was multiplied by the emissions factors in each scenario and year.

In the base case, the battery pack has a capacity of 26.6 kWh (Ellingsen *et al.*, 2014). For the Monte Carlo assessment, a lower boundary was selected of 20 kWh, on the argument that a lower battery capacity would not be useful for the average consumer, and an upper boundary was selected of 60 kWh, as this value was assessed in the India Energy Storage Mission report by the Rocky Mountain Institute (NITI Aayog and Rocky Mountain Institute, 2017).

Thus, if the battery capacity is B, and the emissions factor from the power grid is e, and the rate of T&D losses is t, the emissions from manufacturing the battery (N) are calculated as such:

$$N = (.49 * P * B) + (.51 * B * \frac{e}{1-t}) \tag{11}$$

3.5 End of life

At the end of a vehicle's life, we assume that vehicles are recycled. This applies to both combustion vehicles and electric vehicles, with one crucial difference. The recycling of combustion vehicles is an established technology, while the recycling of electric vehicles has not been fully developed, because so few electric vehicles have as of yet completed a full life cycle.

3.5.1 End of life of vehicle glider and combustion engine

The recycling of vehicles was assessed by using data from the Inventory of Carbon and Energy (Hammond and Jones, 2008), which provides data on the embodied energy of recycled and virgin materials used in vehicle manufacturing, such as steel. If E_R is embodied energy in recycled material and E_V is embodied energy in virgin material, taken from Hammond & Jones (2008) and E_I is the embodied energy of the material made in India, from the IFC, (all figures being on a per-kilogram basis) then the energy recovered is equal to

$$\frac{E_R}{E_V} \times E_I \tag{12}$$

Energy recovered from the vehicle glider and the combustion engine was estimated, and subtracted from the life cycle emissions of the combustion vehicle and the electric vehicle glider. Roughly two thirds of the energy in a combustion vehicle and electric vehicle glider can be recovered when the vehicle is recycled.

3.5.2 End of life for electric vehicle battery

Electric vehicle batteries are a relatively new technology, so estimates for the energy and environmental impact of recycling lithium ion batteries have only recently begun to be published. Ciez & Whitacre (2019) developed estimates for the energy and emissions savings from the recycling of these batteries, which vary by battery chemistry, the recycling process used, and the carbon intensity of the grid in question. We use their findings here.

This study assumed that the hydrometallurgical recycling process is used, as that is the most profitable form of lithium ion battery recycling (Bloomberg New Energy Finance, 2018). It assumed that the lithium-ion batteries use nickel manganese cobalt oxide (NMC) cathode chemistry, to be consistent with the battery chemistry that Ellingsen assessed (Ellingsen *et al.*, 2014). Ciez and Whitacre assessed the impacts of battery recycling on three different electricity mixes, all of which were found in North America. To approximate the Indian electricity mix, this study used the numbers from Ciez and Whitacre's estimates for the electricity on the grid of the ReliabilityFirst Corporation / Michigan (RFCM), which is the most carbon-intensive of the electricity mix that Ciez and Whitacre assessed. The RFCM currently emits roughly 596 gCO_2/kWh (US EPA, 2020). This is the same emissions factor as the Indian power grid in 2030 in the CPS, which means that it is a good proxy for the Indian power grid. This study did not vary the grid intensity for the battery recycling. Ciez and Whitacre found that the recycling 1 kWh of battery capacity on this grid saves 71.3 MJ of energy (Ciez, private correspondence), which is equal to 19.8 kWh.

If the battery capacity is B, and the emissions factor from the power grid is *e,* and the emissions saved from recycling are R, and T&D losses are t, then

$$R = \frac{19.8 * B * e}{1 - t} \tag{13}$$

In CTS and CPS, recycling was the only treatment that the batteries received at the end of their lives. However, in the HRES, we assume that the battery has a second life as grid storage of electricity. Electric grids with high proportions of renewable energy require storage capacity to compensate the absence of dispatchable generation (Solomon, Kammen and Callaway, 2014). This is particularly pronounced for India, where peak demand occurs in the evening, when solar energy is not available (Tongia and Parray, 2019). In the HRES scenario renewables provide

23% of grid electricity in 2030, making storage desirable (Pachouri, Spencer and Renjith, 2018). Ambrose (2020) assessed the lifespan of electric vehicle batteries for grid storage after their vehicular lives, and found that after 8 to 12 years in a vehicle, lithium ion batteries are likely to retain two thirds of their original storage capacity, and that they can deliver an additional 5 to 8 years of service for grid storage.

Here we make the base assumption that in the HRES scenario the battery's second life is 6.5 years with a range of 5 to 8 years, and that the battery cycles daily, with two thirds of its original capacity, with round trip efficiency (RTE) of 80% (Goteti, Hittinger and Williams, 2019). The emissions from the battery manufacture are partitioned between the vehicular life and the second life. This implicitly assumes that the vehicle battery in its second life displaces a new battery that might have been used in its stead. In this scenario, the batteries are recycled after their second life, and the energy savings from recycling are assessed using the same methodology as in the BAU scenarios.

To estimate the emissions credit from battery reuse, we calculated the total quantity of energy that the battery stores in its first life in the vehicle (E_1) and second life on the grid (E_2). If the vehicle's power consumption per km is a, and the lifetime distance traveled is d, then

$$E_1 = ad \tag{14}$$

If the original battery capacity is B, then in light of the 80% RTE, 6.5-year lifespan, and 365 days per year, the energy stored in the battery's second life can be estimated as such:

$$E_2 = B * \frac{2}{3} * 0.8 * 6.5 * 365 \tag{15}$$

The proportion (P) of energy that is used in the first, vehicular, life is the proportion of the battery's cradle-to-gate emissions that we attribute to the vehicle.

$$P = \frac{E_1}{E_2} = 0.3 \tag{16}$$

Thus, if N is the battery manufacturing emissions as described in Eq. 11, the emissions credit from battery reuse (C) is calculated as such:

$$C = N(1 - P) \tag{17}$$

Chapter 4: Results

In the base case, without the Monte Carlo simulations, this study found that under all three scenarios for the power grid, the average electric vehicle has a lower lifecycle carbon footprint than the average combustion powered vehicle. We also found that combustion vehicles had higher emissions from operations than electric vehicles did in every scenario and from manufacturing in almost every scenario. The detailed data can be found in Appendix A. The worst-case scenario for electric vehicles has a lower GHG footprint than the best-case scenario for combustion vehicles. In the year 2030, in the CTS and CPS, the EV emits 129 and 117 gCO_2e/km respectively, which are 23% and 30% lower than their combustion-powered counterparts. In the year 2030 in the HRES, the EV emits only 66 gCO_2e/km, which is 60% below its combustion-powered counterpart. The large difference between the HRES and CPS and CTS is not only because of the reduced carbon intensity of the power grid, but also because of the reuse of the EV battery for grid storage after the vehicular life, which reduces the proportion of the battery's carbon footprint that is attributable to the vehicle.

The results of the analysis are shown in Figures 2 and 3. In both of these figures, the orange line represents the EV in the HRES, the grey line represents the EV in the CPS, and the blue line represents the EV in the CTS. Above that, three lines overlap and appear as one; they represent the ICEV. These lines are slightly different because the carbon intensity of electricity contributes a slight amount to the life cycle emissions of the ICEV, but this difference is negligible. Figure 2 represents the total lifetime GHG emissions of the vehicles in metric tons of carbon dioxide equivalent. Figure 3 represents the emissions normalized on a per-kilometer basis, with the emissions from manufacturing allocated to each kilometer equally.

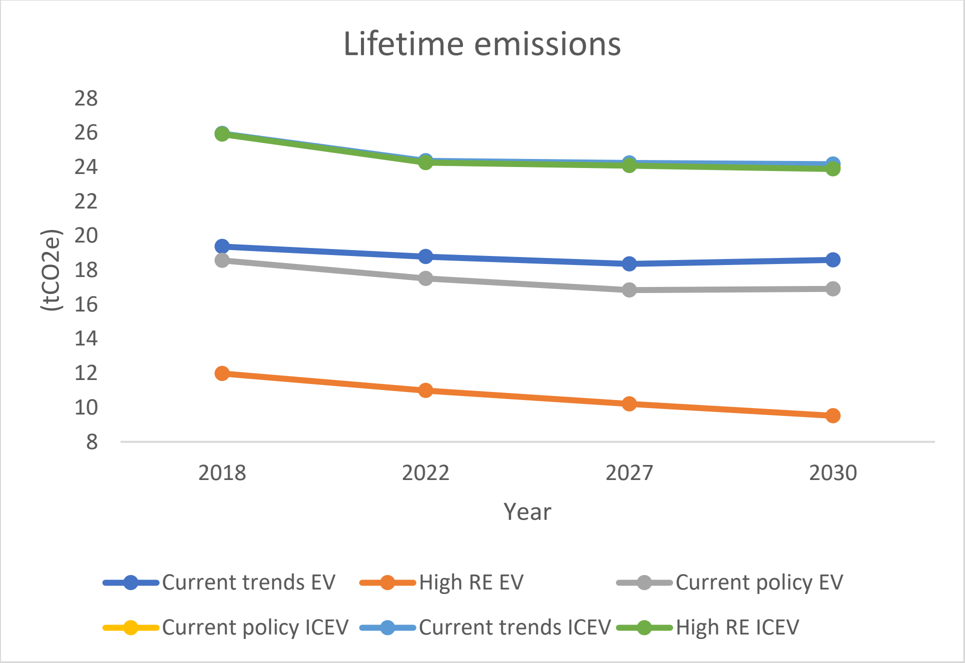

Figure 2-Lifetime emissions of vehicles in different scenarios

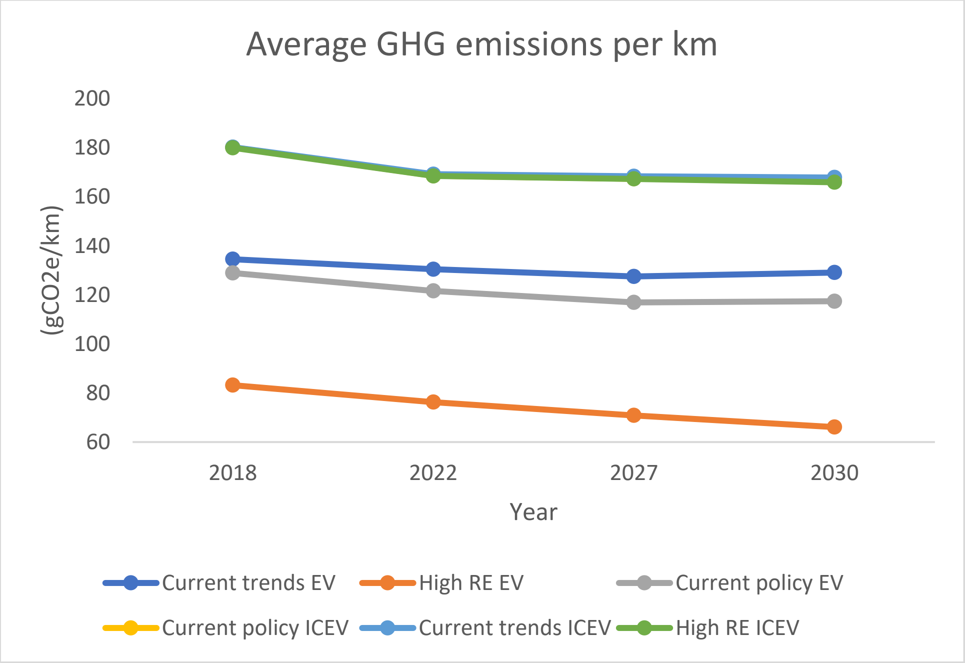

Figure 3-Lifetime average emissions per kilometer of vehicles in different scenarios

Both Figures 2 and 3 show the trend lines for the GHG footprints of vehicles *manufactured* in selected years between 2018 and 2030. The emissions for the combustion vehicles are higher than the emissions for the electric vehicle in every year and scenario. The emissions for the combustion vehicles in the three scenarios differ slightly from each other because electricity is an input for the manufacture of a combustion vehicle, but this impact is negligible. On the other hand, the carbon intensity of electricity has a major impact on the GHG footprint of the electric vehicle. Figure 2 shows the overall lifetime emissions of the vehicle, in tons of carbon dioxide equivalent, while Figure 3 shows the GHG emissions per kilometer.

The high portion of aluminum in the ICEV engine (170 kg) accounts for the high emissions from manufacturing the ICEV. Aluminum has a much higher carbon footprint than most other materials, 31 kg CO_2e / kg. This is because the production of aluminum requires the alumina to be separated from its bauxite ore at 1200°C, after which the alumina is electrolyzed at 960°C (Gautam, Pandey and Agrawal, 2017). As such the aluminum in a combustion engine alone has a GHG footprint of 5270 kg CO_2e and this (combined with its other inputs) gives the motor a GHG footprint of 5721 kg CO_2e.

Figure 4 shows the breakdown of different sources of emissions during the operations phase of the vehicle's life. For the EV, they are all at the power plant, while for the ICEV, they are predominantly from the tailpipe, but also from crude oil extraction, transportation, and refining. This diagram shows the breakdown of emissions in the High Renewable Energy Scenario in 2030.

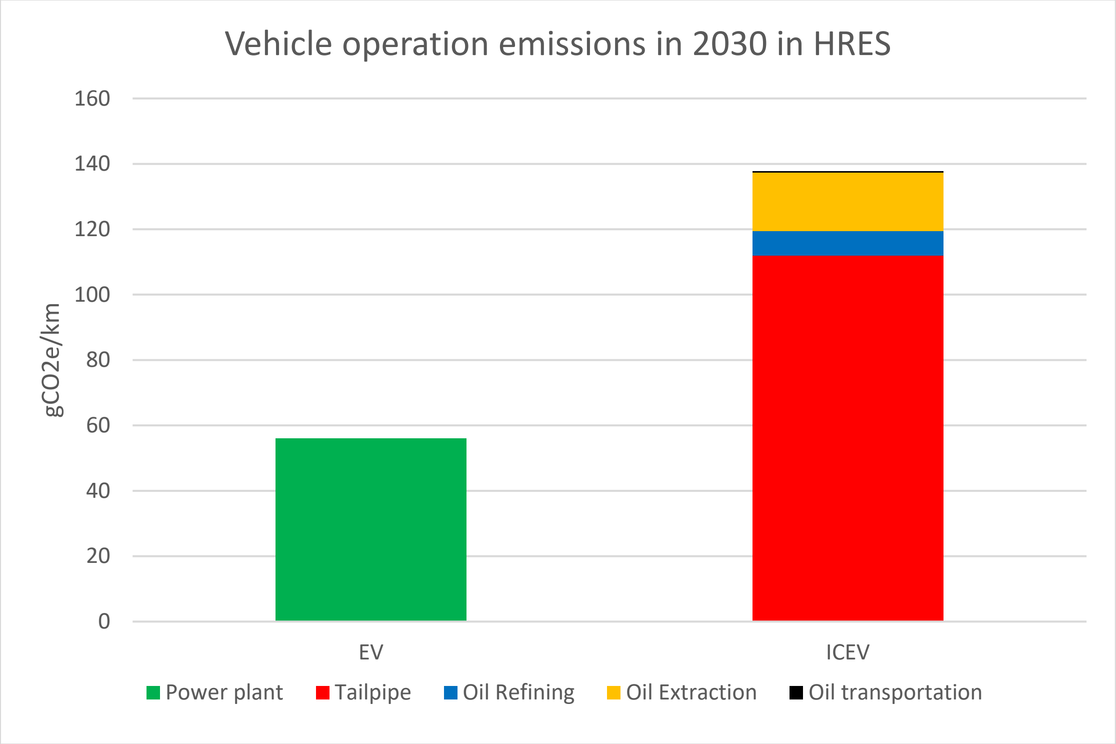

Figure 4 – Emissions per kilometer of operation of vehicles in 2030 in High Renewable Energy Scenario.

Figures 5, 6, and 7 show the net GHG emissions from different components of the vehicle's life cycle, for electric and combustion vehicles, in each scenario for 2030. In the CTS and CTS, the recycling of the ICEV recovers most of the energy embodied in the manufacture of the vehicle, but the recycling of the EV only recovers a minor portion of the energy embodied in the manufacture of the vehicle, because the battery recycling process can only recover a minor portion of the energy embodied in the battery. However, in the HRES, since the battery is reused and recycled, a much larger portion of the energy embodied in the EV can be recovered.

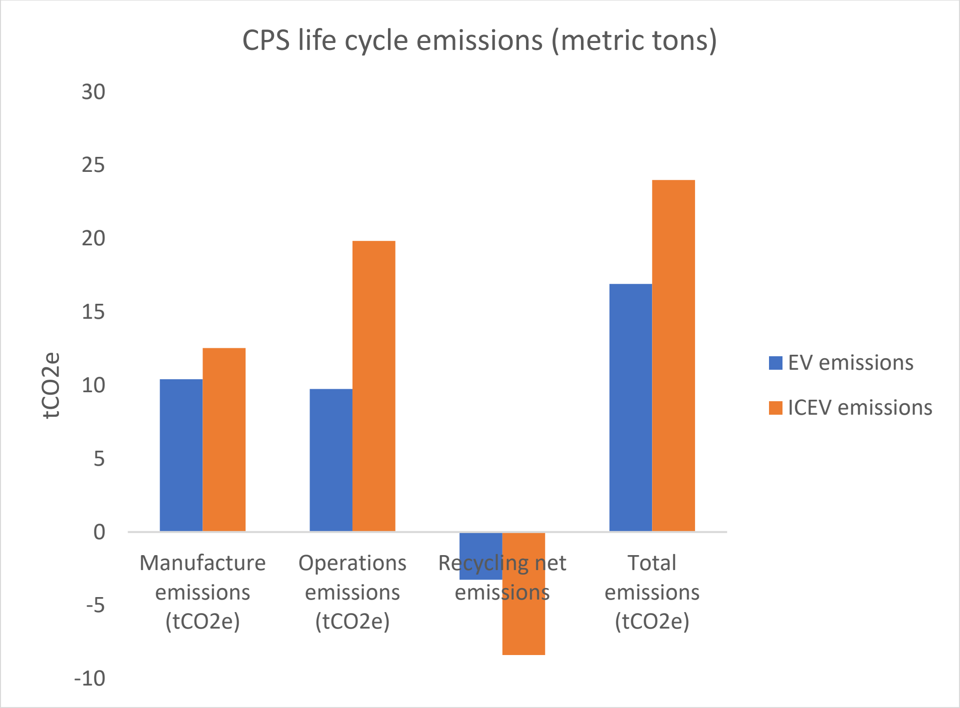

Figure 5 – Emissions from each stage of life for vehicles in Current Policies Scenario

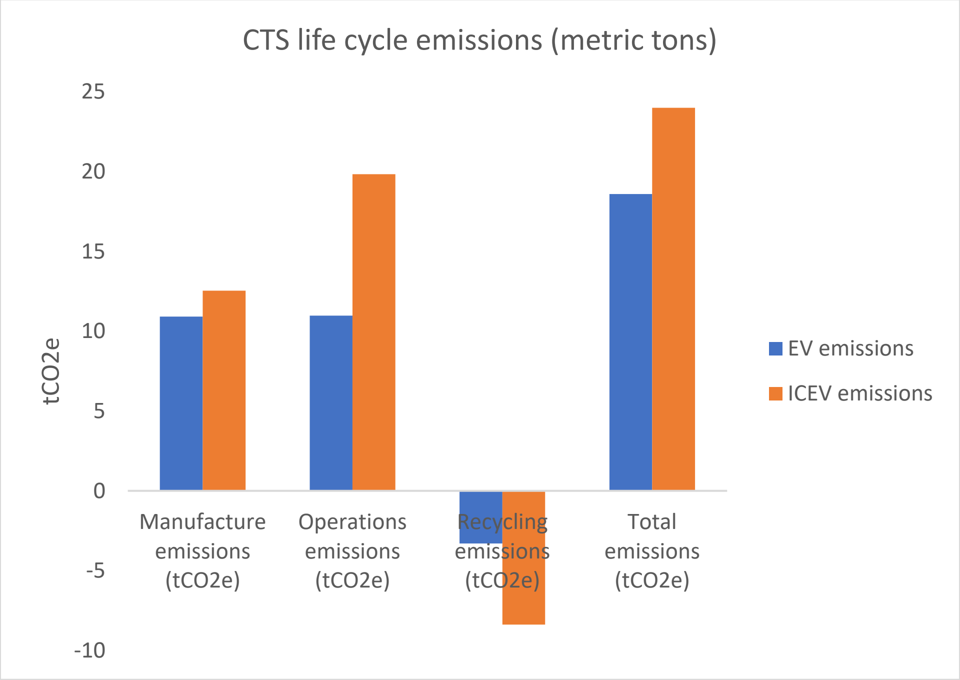

Figure 6 – Emissions from each stage of life for vehicles in the Current Trends Scenario

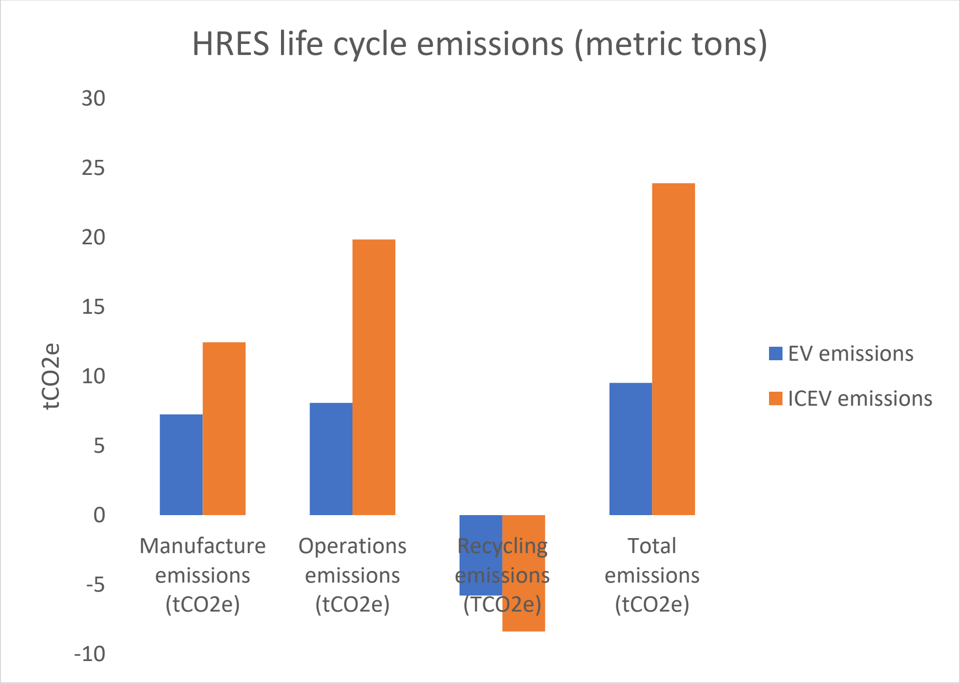

Figure 7 – Emissions for each stage of life for vehicles in the High Renewable Energy Scenario

4.1 Monte Carlo Analysis Results

For each scenario in the Monte Carlo analysis, 10,000 simulations were run with samples randomly drawn for eight key variables from distributions specified in table 1. All other variables were set to their base values. Results are presented in figures 6 through 12. These figures show probability density functions (PDF), and display the results of the simulations. The highest bars indicate a high probability of that value being the correct value. These graphs have an overlay with a cumulative density function (CDF), which is the integral of the PDF. The CDF indicates the percentage of simulation results that are below a certain value. It is important to note the different values on the x-axes for each of these graphs. Since the results for the simulations for ICEVs vary only by a negligible amount, the graphs that show the emissions factors for ICEVs in the CPS and CTS have been omitted here, but are present in Appendix 2.

In the High Renewable Energy Scenario (Figures 6-8) in which the battery was reused and then recycled after vehicular use, 90% of the simulations (5th to 95th percentile) indicated that the life cycle emissions of the electric vehicle would be between 63 and 80 gCO$_2$e/km (Figure 6), and that the 5th - 95th percentile range life cycle emissions range for of the combustion vehicle would be between 154 and 176 gCO$_2$e/km. There is no overlap between these ranges, and are no simulation runs where the electric vehicle had higher emission than the combustion vehicle. The 5th - 95th percentile range for the GHG benefit of driving the electric vehicle is between 81 and 107 gCO$_2$e/km.

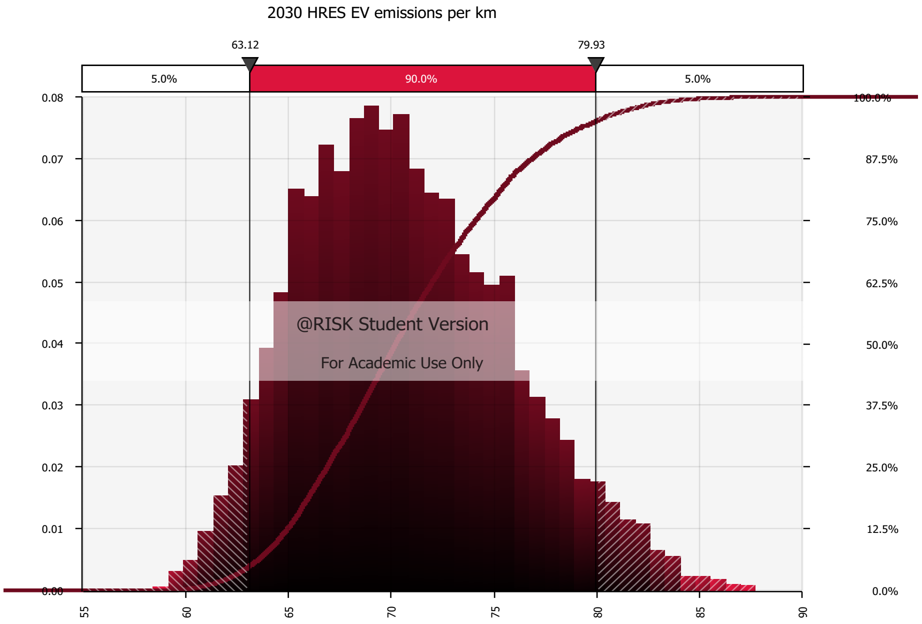

Figure 8-Probability and cumulative density function for emissions from EVs in HRES in 2030

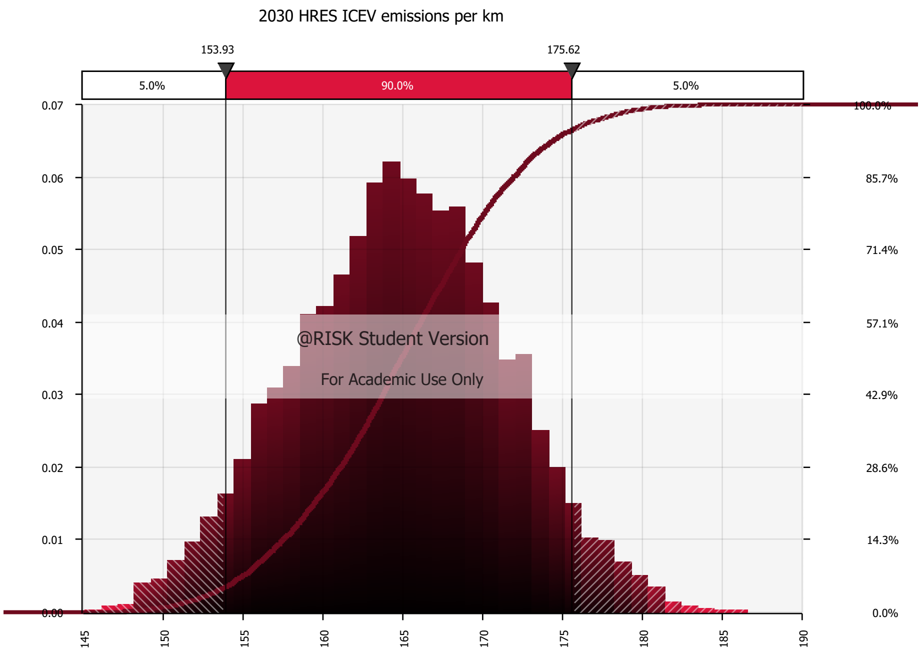

Figure 9- Probability and cumulative density function for emissions from ICEVs in HRES in 2030

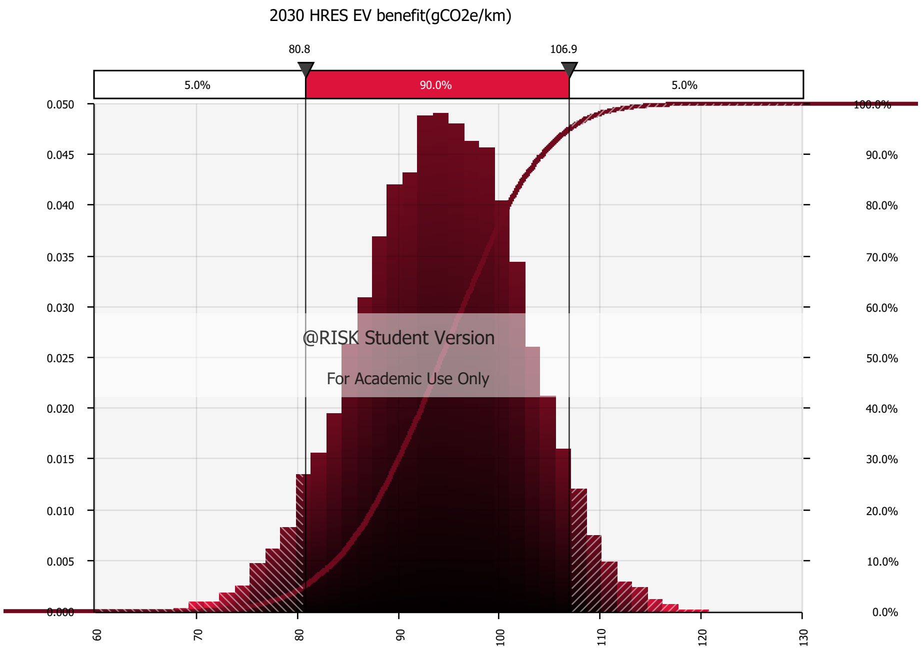

Figure 10-Probability and cumulative density functions for GHG benefit from EV in HRES in 2030

In the Current Policies Scenario (Figures 9-10), in which the electric vehicles' batteries are recycled but not reused after the vehicular life, 90% of simulation runs (5th to 95th percentile) indicated that the electric vehicle's life cycle GHG footprint would be between 116 and 151 gCO_2e/km, and that the combustion vehicle's life cycle GHG footprint would be between 155 and 175 gCO_2e/km. This means that there is some overlap in these ranges. The 5th - 95th percentile range for the GHG benefit of driving the electric vehicle is between 13 and 52 gCO_2e/km. This means that it is overwhelmingly likely that the electric vehicle will have a lower footprint than the combustion vehicle. 99.6% of simulation results in the CPS show that the EV has a lower life cycle greenhouse gas emissions profile than the ICEV.

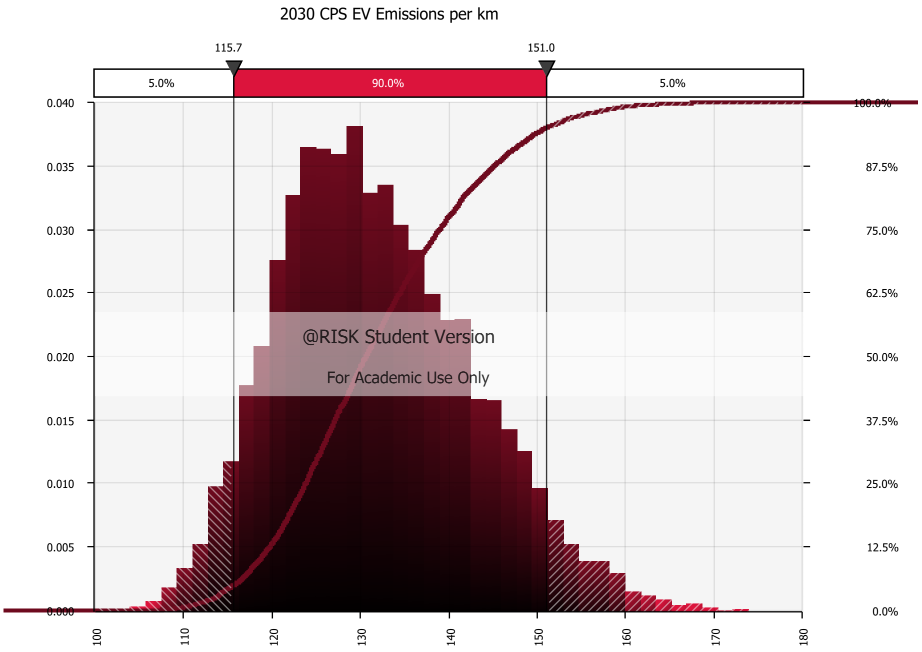

Figure 11-Probability and cumulative density function for emissions from EVs in CPS in 2030

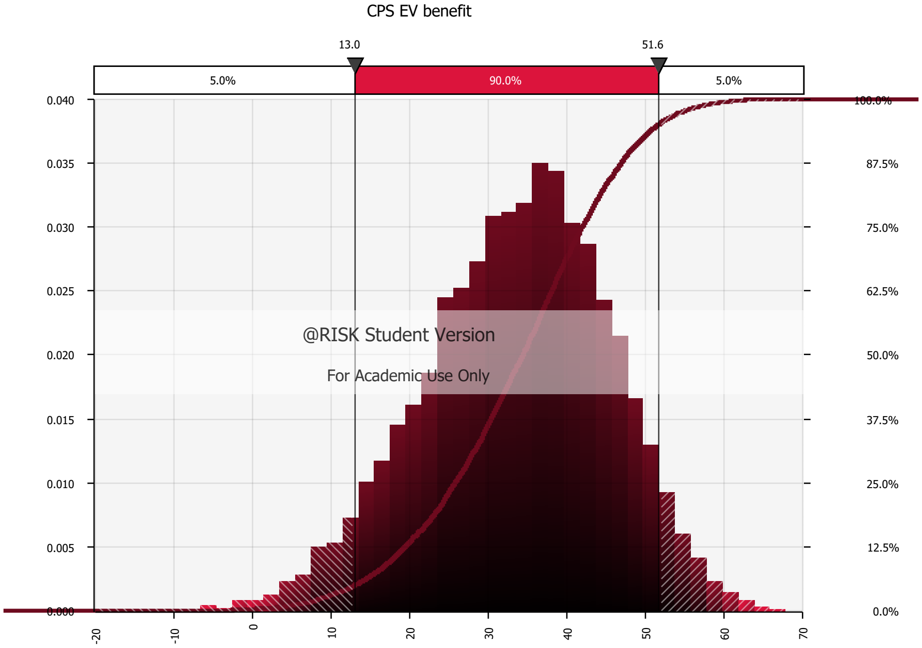

Figure 12-Probability and cumulative density functions for GHG benefit from EV in CPS in 2030

For the Current Trends Scenario (figures 11-12), 90% of simulation runs (5th to 95th percentile) indicated a life cycle GHG footprint between 127 to 166 gCO_2e/km for the electric vehicle, and 157 to 176 gCO_2e/km for the combustion vehicle. However, the electric vehicle is highly likely to have a lower GHG footprint than the combustion vehicle. The 5th - 95th percentile range for the GHG benefit of driving the electric vehicle in the CTS is between 0 and 41 gCO_2e/km, and 94.7% of simulation runs indicated that the EV has a lower life cycle GHG profile.

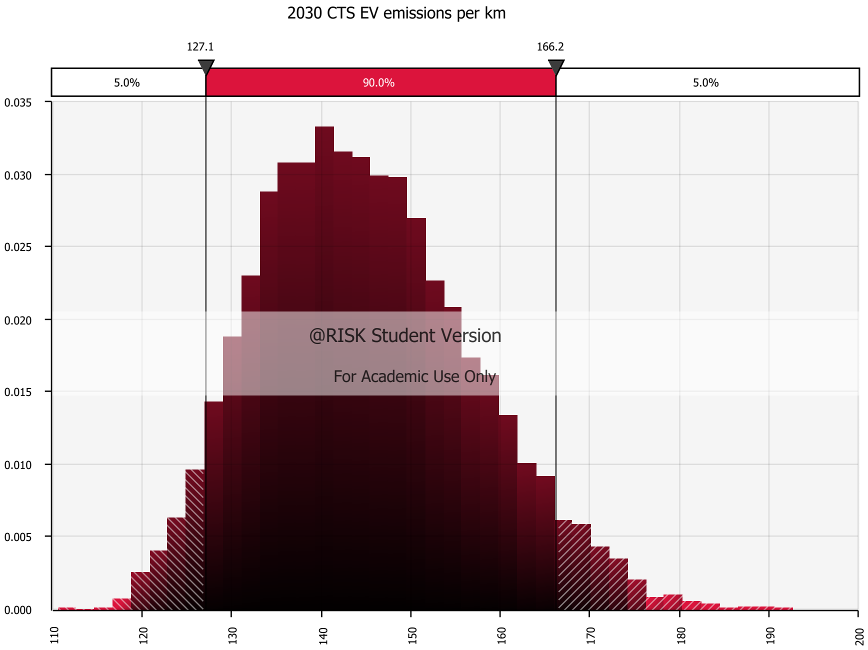

Figure 13-Probability and cumulative density function for EV emissions in CTS in 2030

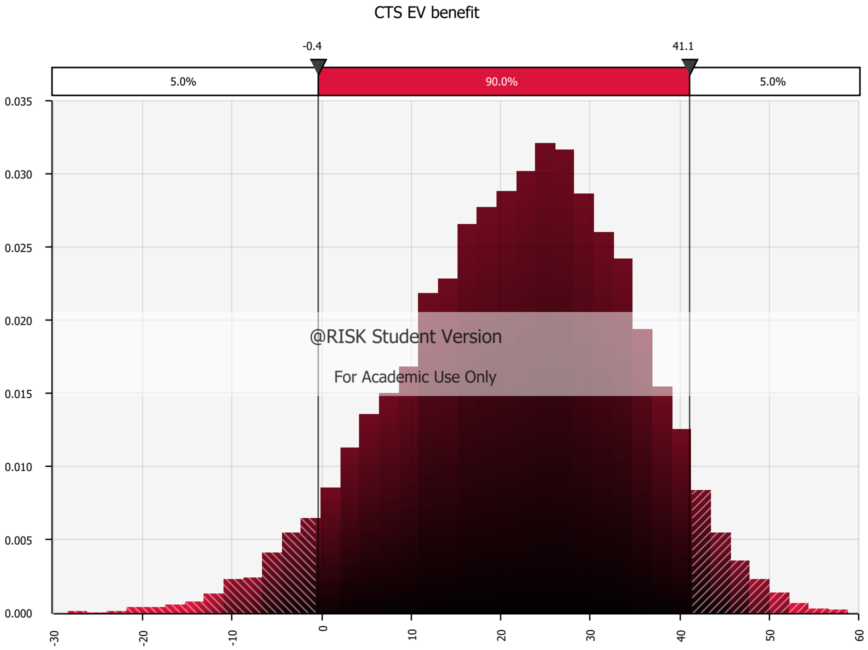

Figure 14-Probability and cumulative density functions for GHG benefit from EVs in CTS in 2030

Across all three scenarios, which have different assumptions for battery disposal and carbon intensity of electricity, there is a consistent result that EVs have a lower lifetime GHG profile than the ICEVs do. The manufacturing of EVs and ICEVs has a similar GHG profile, while EV operation is much lower in carbon intensity than ICEV. ICEV recycling enables the recovery of roughly two thirds of the manufacturing emissions, while EV recycling (without battery reuse) enables the recovery of roughly one quarter of the manufacturing emissions. If the battery is reused in the High Renewable Energy Scenario, then the 79% of the energy from the EV manufacture can be recovered, because the battery will still be used for grid storage after the vehicular life is done.

Under the uncertainty of a Monte Carlo simulation, in the Current Trends Scenario, electrification reduces emissions nine times out of twenty, in 95% of simulations. In the Current Policies Scenario, with the uncertainty of a Monte Carlo simulation, electrification reduces the emissions almost always, in 99.6% of simulation runs. Even without battery reuse and without additional investment in renewable energy, the electrification of vehicles in India is highly likely to cause a net reduction in GHG emissions. If additional renewable investments are made, and batteries are reused for grid storage after their lives in vehicles, then electrification of vehicles reduces lifetime GHG emissions without failure. This implies that electrification of vehicles is a no-regrets strategy, and that it provides an environmental benefit even if additional investments in grid decarbonization are not made. In addition, the synergies between vehicle electrification, batteries, and renewable energy are substantial, especially in the context of a carbon-intensive power grid like India’s.

Chapter 5: Discussion and conclusion

This analysis has not considered the effects of pollutants other than greenhouse gas emissions. However, since EVs operate without tailpipe emissions, inclusion of air pollution would make the use of electric vehicles even more favorable from an environmental and public health perspective. Since people and automobiles are both concentrated in cities, while power plants can be located elsewhere, electrification would reduce the health impacts of particulate and other air pollution even if it does cause an increase in coal combustion. Future work might consider the health impacts of particulate pollution and the impacts of shifting the locations where particulate pollution is emitted. This study also restricted its analysis to four-wheeler cars. Future work can expand the scope of this analysis to include information on two-wheelers, three-wheelers, trucks, and buses. In addition, this analysis also has not factored in the environmental effects of charging or fueling infrastructure.

The assumption that the vehicle components including batteries are all made in India with the average Indian power mix is a conservative one. If the batteries are made using a less carbon-intensive source of energy, or made in a place where the grid is less carbon-intensive, then the emission from the electric vehicle would be lower (Hausfather, 2019). Given the declining cost of solar energy, domestic battery manufacturers in India may elect to use solar energy rather than grid electricity. This is particularly relevant for India, because it has the world’s cheapest solar power (IRENA, 2018; Wood, 2019). In this case, the environmental benefit of vehicle electrification would increase, and the case for electrification would strengthen.

In addition, the calculation for recycling vehicles uses a fixed value for carbon intensity of the grid, which is in the range of estimates for the Indian grid’s intensity of 2030. However, a vehicle produced in 2030 would be recycled much later, and so the energy used in recycle the vehicle would be from a more advanced, and presumably less carbon-intensive power grid. This is another way that the true values for the life cycle emissions could be lower than the values presented here.

This research indicates that electric vehicles are more environmentally benign than their combustion-powered counterparts, even when charged using a carbon-intensive power grid like India's. However, the benefits are blunted by the high carbon intensity of the energy that comes from the power grid. As the grid adds renewable energy capacity and becomes less carbon-intensive, the benefits of electrification will increase further when compared to gasoline and diesel-powered vehicles.

This finding is consistent with some of the previous work that has been done on the topic of vehicle electrification in India. For example, Abhyankar & Sheppard, 2017 found that electrification of India's entire vehicle fleet would reduce GHG emissions in any scenario for India's power grid, even if it does not accomplish the goals in its Nationally Determined Contribution to the Paris Agreement.

However, this finding does contradict other findings of other studies. For example, Upadhyayula, et al. (2018) found that electrification of compact vehicles reduces emissions in any timeframe, but that electrification of subcompact vehicles increases emissions with the current grid and reduces emissions with the projected 2030 grid. For this reason, Upadhyayula, et al., argue that "lightweighting" of vehicles – reducing the weight – is the most effective strategy for reducing vehicular emissions in India.

A key new finding of this piece is that the reuse of the battery for grid storage can greatly improve the environmental outcomes of the electrification of vehicles. Our preliminary quantification of the environmental benefits of the synergy between electric vehicles, energy storage, and renewable energy suggests that it can be substantial. The EV has GHG footprint in the HRES 59% lower than its footprint in the CTS. Our methodology assumes that the energy storage will be added regardless of the presence of the EV, and that the reused EV battery displaces the need for a new battery to be built. The assumption of different counterfactual, one where the presence of low-cost energy storage would enable renewable energy to displace coal, might have led the analysis to find even greater environmental benefits for adding energy storage.

Energy storage for electricity is crucial for India to realize its ambitions to build a future without pollution and with a stable climate. This is particularly crucial because India's peak electricity demand occurs in the evening, after sunset, and so variable renewable energy, which is primarily solar energy in the context of India, cannot meet this demand unless it has access to energy storage (Tongia & Parray, 2019). If energy storage is not available, this peak demand will likely be met with fossil fuels, and most likely coal, because that is most abundant in India. For this reason, the second life batteries from electric vehicles could provide a large environmental benefit if this opportunity is realized.

As such, India should expand its efforts to electrify its transportation sector, and simultaneously add renewable energy to its power grid to maximize the benefits of this shift. In addition, it should enable the development of a second life battery supply chain so that the batteries that are at the end of their vehicular lives can be repurposed for grid storage. This will maximize the environmental benefits of this transition and enable the country to reduce its GHG footprint to the greatest possible extent, while enabling its people to enjoy the full benefits of modern energy and transportation services.

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Appendices

Appendix A - emissions data for electric and combustion vehicles

Combined LCA for electric vehicles	2018	2022	2027	2030
Current policy scenario				
Manufacture emissions (tCO2e)	11	11	10	10
Operations emissions (tCO2e)	10	10	10	10
Recycling net emissions	-3	-3	-3	-3
Total emissions (tCO2e)	19	18	17	17
Total Emissions per km (gCO2e/km)	129	122	117	117
Percent lower than ICEV	28%	28%	30%	30%
Current trends scenario				
Manufacture emissions (tCO2e)	11	11	11	11
Operations emissions (tCO2e)	11	11	11	11
Recycling net emissions	-3	-3	-3	-3
Total emissions (tCO2e)	19	19	18	19
Total Emissions per km (gCO2e/km)	135	130	128	129
Percent lower than ICEV	25%	23%	24%	23%
High Renewables Scenario with battery reuse and recycle				
Manufacture emissions (tCO2e)	8	8	7	7.25
Operations emissions (tCO2e)	10	9	9	8.07
Recycling emissions (TCO2e)	-6	-6	-6	-5.80
Total emissions (tCO2e)	12	11	10	9.52
Total Emissions per km (gCO2e/km)	83	76	71	66
Percent lower than ICEV	54%	55%	58%	60%

Combined LCA for combustion vehicles	2018	2022	2027	2030
Current policy scenario				
Manufacture emissions (tCO2e)	12.90	12.69	12.52	12.54
Operations emissions (tCO2e)	21.43	19.96	19.96	19.84
Recycling net emissions	-8.38	-8.38	-8.38	-8.38
Total emissions (tCO2e)	25.94	24.27	24.10	23.99
Total Emissions per km (gCO2e/km)	180.17	168.55	167.37	166.60
Percent higher than equivalent EV	40%	39%	43%	42%
Current trends scenario				
Manufacture emissions (tCO2e)	13	13	13	13
Operations emissions (tCO2e)	21	20	20	20
Recycling net emissions	-8	-8	-8	-8
Total emissions (tCO2e)	26	24	24	24
Total Emissions per km (gCO2e/km)	180	169	168	168
Percent higher than equivalent EV	34%	30%	32%	30%
High Renewables Scenario				
Manufacture emissions (tCO2e)	13	13	13	12
Operations emissions (tCO2e)	21	20	20	20
Recycling emissions (TCO2e)	-8	-8	-8	-8
Total emissions (tCO2e)	26	24	24	24
Total Emissions per km (gCO2e/km)	180	168	167	166
Percent higher than equivalent EV	116%	121%	136%	151%

Appendix B – Graphs of Monte Carlo simulations of ICEV emissions