The March Towards Zero-Emission Transport

To preserve life on earth by eliminating Fossil Fuels and GHG emissions

CENTER FOR EXCELLENCE IN ENERGY AND TELECOMMUNICATIONS

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Executive Summary

Background

Greenhouse gas is slowly but surely killing the life on the earth. The main culprit is the use of fossil fuels. To save life on earth, fossil fuels must go. Fortunately, technology and economics of alternate energy sources are available and favourable today to phase out usage of fossil fuels. Electricity produced from solar, and wind is now less expensive than that from fossil fuels and even the electricity storage technology is available today and costs have fallen drastically. Stage is set to make electricity fully green.

Road transport is a major consumer of fossil fuels and emitter of GHG emissions. Technologies to replace petrol (IC engine or ICE) vehicles is ready and economics is moving in favour of such battery-based electric vehicles (BEV). As the world pursues decarbonization, electrifying road transport is seen as a key strategy, yet questions remain about the true environmental impact of electric vehicles, especially when considering their entire lifecycle—from raw material extraction and manufacturing to operation and end-of-life disposal. The fact that electricity produced today is not fully Green, further complicates matter and doubts are raised whether BEVs do have more GHG emissions than that from the petrol vehicles.

Purpose of the study

The study aims to provide a rigorous, evidence-based comparative analysis GHG emissions from the petrol-powered ICEVs and BEVs, addressing the ongoing debate regarding the true environmental impact of electric vehicles across their *entire lifecycle*. Unlike previous static analyses, this study employs a dynamic model that accounts for the evolving scenarios of

(i) *increasing renewable energy integration in electricity generation and*
(ii) *enhanced recycling rates of materials*.

The primary objective is to determine if BEVs are truly a greener alternative to ICEVs, considering all stages of their existence.

Methodology

By leveraging the “Greenhouse gases Regulated Emissions and Energy use in Technologies” (GREET) model[1] for life cycle assessment (LCA) framework and incorporating India-specific data on electricity grid mixes and recycling rates, the study aims to quantify emissions from raw material extraction through to end-of-life disposal[1]. The study assumes a standardized operational lifespan

[1] Refer https://www.energy.gov/eere/greet

of 3 lakh Kms (300,000 kilometres) for both BEVs and internal (ICEVs), representing a realistic long-term usage benchmark. Special emphasis is placed on evaluating how advancements in renewable energy integration and battery recycling influence the environmental footprint of BEVs compared to ICEVs.

Key findings

1. ***Emissions from Manufacturing:*** These include mining, processing, and assembly, are strongly influenced by the energy mix and recycling rates. Without renewables or recycling, ICEV manufacturing emits about 8.66 tons of CO2e, while BEVs emit around 9.66 tons. With 100% renewable energy and recycling, these figures fall to 2.89 tons for ICEVs and 2.54 tons for BEVs.
2. ***Emissions from Operation:*** Vehicle operation clearly puts the BEVs in advantage. ICEV emits 53.84 tons of CO2e over 3 lakh Kms (300,000 kms), compared to 33 tons for a BEV with India's current 28% renewable grid, and just 0.03 tons with fully renewable electricity. This operational phase is the main driver of ICEV emissions.
3. ***Energy Efficiency:*** BEVs are significantly more energy-efficient than ICEVs, converting approximately 90% of electricity into traction energy, compared to less than 25% for petrol engines (see Section 5.4.3). This inherent efficiency further reduces the overall energy demand and associated emissions for BEVs.

Emission Source	**Scenario**	**ICEV emission (tons of CO2 eq.)**	**BEV emission (tons of CO2 eq.)**
Emissions during Manufacturing	Zero Renewables & Recycling	8.66	9.66
	100% Renewables & Recycling	2.89	2.54
Emissions during Operations (300K kms)	28% Renewables (current)	53.84	33.0
	100% Renewables	53.84	0.03

Major Insights

The findings highlight a dual-action strategy for the Original Equipment Manufacturers (OEMs) and policymakers: prioritizing grid decarbonization and investing in circular battery ecosystems. Together, these approaches establish BEVs as the most viable solution for phasing out ICEVs and significantly reducing transportation-related GHGs. The emissions profile of BEVs is highly dependent on the electricity mix used for charging—regions with a high share of renewables enable near-zero operational emissions, while even in coal-dependent areas, BEVs still outperform ICEVs due to the latter's ongoing reliance on fossil fuels.

Battery production remains the most emissions-intensive stage for EVs, primarily because of the extraction and processing of critical minerals. However, advancements in battery technology, energy efficiency, and recycling are rapidly lowering these emissions, with projections suggesting that by 2040, advanced recycling could recover up to 95% of key materials and cut manufacturing emissions by 30–40%. In contrast, ICEVs are fundamentally constrained by their carbon-intensive combustion process, with about 80% of their lifecycle emissions occurring during operation and limited potential for significant efficiency improvements.

Summary and Outlook

In summary, it is not just adopting BEVs, but also greening of electricity and adopting full recycling, that will make the earth deal with global warming. Even with the current fraction of renewables in electricity production, BEVs remain the most promising route for deep decarbonization of the transportation sector. Their environmental performance is set to improve further as advancements in technology and supportive policies continue, whereas ICEVs are fundamentally limited by their carbon-intensive nature. Strategic collaboration between the automotive industry and government will be essential to fully realize the climate and economic benefits of electrified transport.

Beyond reducing emissions, the shift to EVs is expected to drive a 20–30% increase in renewable electricity generation by 2035, strengthening the case for grid decarbonization. At the same time, the growing need to manage battery waste is accelerating innovation in recycling and reuse, fostering a circular economy for critical minerals. These interconnected developments create a positive feedback loop, where progress in one area amplifies gains in others, collectively advancing society toward greater sustainability.

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FOREWORD

Perspective of the Study

The report is a comparative study of GHG emissions from a petrol-powered passenger vehicle and a similar-sized electric vehicle. But unlike several earlier studies (refer Appendix - II), this report examines the continuously evolving scenarios of emissions as the world combats the gradual march towards destruction of life on earth due to climate change. It therefore carries out a techno-economic examination of the concurrent efforts of the world to (i) move away from fossil fuels by generating and using green electricity in all its endeavours, (ii) recycle and reuse everything to avoid piling up waste and (iii) electrification of transport, especially that of passenger vehicle. It therefore does not look at the data of only today but examines evolving scenarios over the next ten to twenty years, as technologies evolve and become economically viable, to preserve life on earth. The focus however remains on a passenger car.

Emergence of Passenger Car In 20th Century

Passenger cars emerged in the world in the late 19th and the beginning of 20th century[2]. There were some steam-powered cars, and some gasoline powered cars. But it is the electric-powered cars that dominated the early market. From around 1915 onwards, the gasoline powered cars emerged initially as a strong contender and soon eclipsed electric cars. The Electric cars of the early 20th century were too early for its time.

The Industrial Revolution had driven an unprecedented growth in the world since the latter half of the 18th century. Steam engine and Internal Combustion (IC) engine had become the motive power of the revolution and drove the growth in this early period. Electricity, the transmission of electricity on wires and the Electric Motor emerged towards the end of 19th century. But whereas gasoline was light and easy to store (and transport), the storage of electricity was expensive and bulky, and electricity could not be transmitted without wires. Energy density[3] of gasoline is almost fifty times that of any electric battery. Naturally, the gasoline powered IC engine drove the automobile industry. Though, Gasoline is a highly combustible fuel and could be easily ignited, causing safety concern, technology was used overtime to overcome this risk.

It was recognised that the gasoline vehicles polluted the environment. The air on the roads would become polluted making it difficult to breathe. Therefore, there was a strong focus on reducing emissions from these vehicles since the middle of the twentieth century. Even then the pollution became a serious concern as the density of these vehicles on the roads increased. But for a long

[2] History of the Electric Car: 1828 - 1912, from Trouve to Morrison
[3] Energy Density of some Combustibles | The Geography of Transport Systems

time, there was no convenient alternative, and the inexpensive gasoline fuel allowed these IC engine vehicles to rule.

Gasoline in IC engine vehicles were not the only culprit polluting the environment. In fact, the Industrial Revolution had exponentially enhanced the use of energy, primarily using coal, gas and oil (all fossil fuels) since the 18th century[4]. These fossil fuels were inexpensive and therefore critical to the economy. The pollution needed to be handled using technology.

The Threat of Fossil Fuels: Emergence of Post-Industrial Revolution Era

Towards the end of the 20th century, it started getting recognised that the fossil fuels were not only hurting by polluting the environment, but the Greenhouse Gas (GHG) Emissions from the fossil fuels and the resulting global warming was slowly threatening the life on the earth. The fossil-fuel based 20th century technologies needed to give way to something different.

Fortunately, towards the beginning of 21st century, several technologies emerged to counter GHG emissions and global warming. They were initially very expensive and did not make any economic sense. But R&D and Innovation since the late 20th century was slowly changing that. By the turn of century, one after another, the technologies started making commercially viable products. This happened concurrently in four areas:

(i) Electricity generated using Renewable Energy: Cost of electricity production using Solar and Wind became comparable to that from coal-based plants about ten years ago and have been falling since then. Other renewable sources of electricity, Hydro, Biomass and Nuclear were already available.

(ii) Storage: As electricity from Solar and Wind could not be generated twenty-four hours, seven-days a week, energy storage became critical, if such renewable energy generation had to match the demand. Battery Storage technologies evolved rapidly. Fortunately cost of energy storage using Li Ion batteries fell considerably over the last few years and scaled deployment of such storage with grid has started. Other chemistries are evolving, which could make even long-term energy storage commercially viable.

(iii) Electric Vehicles (EVs): technologies for EVs evolved rapidly since 2015, driven especially by emergence of inexpensive Li Ion batteries for energy storage. The costs of these vehicle are falling down every year and today compares well with that of petrol vehicles.

(iv) Reuse and Recycling technologies: Recognising that the human being on earth is generating too much waste, which cannot be naturally recycled, development of reuse and recycling technologies became an important endeavour. It is recognised today that recycling will imply that less minerals will have to be drawn out of earth (which itself uses

[4] In 18th century, the world is known to use less than 5000 TWh of energy, primarily through biomass. By the year 2000, the energy usage had increased to 120,000 TWh, with the balance coming from fossil fuels.

a lot of energy). Concepts like Zero-waste and Circular technologies became prominent and is considered today critical to make the earth sustainable for life.

Each of these developments would steer the world away from GHG emissions and the climate change. These technologies have been evolving concurrently. Progress in one gives a push to the other, even though the dynamics of each technology development is independent of the other and the effort in each area involves not only the development of technology but also making it economically viable and acceptable to user. But it is together, that they will help in containing GHG emissions. Constraining or slowing down any one of these efforts hurts takes us closer to the destruction due to climate change.

Therefore, in this report, we do not collect and analyse data on a static basis[5]; we look at the data of EVs and ICE as there is a progress in each of the following axis, (i) electricity becoming increasingly more renewable and (ii) larger and larger percentage of recycling. We will argue that the march towards EV will help us march towards greater percentage of Renewable electricity generation and larger percentage of reuse and recycling of each component that an EV uses. That alone will build a sustainable world.

There is no other place in this universe, where we know life flourishes. If we destroy this eco-system, we are committing the biggest crime and destroying ourselves. Our task is clear. Move towards hundred percent renewable electricity, recycle 100% all materials as well as electrify all transport at the earliest. Do not constrain any axis. Development on any axis will help propel others.

We end by noting that petrol-powered vehicle emits CO and CO_2 to a great extent[6], particularly in operation (the emissions during manufacturing cycle is smaller compared to that during the operation stage). The arguments to allow some of these emissions today and later fix it by capturing Carbon are ridiculous. Financially viable Carbon Capture technologies do not appear to be even on the horizon, and it would be impossible to do carbon-fixing of the scale required. STOP these emissions today. Similarly, the arguments that EVs need not be used today as electricity generated is anyway significantly based on fossil-fuels, is equally ridiculous. One would fully support the demand to move electricity generation from fossil fuels to more and more renewable sources, along with move away from petrol-vehicles to Electric vehicles.

[5] Other reports did not take this approach and presented static picture to argue in support of ICE vehicles. We think this was self-serving, serving a narrow interest of a technology that is moving towards obsolescence, while at the same time destroying the eco-system of our earth, where life has emerged and flourished.

[6] Equally ridiculous is the argument that one would reduce emissions by better IC engine or by using hybrid technologies. Why emit these gases at all, especially when alternatives are available.

CHAPTER 1: INTRODUCTION

1.1. Impact of GHG Emissions on Planet Earth

Greenhouse gas (GHG) emissions represent one of the most pressing challenges of our era, fundamentally and rapidly altering the Earth's climate in ways never observed. What was once regarded as a gradual environmental concern has now escalated into a global emergency, demanding urgent attention. Human activities—including the combustion of fossil fuels, large-scale industrial operations, and intensive agricultural practices—are releasing substantial amounts of heat-trapping gases into the atmosphere[7].

These emissions comprise carbon dioxide, methane, nitrous oxide, and fluorinated gases, the latter of which are synthetic compounds widely used in refrigeration, air conditioning, electronics, and industrial processes as shown in Figure 1.1. Although fluorinated gases are present in smaller concentrations, their global warming potential is extremely high, and they can remain in the atmosphere for decades or centuries. The cumulative effect of these gases is an intensified greenhouse effect, which disrupts the planet's natural climate regulation mechanisms. This ongoing process results in rising global temperatures, an increased frequency of extreme weather events, environmental degradation, and significant threats to ecosystems.

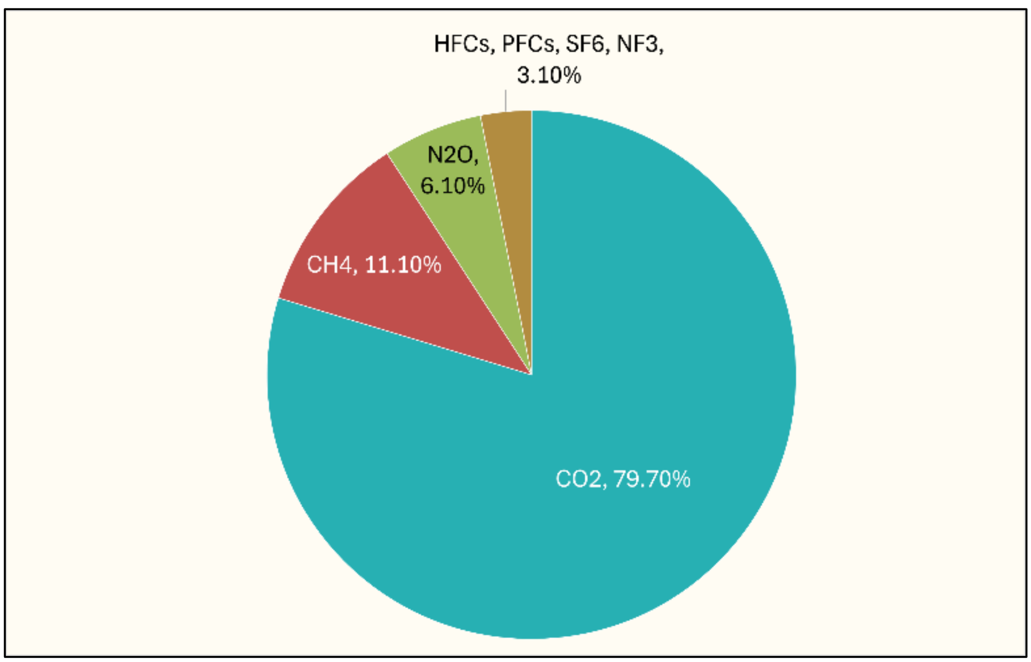

Figure 1.1. Greenhouse gas emissions by type of gas

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[7] U.S. Environmental Protection Agency. (2024). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*. Washington, DC: EPA. https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks

Communities worldwide are already experiencing the consequences through prolonged droughts, more severe storms, and rising sea levels. Addressing this crisis is no longer a matter for the future; it is an immediate imperative that requires coordinated global action. Reducing greenhouse gas emissions—including those from fluorinated gases—is essential for preserving planetary stability and securing a sustainable future for generations to come.

In 2022, total U.S. greenhouse gas emissions were approximately 6,343 million metric tons of CO_2 equivalent, excluding the land sector. Land use, land-use change, and forestry acted as a net carbon sink, offsetting about 13% of these emissions.

1.2. Combatting GHG Emissions and the March Towards Net-Zero

India has already committed that it will get to net-zero by 2070. Many other countries have promised to do this even earlier. India needs to act now to move towards its target and if possible, even earlier.

Towards this it will have to take up three major tasks (i) move usage of fossil fuel consumption today to usage of only Renewable Energy (RE)[8], (ii) use energy far more efficiently than it is done today, so that the total quantum of energy usage levels rather than continuously increase exponentially as shown in Figure 1. 2. (iii) recycle everything that we use today, so that less and less waste is generated, and minimal new mineral resources are needed.

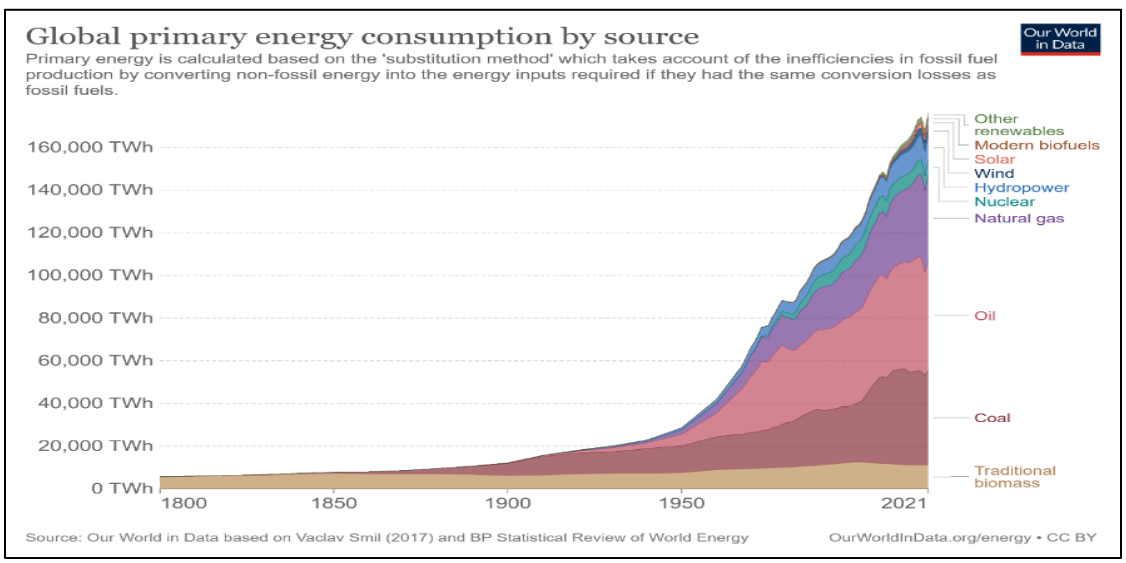

Figure 1. 2. Exponential increase in energy consumption since 1800

[8] Also considered as Green

1.2.1. Fossil Fuel a Green Energy Usage

Fortunately, Green Electricity (GE) has emerged over the last ten years to be more cost-effective as compared to the electricity generated from fossil fuels. For example, electricity generated from solar PV in India costs about ₹2[9] per kWh, and from wind is less than ₹3 per kWh; This is lower than the cost of electricity generated from coal, which is closer to ₹4.50 per kWh, when new plants are set-up with equipment for reducing emissions. The electricity production from gas is above ₹15 per kWh and that from diesel is at ₹35 per kWh. The only issue with solar and wind-based electricity is that they cannot be generated 24x7 and its output is not controllable. To match supply with demand, such electricity may require storage. Fortunately costs of large-scale Li-Ion bases grid storage has also fallen rapidly and GE even with storage for use costs less that the electricity produced form fossil fuels. Clearly, India's task is to accelerate its production of GE and where required with adequate storage.

Equally important task is to convert all direct usage of fossil-fuels to use of Green Electricity. Fossil fuel is directly used today in industry, for heating as well as for manufacturing processes, for example in steel manufacturing, cement manufacturing, aluminium manufacturing, glass manufacturing, ammonia manufacturing as well as in many chemical industries. Moving these processes to using Green Electricity is a major challenge but the technologies are fast evolving to do this. Direct use of Green Hydrogen will complement and supplement in some of these processes. Fossil fuel is used today for heating homes and offices, even though technologies to do this using green electricity exist today. Fossil fuel in used today in transport using Internal Combustion Engine (ICE). Sooner we move towards using Electric Vehicles (EVs) instead of ICE (or petrol) vehicles, faster we will move to net-zero.

1.2.2 Increasing Energy Efficiency

As shown in Figure 1. 2, the world has been increasing its energy consumption almost exponentially since the year 1800. It also shows that fossil-fuels dominate the energy usage, thus accelerating the GHG emissions. One of the reasons for this increase is a careless use of energy and using energy highly inefficiently, as the fossil fuels were very inexpensive all these years; the compulsion to enhance energy efficiency was missing. As global warming start impacting the earth, one is forced to pay attention to use energy more efficiently and not accelerate the energy usage.

A measure of energy efficiency is what percentage of total energy used is really utilised. When fossil fuel is converted to useful heat, the total heat-energy used, divided by the total energy content is fossil fuel, provides this efficiency number, also referred to as COP or coefficient of performance

[9] Throughout the report, we will use Indian rupees (₹) as currency. The current conversion rate is $1 = ₹85 approximately. All costs referred to here, assume Long-term Indian Interest rates, which is high at 10% today. This pushes up the cost considerably as compared to that in other countries, where the long-term interest rates are much lower.

for heating and cooling. 1kWh of electrical energy when used for heating will only provide 1kWh of heat with COP of 1 while the current heat pumps[10] and chiller technologies operate within a COP range of 2.5 to 4.5 under typical conditions for individual heating or cooling application. The combined COP is generally 5.0 or higher, which is well below the combined theoretical COP values of 8–10, constrained by thermodynamic limitations and real-world inefficiencies. Most heating and cooling between -100 ^{0}C and +200^{0}C can be carried out by such heat-pumps and chillers. This has not been widely used by the world, as this would cost today higher than using inexpensive fossil-fuel, even with all its inefficiency. That fossil fuel uses earth's precious resources and has GHG emissions were never considered. In other words, the artificially priced cheap fossil fuel has been source of using energy inefficiently as well as exponential rise of use of energy in the world.

The story is the same with respect to using petrol in transport vehicles. The IC engines have an energy efficiency of less than 25%[11], implying that less than 25% energy content of petrol is converted to traction energy[12]; rest is dissipated as heat. This is in contrast with energy efficiency of electric vehicles, where near 90% of electricity used or even more can be used for traction[13]. The only reason for resistance to rapid transition to EV is inexpensive fossil fuel, which drives the petrol vehicles.

1.2.3 Recycle Everything

The world is increasingly adopting use and throw culture, use and throw everything. What is thrown contains a whole range of metals, minerals and other materials. First, extracting and processing them takes energy. Secondly, thrown away, they can be a major source of pollutants. Technologies are now evolving of extracting these materials from the waste, processing it as required and reusing it. Recycling will reduce energy required as well as pollution. Sooner we adopt to recycle everything and produce ZERO Waste, better it is for the earth. The percentage of materials that are recycled and reused, should be an important benchmark for any industry. Over time, this percentage could be increased.

Combatting GHG emissions and Global warming, require choices to be evaluated as fossil fuel usage is replaced by green energy usage, energy efficiency is enhanced in all sectors and recycling starts becoming a norm.

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[10] Heat pump/Chiller is a device that works on the principle of vapour compression refrigeration, providing heating and cooling capabilities.
[11] https://doi.org/10.2478/rtuect-2020-0041
[12] There have been a few attempts in recent time to recover some of the unused energy in traction (for example during braking), store it as electric energy in a battery and use it later; hybrid vehicles do this, enhancing the overall energy efficiency to even 35%.
[13] https://doi.org/10.2478/ttt-2018-0005

1.3 Transport: A Major Fossil Fuel Consumer

Road transport is a major consumer of fossil fuel in the form of petrol and diesel. They use Internal Combustion engines (ICE) which converts petrol and diesel into motive power. Over the last hundred plus years, these vehicles have very significantly contributed to economic growth of the world, while moving people and goods within cities, towns and villages and across the country. However, today they are hurting the earth badly as (i) they are major cause of pollution, especially in the cities, (ii) use energy very inefficiently (as discussed in section 1.2.2) and (iii) contributes significantly to global warming. Sooner do these ICE vehicles disappear, better it is for the world. But what is the alternative as today they are a significant driver of economy.

There are two reasons why the ICE vehicles have grown so prominent. One is that the petrol and diesel have been inexpensive, making travel per km rather inexpensive. The second reason is that petrol and diesel, the carriers of energy, have very high energy density both in terms of weight (kWh/kg) as well as in terms of volume (kWh/litre). No other energy source come close, as illustrated in Figure 1. 3. And, the energy density, both in terms of weight as well as volume, are very important, for the vehicles must carry this energy along with passengers and goods; higher the energy it carries, longer will it be able to travel before refilling. The fact that petrol/diesel stations have been built over the years, even in the remotest areas, have made the fuel very accessible and thereby aided in the growth of ICE vehicles.

The alternative to petrol and diesel vehicles were always there, as an electric vehicle had emerged concurrent to ICE vehicle in the beginning of 20th century. But, as Figure 1. 3 shows, the problem was the battery, whose energy density (both in terms of weight and volume) was so low that energy for only a very limited travel range could be carried in the vehicle.

But as stated above, petrol vehicles area a major source of pollution, uses energy very inefficiently and significantly contributes to Global warming. So, alternatives had to be found. Work on batteries had started aggressively about forty years back and the solution emerged only about ten years back. The energy density of Li Ion batteries is far higher than that for the lead acid batteries used earlier, even though it is still a fortieth of petrol energy-density in weight terms and a tenth in terms of volume. Yet, considering that an electric vehicle uses energy 3-4 times more efficiently than petrol-engine and that energy density of Li Ion batteries was continuously increasing, Electric vehicles began a new life about ten years back. To begin with these Li Ion batteries were very expensive, and as the batteries needed to be purchased upfront along with the vehicle, the EVs were very expensive. But, as R&D and mass manufacturing started dropping the price of Li Ion batteries, the EV prices started falling. Today, depending on the kind of electric vehicle and the size of the battery used (determining the range that the vehicle will travel before recharging is required), the cost of an EV is on par or up to two times that of an equivalent petrol vehicle (not considering the long-distance trucks). Further, the operation cost of EV using electricity, is far less than that of an ICE vehicle using petrol. This has made EVs, especially 2-wheelers, three-wheelers, cars and pick-up trucks, an alternative to petrol vehicles.

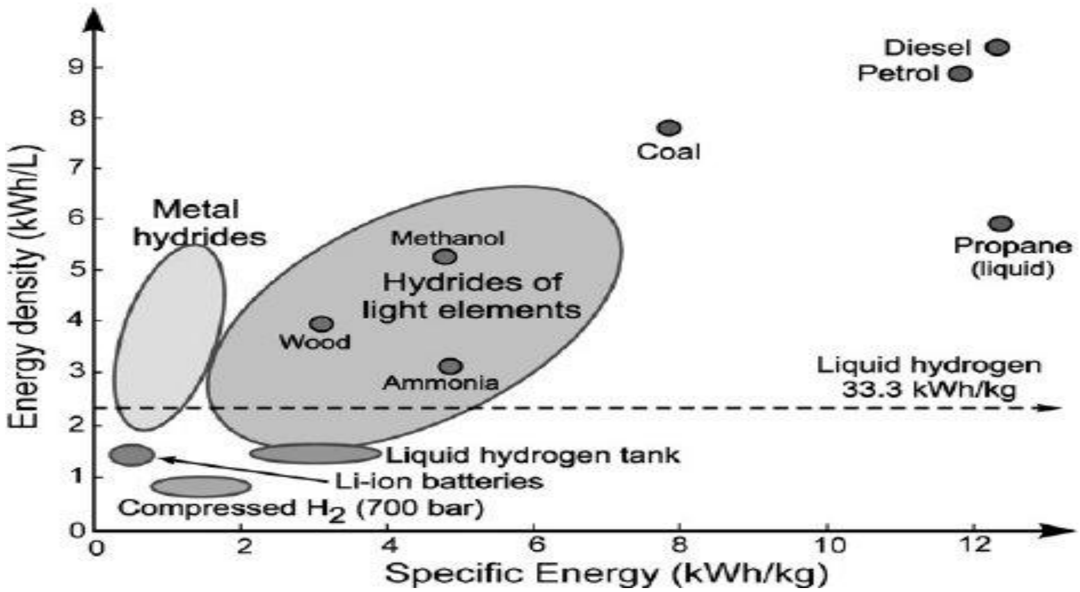

Figure 1. 3 Energy Density in terms of weight (kWh/kg) and volume (kWh/litre) of different batteries and materials used to store energy

1.4. Purpose and Approach of this Study

Even as EVs have emerged as a viable alternative to petrol vehicle for transport and can help the world in its effort to slow down and reverse the global warming, doubts continue to be raised whether EVs are really all that green as compared to the petrol vehicles. Questions are raised whether the state should indeed subsidise EVs, so that the transition from petrol vehicle to electric vehicle is accelerated. There is little doubt that EVs score high as compared to petrol vehicles, which is a major fossil fuel consumer, use energy very inefficiently, also causes tail pipe emissions and air-pollution. The questions are only about the relative GHG emissions for EVs and petrol vehicles. The questions are whether EVs is indeed as much Green as it claims, considering the GHG emissions from mining, mineral processing, manufacturing and usage, all the way from cradle to grave. This is indeed the focus of the study.

This study will examine a medium sized 4-wheeler: its petrol version and its electric version, as the march towards combatting GHG emission evolves and (a) as electricity becomes more renewable, (b) all processes are increasingly driven by electricity rather than by fossil fuel and (c) as Recycling becomes a norm.

Therefore, in this report, we do not collect and analyse data on a static basis; we look at the data of EVs and ICE as there is a progress in each of the following axis, (i) electricity becoming increasingly more renewable and (ii) increasing percentage of recycling. We will argue that the march towards EV will help us march towards greater percentage of Renewable electricity generation and larger percentage of reuse and recycling of each component that an EV uses. That alone will build a sustainable world.

1.5. Organisation of the Report

Chapter 2 of this report examined the enablers to clean energy transition. The next chapter will discuss the In-house LCA Model Development and Data Generation. Chapter 4 will provide a detailed LCA of a passenger car, its petrol version, as well as electric version, including that of a battery. The detailed results and discussion including conclusions are reported in Chapter 5 followed by the report closure in Chapter 6.

For the completeness of the report, Appendices are added. A brief presentation of direct impact of GHG emission on the earth's climate is added in Appendix I. Appendix II discusses the relevance or lack thereof, of Hybrid EVs. Appendix III provides a state-of-the-art review on life cycle assessment and transportation technology. Appendix IV provides further details on the inhouse LCA model development along with the computation and extensive data generated for the present study. The ICE vehicle manufacturing data and Basic EV manufacturing data is provided in sections (b) and (c) of this Appendix IV Section (d) provides the LFP Battery Manufacturing data, and the section (e) combines the data of Basic EV and the LFP Battery.

CHAPTER 2: ENABLERS TO CLEAN ENERGY TRANSITION

2.1. The Case for Clean Energy

This report examines the GHG emissions in equal sized petrol vehicle and battery electric vehicles (BEVs). But as stated in the introduction, this comparison is carried out in midst of the broader global shift toward sustainable and clean energy systems in the context of urgent climate goals, technological advancements, and the evolving energy landscape. To fully realize the potential of clean technologies, it is essential to understand the foundational elements—*enablers*—that support and accelerate the clean energy transition. This chapter is all about these enablers.

These enablers span across robust infrastructure development, supportive policy and regulatory frameworks, resilient supply chains, skilled workforces, and the mobilization of finance, all underpinned by international collaboration. Together, they form the backbone of an energy system capable of integrating renewables and electrified transport at scale, driving economic growth, job creation, and environmental stewardship [1]. In this chapter, we therefore explore these critical enablers of clean energy, setting the stage for a just and effective transformation of our energy and mobility systems.

2.2. The Critical Imperative: Phasing Out Fossil Fuels to Reduce GHGs

Global fossil fuel carbon dioxide emissions are projected to reach a record 37.4 billion tonnes in 2024, up 0.8% from the previous year, with total CO_2 emissions—including those from land-use change—expected to hit 41.6 billion tonnes [2]. Leading scientific bodies, including the IPCC and International Energy Agency warn that to limit global warming to 1.5°C, the vast majority of fossil fuel use must be phased out by 2050, with emissions needing to peak by 2025 and decline by half by 2030 [3][4]. These alarming trends underscore the urgent need to transition completely from a fossil fuel-based economy to one powered by clean, renewable energy.

Despite ample evidence demonstrating the significant role of fossil fuels in greenhouse gas emissions, there remains considerable hesitation to transition from fossil fuel-powered vehicles to cleaner, electricity-based alternatives [5]. The shift from fossil fuels to clean energy is hindered by high upfront costs, entrenched fossil fuel infrastructure, and concerns about renewable energy reliability and storage. Social and economic challenges, like job losses in fossil fuel industries and low public awareness, also contribute to resistance. Political inertia and lobbying from the fossil fuel sector further slow the transition.

Sugarcane ethanol blending with gasoline reduces the GHGs and fossil fuel use, they come with trade-offs like land use changes, water impacts, and potential increases in certain pollutants [6]. Sustainable sourcing and production practices are key to maximizing their environmental benefits.

2.3. Clean Energy Surge: Investments, Policies, and Innovation

Over the past few years, the narrative supporting the transition to clean energy has shifted significantly, driven by technological, economic, and policy developments. Clean energy investments have surged, with 2024 marking the first year that solar photovoltaic investment ($500 billion) surpassed all other generation sources, and battery storage investment exceeded $50 billion, reflecting rapid cost declines and growing market confidence [7]. Major economies have adopted new industrial strategies and policies—such as the U.S. Inflation Reduction Act [8] and the G7's commitment [9] to end public support for unabated fossil fuels—to spur clean energy manufacturing, innovation, and deployment. The rapid growth of cleantech manufacturing, artificial intelligence, and carbon management industries has generated an unparalleled need for dependable, 24/7 clean energy, which is driving the accelerated adoption of renewable power sources. Social and financial attitudes have shifted, with the energy transition increasingly viewed as an essential and advantageous technological advancement. Rather than being perceived as an expensive obligation, it is now recognized as a driver of economic competitiveness, job creation, and greater resilience.

2.4. India's Commitments to Net Zero – Tackling Vehicular Pollution

India set a target to achieve 50% of its installed electricity capacity from non-fossil fuel sources by 2030 as part of its commitments under the Paris Agreement. In July 2025, the Government of India announced that this ambitious goal had been met five years ahead of schedule. As of mid-2025, non-fossil fuel sources—including renewables, large hydro, and nuclear—constitute half of India's total installed power generation capacity of 242.8GW, highlighting rapid progress in clean energy deployment [10].

The economic and health costs of greenhouse gas emissions from vehicular pollution in India are significant. Vehicles are responsible for about 8–12% of the nation's total GHG emissions, with road transport alone contributing 12% of India's energy-related CO_2 emissions and generating roughly 147 million tonnes of GHGs from passenger vehicles in 2023 [11]. The overall economic burden of air pollution—including that caused by vehicles—surpasses $150 billion annually[14], representing nearly 3% of India's GDP. Health impacts are also severe, with air pollution-related health costs estimated at around $12 billion in 2019 [12]. Furthermore, premature deaths and illness linked to air pollution led to economic losses of approximately $36.8 billion each year, or about 1.4% of GDP [13] in the same year. These numbers underscore the pressing need to shift toward cleaner transportation to reduce both environmental harm and economic losses. Fortunately, Battery Electric Vehicle (BEV) technology is now available and provides a path forward for not only tackling

[14] https://health.economictimes.indiatimes.com/news/industry/air-pollution-2nd-biggest-health-risk-in-india-annual-economic-cost-over-usd-150bn-report/90412222

vehicular pollution but also help in overcoming climate change. This report will compare these BEVs with ICE Vehicles. Today, a section of manufacturers of petrol vehicles have come up with a whole variety of new type of vehicles called hybrids. They come in different forms and called mild-hybrid, strong hybrid and plug-in hybrids. These vehicles continue to use fossil fuels and therefore continue to pollute immediate environment and contribute to GHG emissions. They are here to create a confusion and claim to be fake EVs. They will not be therefore discussed in the report. The issue of hybrids is instead presented in an Appendix II along with a series of articles.

2.5. Vehicle Manufacturing - GHG Footprint of Materials

Vehicles are significant user of Copper, Aluminium, and battery-specific minerals like Lithium, Nickel, Cobalt, Graphite, and Manganese. Furthermore, some vehicles incorporate rare earth elements in their motors. We examine here whether these materials can be recycled and reused, rather than extract it from mines each time and what would be the impact on GHG emissions, if they are recycled.

2.5.1. Copper and Aluminium

Global average GHG emissions for primary copper production are approximately 1.1–8.5 tonnes of CO_2e/t of copper and that of aluminium production is 19.63 tonnes of CO_2e/t of aluminium. Using renewable energy (e.g., solar, wind) in the production of Copper and Aluminium significantly reduces greenhouse gas (GHG) emissions to 1–3 tonnes of CO_2e/t of copper and 17.67 tonnes of CO_2e/t of Aluminium when compared to fossil fuel-based production (e.g., coal, natural gas). Further, recycled metals bring down the GHG emissions significantly in comparison to virgin metals [13][15][16] as shown in Figure 2. 1.

Recycling the metals has a marginal (up to 10%) cost benefit for both Copper and Aluminium since there is still some refining to be done. In Renewable energy favoured economies (wind, solar, geothermal as main sources E.g., Norway), cost savings of upwards of 20% is possible [17]. On the other hand, for countries transitioning into renewable energy, there may be a preliminary increase in cost (up to 20%) to produce these metals.

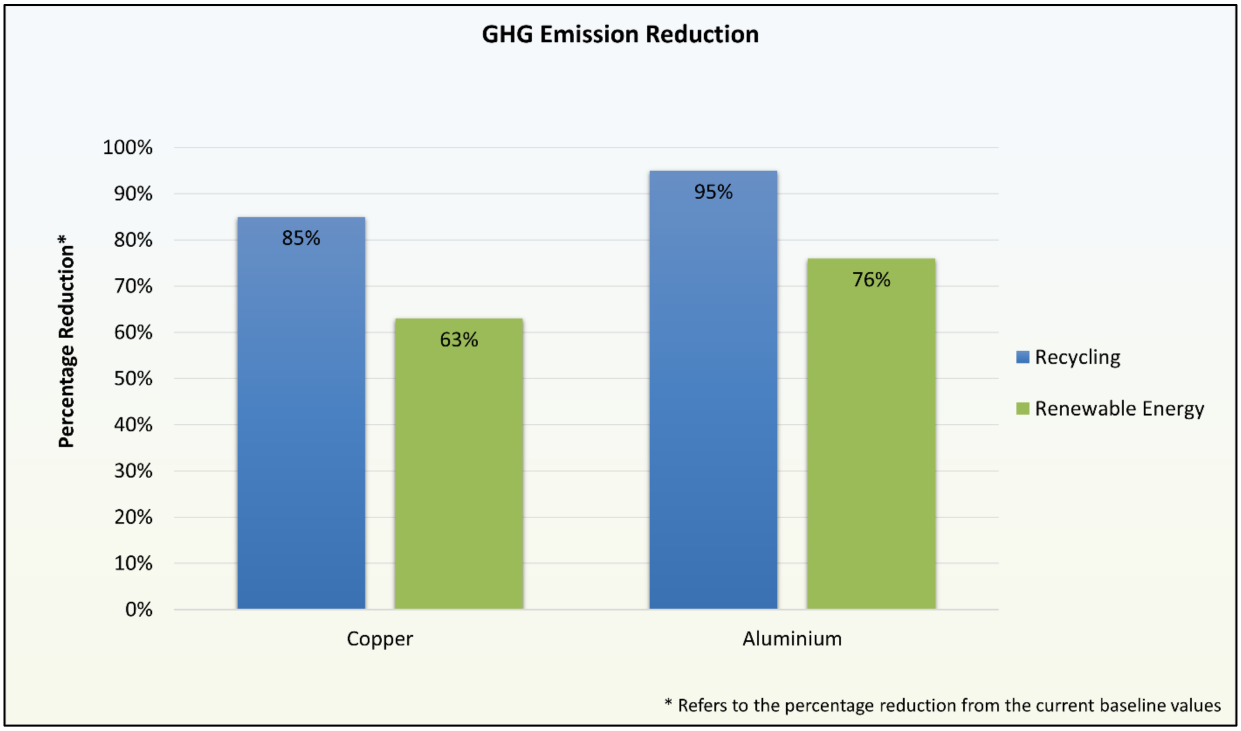

Figure 2. 1. GHG reductions under two independent considerations: a) Recycling b) Renewable Energy

2.5.2. Steel

Iron and Steel uses is significant (up to 50%) in all vehicles. As per the as per Ministry of Steel Annual Report (2022-23) [18], India is actively promoting the use of renewable energy in the steel sector as part of its broader decarbonization and “Green Steel” initiatives. This includes incentives for adopting renewable energy and mandates for government agencies to procure green steel, which is defined by lower emissions and higher renewable energy use in production. The report highlights the need for dedicated renewable energy supply, especially for Electric Arc Furnace (EAF) and Induction Furnace (IF) units (Figure 2. 2).

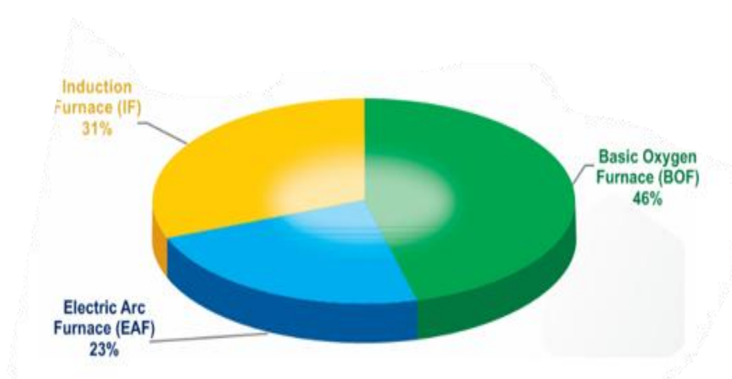

Figure 2. 2. Crude steel production by process route

This approach aims to significantly reduce indirect (scope 2) emissions by replacing grid electricity—often coal-based—with renewable power.

2.5.3. Battery - Lithium Iron Phosphate (LFP) Example

For a typical LFP battery manufacture, raw materials include lithium, iron, phosphate, graphite, copper, and aluminium. The cradle-to-gate greenhouse gas (GHG) emissions associated with LFP battery production are approximately 60-70kg [19] Carbon dioxide equivalent (CO_2 eq.) per kWh. Electricity consumption during manufacturing accounts for 39.71% of GHG emissions in LFP production. Assuming that shifting to 100% renewable energy (solar, wind) or nuclear power for manufacturing processes, can reduce emissions by today, instead of 2050 target. Cathode materials (27.85% of emissions) and anode materials (18.46%) are energy-intensive due to high-temperature synthesis [20]. Innovations like dry electrode manufacturing (used by Dragonfly Energy) [21] reduce energy use by 71% and carbon footprint by 9% during production.

In addition to their reduced greenhouse gas (GHG) footprint—typically around 54–55kg CO_2eq/kWh, which is about 30% lower than that of nickel-based lithium-ion batteries—innovative recycling processes such as the direct cathode recycling method can further decrease both environmental impact and manufacturing cost for LFP batteries. Direct cathode recycling, also known as "cathode-to-cathode" or "re-lithiation," preserves the original structure of spent cathode materials, enabling them to be directly regenerated into new battery-grade cathodes. This process avoids the intensive steps required in hydrometallurgical or pyrometallurgical recycling, resulting in significant energy savings and less material degradation. Studies suggest that the cost of direct regeneration can be reduced to as low as $2.10 per kilogram of spent LFP cell, compared to $3.40 and $2.40 for pyro- and hydrometallurgical methods respectively. This translates into manufacturing cost reductions of at least 20% [22]

2.6. Outlook for Vehicle Manufacturing

As captured in the previous section, several areas of vehicle manufacturing can be further optimized by including renewable energy and recyclability. By integrating renewable electricity into the manufacturing process and maximizing the use of recycled materials, vehicles can achieve significant reductions in both production costs and cradle-to-gate greenhouse gas emissions. Studies show that electricity accounts for a substantial portion up to 39% of the emissions from battery manufacturing, so shifting electricity to renewables can dramatically lower the carbon footprint of vehicles [23].

Additionally, the development of closed-loop recycling systems enables the recovery and reuse of critical battery materials, further decreasing reliance on primary raw materials and mitigating associated environmental impacts [24]. These strategies not only support the economic viability of vehicles by stabilizing material costs and reducing supply chain risks, but also enhance their environmental benefits compared to internal combustion engine vehicles. As a result, the combined adoption of renewable energy and advanced recycling practices positions vehicles as a more sustainable and cost-effective solution for the future of transportation **Error! Reference source not found.**.

2.7. Emerging Technologies

Emerging technologies are driving significant reductions in the lifecycle emissions of lithium-ion batteries with pioneering innovations across extraction, recycling, second-life use, and manufacturing [26-32]. An outlook on some of the prospective technologies are discussed herein.

2.7.1. Mining Electrification

A promising technology to reduce emissions from lithium mining operations include novel battery-powered mining vehicles. Electrification of mining equipment is hindered due to limitations in battery capacity and the need for redesign of existing charging infrastructure and mining trucks to cope with the operational needs. Despite these bottlenecks, pilot programs are being initiated across the globe. For instance, in 2024, Fortescue signed a $2.8 billion deal with Liebherr for 475 zero-emission mining machines in Western Australia, while BHP and Rio Tinto are testing battery-electric haul trucks with Caterpillar and Komatsu in the Pilbara region [33].

2.7.2. Lithium extraction

Electrochemical extraction from geothermal brines offers substantial greenhouse gas (GHG) savings and significant reductions in water and land use compared to conventional lithium methods. This process, powered by geothermal electricity in a closed-loop system that reinjects brine, can reduce water use to as low as 24.8 Liters of freshwater per kilogram of lithium hydroxide produced and decrease battery lifecycle GHG emissions by up to 47%. It requires about 1.4 acres of land per 1,000 metric tons lithium carbonate equivalent (LCE), markedly less than the 65–115 acres needed for traditional methods [34]. Similarly, absorption-based direct lithium extraction (DLE) methods demand minimal land and water, using roughly 1.4 acres and 20–80 million gallons of water per 1,000 metric tons LCE—much less than the over 550 million gallons needed for solar evaporation. These DLE processes emit about 1.5 million kg CO_2 per 1,000 tons LCE, which is under one-third of traditional brine extraction emissions and only a tenth of those from hard rock mining, demonstrating significant reductions in land, water, and GHG emissions [35] [36] [28]. Geothermal lithium extraction, utilizing existing geothermal plants with no additional land and a closed water loop, uses about 20 million gallons of water per 1,000 metric tons LCE with a 1.4-acre land footprint. When powered by renewable geothermal energy, it is considered carbon neutral, with battery lifecycle studies estimating over 47% GHG savings and lithium yields exceeding 95% compared to conventional techniques [37].

2.7.3. Novel battery and manufacturing technologies

New technologies such as solid-state batteries [38], combined with greener manufacturing processes like dry electrode production and AI-driven optimization, are further reducing energy consumption and environmental impact. Solid-state batteries utilize solid electrolytes that enhance safety, energy density, and longevity while minimizing the use of volatile and hazardous materials. Dry electrode manufacturing eliminates the need for toxic solvents and energy-intensive drying steps. Nearly half (around 47%) of a conventional cell manufacturing plant's total energy goes just to drying and solvent recovery. By eliminating these steps, dry electrode production can reduce the carbon footprint of cell manufacturing dramatically [39] [40]. Artificial intelligence accelerates materials discovery, fine-tunes manufacturing parameters, and improves battery design to boost performance and sustainability. Together, these advances are driving the battery sector toward a more sustainable, circular economy by enabling cleaner production, longer-lasting batteries, and improved resource efficiency.

2.7.4. Second-life applications

Repurposing used EV batteries for stationary energy storage gives it a second-life thereby reducing waste. Used EV batteries, which still retain up to 80% of their capacity, are increasingly repurposed for stationary storage in renewable energy or grid-support systems. European leaders like Fortum [41] are at the forefront, partnering with automakers to give batteries a valuable second life, further reducing environmental impacts. At IITM research park, we have deployed a stationary battery energy storage system of 46kWh capacity as an UPS system to power the Office space in the unlikely power cut or grid shutdown. This is completely built out of the end-of-life batteries from electric bus and being operational for 3 years now.

2.7.5. Advancements in battery recycling

Direct recycling is expected to grow significantly, achieving up to 95% material recovery while consuming substantially less energy by preserving the structural integrity of battery components [42]. Emerging eco-friendly alternatives to traditional hydrometallurgy include deep eutectic solvent (DES) solvometallurgy and microbial bioleaching, which reduce chemical use and environmental impact [43].

Venture capital investment in battery recycling startups, including companies like Ascend Elements [44], has reached approximately $1 billion annually, highlighting growing industry confidence and innovation [45].

2.8. Next Step – Development of Comprehensive Model

Having explored the key enablers that underpin the transition to clean energy, it is evident that technological innovation, supportive policies, and robust infrastructure collectively set the stage for meaningful progress in sustainable world. However, to truly assess the environmental benefits of such advancements, especially in the context of mobility—it is essential to move beyond theoretical enablers and examine real-world impacts. In the next chapter, we turn our attention to a detailed analysis of lifetime GHG emissions from IC engine vehicle and a battery electric vehicle. By developing a comprehensive model, we aim to quantify and compare the environmental footprint of petrol and electric vehicles, providing a data-driven foundation for evaluating the effectiveness of clean energy solutions in the transport sector.

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CHAPTER 3: IN-HOUSE LCA MODEL DEVELOPMENT AND DATA GENERATION

3.1. Introduction

Having discussed the Enablers of the Clean Energy transition in the last chapter, we proceed with the task of determining the life-time emissions of petrol and electric vehicles. Towards this, we first undertake the task of building a model, which will help us to determine the lifetime emissions of any vehicle. The development of the model will be the subject matter of this Chapter.

Life Cycle Assessment or LCA is a systematic procedure utilized to evaluate the potential environmental impacts of a product, process, or service throughout its entire life cycle, ranging from raw material extraction to production, distribution, use, to end-of-life disposal or recycling [1]. Through analysis of all phases, often called "cradle to grave", LCA provides a comprehensive understanding of how a product interacts with the environment. This includes not only direct emissions and resource utilization in use and production, but also the upstream impacts via suppliers and downstream impacts of treating and recycling waste. The analysis involves an intensive listing of all relevant energy and material inputs, with associated emissions to the environment such as air, water, and land. This input and output are then analysed to approximate the potential effects across categories of climate change, resource use, and human health. LCA operates by standards established internationally, specifically ISO 14040 [1] and 14044 [2], that identify its four central phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

The final goal of LCA is to enable more sustainable decision-making by determining possibilities to lessen harmful environmental impacts, prevent burdens between life cycle phases, and enhance the sustainability of products and services. This section outlines the goals and scope of the assessment conducted, along with the inventory analysis and methodology developed.

3.2. Stages and Boundaries in Transportation LCA

One of the most important elements of LCA methodology is the determination of suitable system boundaries under different stages of the life cycle. For technologies in road transport, several system boundary definitions emerge across different studies, as follows:

3.2.1. Cradle-to-Gate (C2G)

Cradle-to-gate boundaries define the scope of a life cycle assessment by including all processes from the extraction of raw materials up to the point when the vehicle leaves the manufacturer’s facility but excluding both the use phase and end-of-life treatment. This boundary begins with raw material extraction and processing, which involves sourcing materials such as steel, aluminium, lithium, cobalt, and rare earth metals through mining and refining activities. These processes are energy-intensive and can lead to significant environmental impacts, including habitat destruction, water and soil pollution, and the generation of hazardous waste. The next stage is the transportation of these raw materials to manufacturing sites, which contributes further to the environmental footprint through fuel consumption and associated emissions. Finally, vehicle manufacturing and assembly involve transforming raw materials into components and assembling them into complete vehicles, thus, C2G phase emission can also be referred as manufacturing emission.

3.2.2. Well-to-Wheel (W2W)

Well-to-Wheel boundaries focus on the entire life cycle of the energy source, during its use in powering the vehicle. Encompasses the energy use and emissions during vehicle operation, electricity generation (in case of EVs), efficient conversion of stored energy into movement, and the emissions produced at the tailpipe, thus can also be known as tailpipe emissions.

3.2.3. End-of-Life (EOL)

End-of-life boundaries in a vehicle's life cycle assessment encompass all processes that occur once the vehicle is no longer in use. This stage includes dismantling and disassembly, where the vehicle and its components, such as batteries, are carefully taken apart to separate valuable or hazardous materials. Following disassembly, recycling processes are implemented to recover reusable materials like metals, plastics, and battery components. Non-recyclable components are directed to landfills for disposal, while incineration may be used where applicable, especially for materials that cannot be recycled or reused.

3.2.4. Cradle-to-Grave

The complete boundary incorporates all three prior boundaries [C2G, W2W, and EOL] to offer a holistic view of environmental effects across the whole life cycle. This can allow for the full comparison of various transportation technologies and is progressively becoming more widely accepted as the norm for policy-directed LCA research.

Figure 3. 1 illustrates the system boundary for transportation technology, showing all processes from raw material extraction through end-of-life management.

3.3. Key Assumptions and Sensitivity Analysis

Life Cycle Assessment (LCA) is based on a bunch of key assumptions that influence the outcome significantly. One such assumption is vehicle lifetime distance, which is taken to be 3 lakh Kms (300,000 kms) after which the vehicle is considered obsolete. The other important assumption has been the replacement of the vehicle battery after 8 years of vehicle operation. Also, the processes involved in vehicle manufacturing and electricity generation are assumed to remain consistent across different locations. Therefore, the existing procedures for these activities have not been altered.

Beyond these baseline assumptions, the LCA also examines how changes in various parameters can alter its outcomes. Notably, the proportion of renewable energy used in the energy mix and the percentage of materials that are recycled are crucial factors in assessing the sensitivity of the study. It is important to mention here that the recycled materials only include the materials that can be recycled.

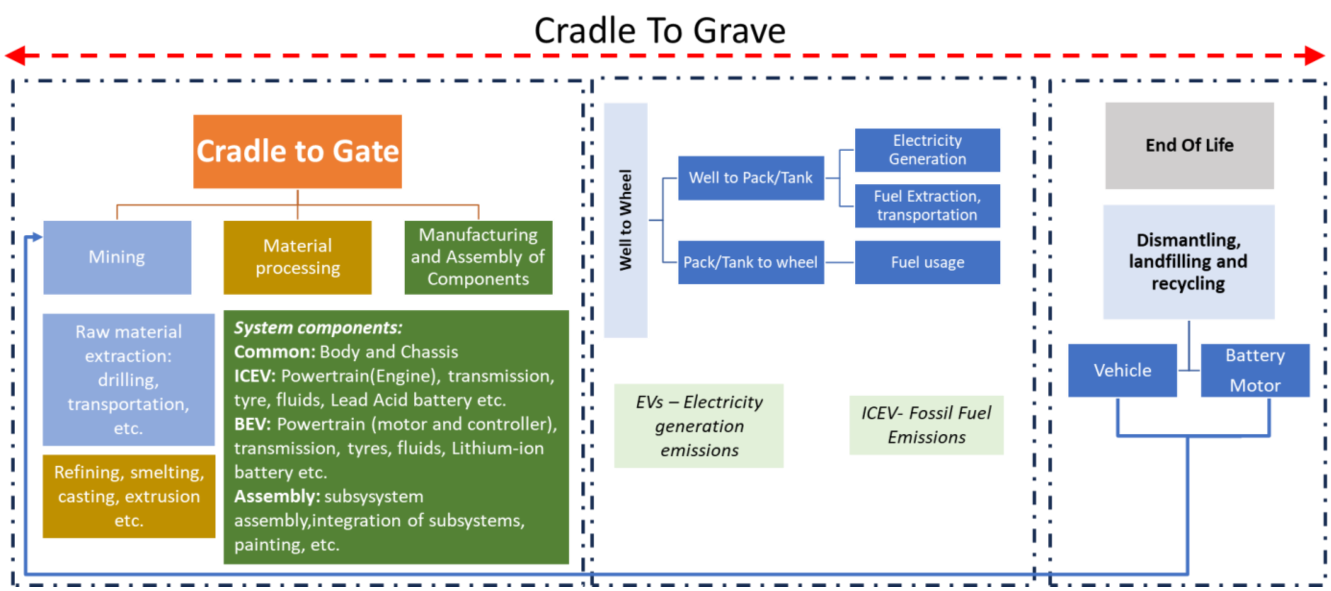

Figure 3. 1. LCA Stages and System Boundaries for transportation technology

3.4. Model Development

The above model, while deemed complete from Cradle to Grave, does not consider the evolving scenario, especially as electricity becomes increasingly renewable and recycling and recovering materials increase. We therefore created this new model, incorporating both recycling and renewable energy, as shown in Figure 3. 2. Taking cognizance of the state-of-the-art review on LCA of transportation technology (refer Appendix - III), the major pitfalls of the earlier studies are identified below

1. Input data is obsolete, only few data sources are India specific, origin of data is unknown in many cases.
2. Only a few studies reported LCA of whole vehicles while others focus on subsystem or component level
3. Earlier studies are non-comprehensive and unsustainable as they overlook the impact of combined recycling and renewable energy scenarios

Thus, the uncertainties in input data inventory, and non-comprehensiveness make the earlier LCA outcome questionable. The new model along with the well-built and reliable data inventory (Section 3.5) facilitates a comprehensive LCA and makes the outcome more reliable.

To ease with the present study on comparative GHG assessment, the proposed model is structured into two major phases: the manufacturing phase (cradle to gate) emissions and the on-road (use phase) emissions. The manufacturing phase for ICEVs focuses on emissions from material extraction, component production, and vehicle assembly. For BEVs, the manufacturing phase is further divided into two critical components: the vehicle itself and the battery. The battery production stage is particularly significant due to its high GHG emissions, largely stemming from energy-intensive processes and the sourcing of critical raw materials.

Figure 3. 3 showcases the step-by-step procedure used in the LCA assessment. The total GHG emissions during the manufacturing of ICEVs and BEVs shall be assessed separately using the GREET model[15]. It may be noted that GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) is a comprehensive life cycle analysis tool developed by the U.S. Department of Energy to assess the environmental impacts of various energy and transportation systems. At the outset, vehicle specifications such as weight and type shall be extracted from the OEM brochure. Next, an equivalent vehicle model can be selected from the GREET model [3] that corresponds to the chosen vehicle for LCA. This vehicle model shall be used as a reference to calculate the mass of individual components (e.g., chassis, engine, electronics) within the vehicle. Replacements for wear-prone parts over the vehicle's lifetime can be assumed and added to the vehicle component s overall weight, ensuring the total weight reflects real-world usage patterns.

[15] For further details, refer Appendix IV. b and IV. c.

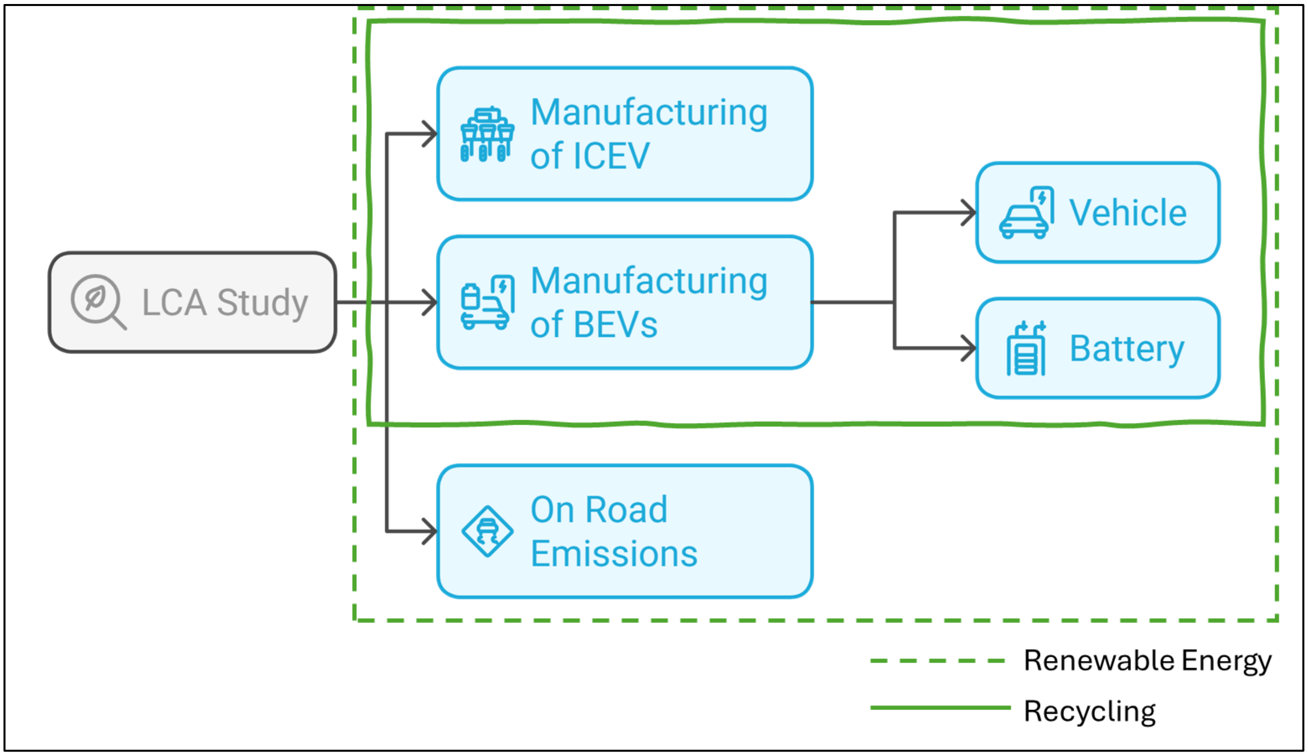

Figure 3. 2. In-house LCA Model for GHG emissions from different phases of transportation technology, with specific considerations to both renewable energy and recycling

Battery production emissions may be derived from dedicated literature [4], accounting for material extraction, cell manufacturing, and pack assembly.

For ICEVs, tailpipe emissions shall be computed using fuel efficiency metrics and total fuel consumption over the vehicle's lifetime. Finally, the net GHG emissions aggregate manufacturing (including replacements) and use-phase impacts, enabling comparisons across varying recycling and renewable energy scenarios.

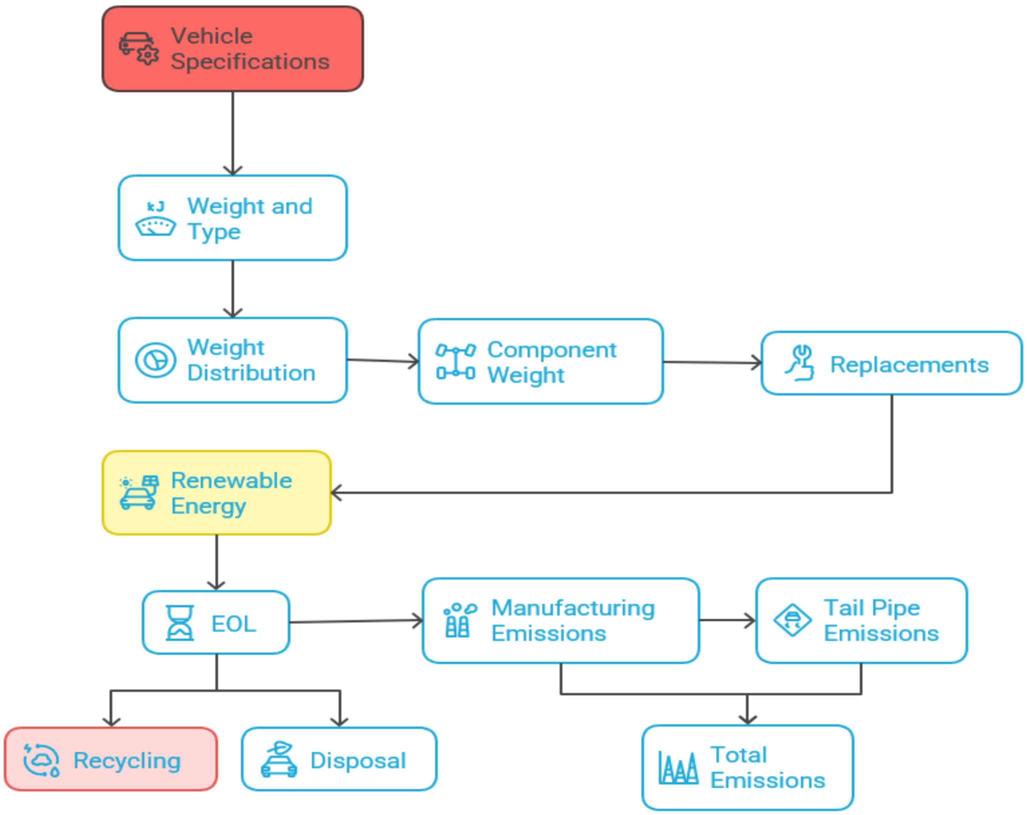

Figure 3. 3. Step-by-step procedure to conduct an LCA study

3.5. LCA Data Inventory

The inventory structure for the proposed LCA model is organised into four key modules, as illustrated in Figure 3. 4.

1. The first module, "Vehicle (OEM)," gathers essential vehicle specifications, including vehicle lifetime, fuel efficiency, battery specifications, and overall vehicle weight. These parameters, highlighted in light blue, serve as foundational inputs for the assessment.
2. The second module, "Vehicle model selection," integrates user-defined data such as replacement schedules and leverages an established database (GREET) to determine component composition, emissions per component weight, and specific emissions for battery weight. Inputs in this section are colour-coded to distinguish between user-defined (pink), GREET database (grey), and battery-specific (blue) data.
3. The third module, "Electricity mix," incorporates country-specific generation capacity distribution for each energy source (shown in green), ensuring that the emissions associated with electricity use in manufacturing and vehicle operation reflect the regional context (e.g., CEA, India, 2025).
4. The final module, "Outcomes," compiles results on emissions from vehicle manufacturing, tailpipe emissions, and total greenhouse gas (GHG) emissions, marked in orange.

This structured inventory enables a transparent and comprehensive LCA, facilitating accurate quantification and comparison of emissions across different vehicle technologies and scenarios.

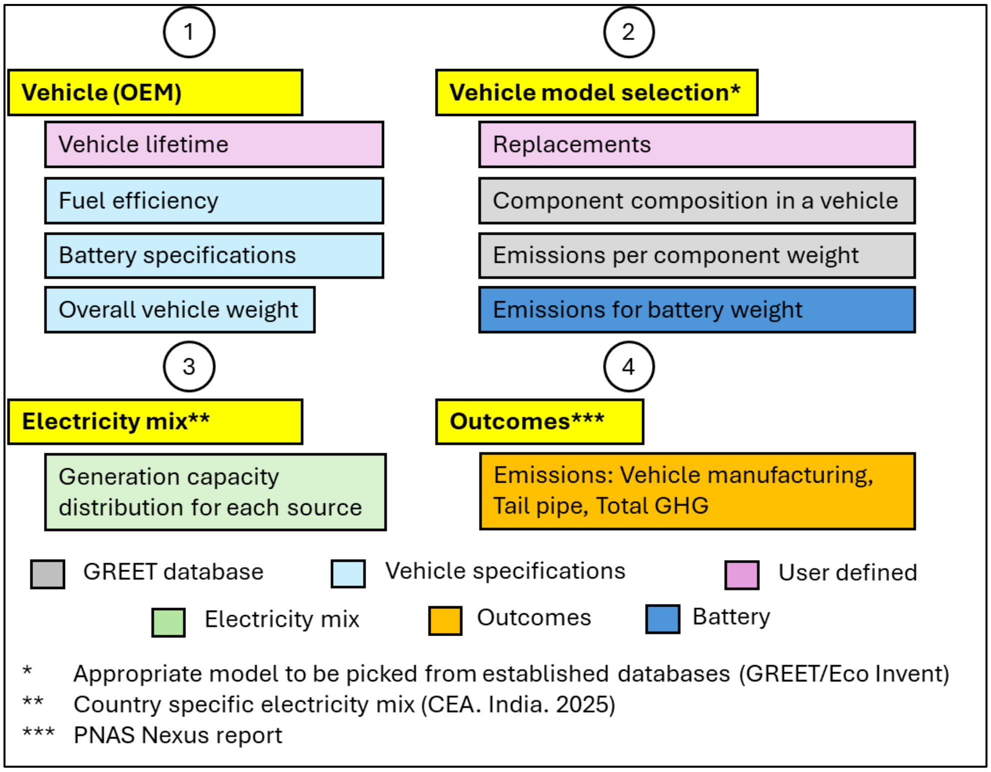

Figure 3. 4. Data inventory and its sources

3.6. Closure

We introduced a new LCA model, which considers both recycling and renewable energy aspects, which were hitherto non-existent. The model, together with the well-structured inventory, is now a complete one and can be applied across different vehicle technologies, be it a conventional ICEV or a thriving BEV. In the next chapter, we will demonstrate this methodology to a specific transportation segment (passenger car) for computing GHG emissions from cradle-to-gate and operational phase for a range of percent recycling and renewable energy.

Chapter 3 References

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CHAPTER 4: LCA OF A PASSENGER CAR

4.1. Introduction

Having described the Life Cycle Assessment model in detail in Chapter 3, we will now take up the exercise of computing GHG emissions for an ICE vehicle and an equivalent BEV. This Chapter demonstrates the applicability of the LCA model developed in the foregoing chapter. The key focus is on the assessment of a specific vehicle segment, i.e. passenger car with the identification of vehicle cases across transportation technology, viz., ICEV and BEV., which is reported in Section 4.2.

In Section 4.3, we take up GHG emissions during the lifecycle of an ICE vehicle. In Section 4.3.1, we will be discussing the emissions due to manufacturing (Cradle-to-gate) of the ICEV. In Section 4.3.2, we examine the total emissions during the operation of the vehicle on-road, for up to 3 lakh Kms (300,000 kms). Subsequently, we perform the same exercises for the Battey Electric Vehicle (BEV) in Section 4.4. In Section 4.4.1, we compute the manufacturing (Cradle-to-gate) GHG emissions for a BEV without battery. We do the same for the Cradle-to-gate GHG emissions of an LFP battery in Section 4.4.2. Following this, we present the combined data of a BEV with an LFP battery in Section 4.4.3. Then in Section 4.4.4, we carry out the computation of the on-road GHG emissions of a BEV, also for 3 lakh Kms (300,000 kms).

Further details on the calculation and supplementary data generated out of the analysis can be referred to **Error! Reference source not found.**V.

4.2. Vehicle Cases

In the present study, an ICEV version Tata Nexon Creative + S 1.2 New (Petrol), and an equivalent BEV version Tata Nexon EV Creative 45 has been considered as vehicle cases. The key specifications of the individual vehicles are given in Table 4. 1 and Table 4. 2.

Table 4. 1. ICEV Vehicle Specifications

ICEV		
Vehicle model	**Tata Nexon Creative + S 1.2 New, Petrol**	
Engine Capacity	1199	*cc*
Fuel-tank capacity	44	*L*
Dimensions	3995*1804*1620	mm
Weight	1315	*kg*
Mileage	17.44	***Km/L***

Table 4. 2. BEV Vehicle Specifications

BEV		
Vehicle model	**Tata Nexon EV Creative 45**	
Battery Capacity	46.08	*kWh*
Battery Chemistry	LFP	
Range	489	*km*
Dimensions	3994 x 1811 x 1616	mm
Weight	1400	*kg*
Motor power	110	*kW*
Charging time	40	*mins*
Mileage	10.61	***Km/kWh***
Battery Warranty	8 years or 160,000 kms	

4.3. ICEV

Life Cycle Assessment of a 4-wheeler passenger car is studied based on the GHG emissions of the vehicle throughout its lifetime. These GHG emissions can be broadly divided as:

i. Emissions due to vehicle manufacturing (Cradle-to-Gate)
ii. Operational Emissions (On-road emissions)

The GHG emissions from cradle-to-gate and operations, with specific considerations given to recycling and renewable energy for the ICEV version are reported herein.

4.3.1. ICEV Cradle-to-Gate Emissions

Even in the ideal world, the GHG emissions do not drop to zero. To delineate this, the cradle-to-gate process has been breakdown into three sub-processes namely,

i. **M**ining
ii. **M**aterial Processing
iii. **M**anufacturing & Assembly

All cradle-to-gate stages involve various processes which use either fossil fuels or electricity for energy. If the processes using fossil fuels can be electrified, it enables the possibility of eliminating emissions in those processes, as the electricity used can be sourced from renewable sources. However, this electrification process depends on a multitude of factors including technological progress, technology adaptation costs, national / international policies and other geographical / economic factors. It is important to note that the term "recycling" in this context applies only to materials that can be recycled. When referring to 90% recycling, it means that 90% of the recyclable portion of the material input is sourced from recycled content, while the remaining 10% consists of virgin materials from mining. The primary materials used in the manufacturing of passenger car components are Steel, Aluminium, Magnesium, and Nickel. These materials are accounted for in the recycling processes within the GREET model pathways. Excluding batteries, about 47% to 48% of 4W passenger car vehicle components can be considered as recyclable.

The parameters considered in this study are Renewable Energy and Recycling percentage, as seen in Table 4. 3. By varying the percentage combinations of both these variables, we arrive at various GHG emission values. Each GHG emission value (calculated in Ton-Co2 eq.), is split into emissions due to fossil fuels (colour coded as red, in the table) and emissions due to the usage of electrical energy (colour coded as green in the table). For a given recycling percentage, when the percentage of renewable energy is increased, it affects only the emissions due to electricity usage, i.e., the ones coded in green colour. Hence, for every recycling percentage, the emission due to fossil fuels is kept constant, because of which the emission due to electrical energy decreases with increase in renewable energy percentage. Also, for every renewable energy percentage, the emission in the third phase i.e., manufacturing and assembly phase are kept constant, as there is no requirement for additional raw materials in this phase[16]. The highest contribution comes from Material processing as it often requires refining and processing raw materials at extremely high temperatures, for which the current preference of energy source is fossil fuels. It is also to be noted that complete recycling greatly reduces the reliance on mining for procuring raw materials.

[16] For detailed explanation and reasoning behind these inferences, refer raw data in Appendix IV. b

Table 4. 3. ICEV Cradle-to-Gate emissions

TOTAL MANUFACTURING GHG EMISSIONS – ICEV (Unit: Ton-CO_2 eq.)												
Renewable Energy (%)	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	0.64 + 0.17	3.5 + 1.13	1.38 + 0.96	0.64 + 0.14	3.5 + 0.94	1.38 + 0.8	0.64 + 0.07	3.5 + 0.47	1.38 + 0.4	0.64 + 0.00	3.5 + 0.00	1.38 + 0.00
	5.52 + 2.26 (7.78)			5.52 + 1.88 (7.4)			5.52 + 0.94 (6.46)			5.52 + 0.00 (5.52)		
50	0.5 + 0.15	2.32 + 1.04	1.38 + 0.96	0.5 + 0.13	2.32 + 0.87	1.38 + 0.8	0.5 + 0.06	2.32 + 0.43	1.38 + 0.4	0.5 + 0.00	2.32 + 0.00	1.38 + 0.00
	4.2 + 2.16 (6.36)			4.2 + 1.8 (6)			4.2 + 0.9 (5.1)			4.2 + 0.00 (4.2)		
90	0.39 + 0.14	1.38 + 0.97	1.38 + 0.96	0.39 + 0.12	1.38 + 0.81	1.38 + 0.8	0.39 + 0.06	1.38 + 0.41	1.38 + 0.4	0.39 + 0.00	1.38 + 0.00	1.38 + 0.00
	3.15 + 2.08 (5.23)			3.15 + 1.73 (4.88)			3.15 + 0.87 (4.02)			3.15 + 0.00 (3.15)		
100	0.37 + 0.14	1.14 + 0.96	1.38 + 0.96	0.37 + 0.11	1.14 + 0.8	1.38 + 0.8	0.37 + 0.06	1.14 + 0.4	1.38 + 0.4	0.37 + 0.00	1.14 + 0.00	1.38 + 0.00
	2.89 + 2.06 (4.95)			2.89 + 1.71 (4.6)			2.89 + 0.86 (3.74)			2.89 + 0.00 (2.89)		

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Direct Fossil Usage Emission

Electricity Usage Emission

Total Emission

The emissions due to usage of fossil fuels and electricity are shown separately in Table 4. 3, for each stage of manufacturing i.e., Mining / recycling, Material Processing and Manufacturing and Assembly, in the cradle-to-gate pipeline for different percent recycling and renewable energy scenarios. The emissions due to fossil fuel usage are colour coded in red, while the emissions when using electricity as energy source are colour coded as green. The total emission at each step is given in black. As can be seen, the emissions due to electricity become zero with the increase in renewable energy percentage.

It is to be noted that all emission values reported in this Section and the later Section 4.4.1 are obtained from GREET 2024 model[2]. The GREET model furnishes comprehensive details about the resources used and emissions during the entire production process for each vehicle component. The production process of these components is organized in the form of "pathways", which converge and diverge at different points in the production process, resulting in a web of processes, rather than a linear path. These pathways even start at the mining process, with different pathways for mines from different parts of the world. Such an extensive approach provides a precise calculation of resources and emissions at any given point in the production process. This approach is adopted for vehicle manufacturing due to lack of supply chain data reported by the OEM. Recycling and renewable energy percentages are modified to arrive at the values to be used in this study (see Table 4. 3). The exact process is given in Appendix IV(a) and here we only present the results.

4.3.2. ICEV On-Road Emissions:

The On-road emissions refer to the vehicle GHG emissions throughout its lifetime operation i.e., during driving. The average vehicle lifetime considered here is about 3 lakh (300,000) kilometres. Operational emissions due to an ICEV throughout its lifetime are shown in

Table 4. 4. These tailpipe emissions are computed as a function of the vehicular distance travelled (VDT), vehicular efficiency (calculated for a fixed mileage value for Tata Nexon Petrol vehicle) (refer Table 4. 1), and emissions per litre of fuel. The global average value of gasoline upstream emission (Well-to-Pump) is 17.3 g CO2eq/MJ [1] [2]. In addition, combustion of gasoline produces 72.89 CO2eq/MJ GHG (Pump-to-Wheel) emissions [3] netting to 90.19 CO2eq/MJ (Well-to-Wheel). As per GREET, Higher Heating Value (HHV) of conventional gasoline is 46.536 MJ/kg and considering petrol density of 750 g/l the HHV value is 34.7 MJ/L. Thus, multiplying by the HHV factor of 34.7 MJ/L, the net emission due to fuel alone becomes 3.13 kg CO2eq/L.

A sample tailpipe calculation for 3 lakh Kms (300,000 kms) is given below.

$$Vehicular\ efficiency\ =\ 0.057339\ l/km$$

$$Petrol\ emissions\ per\ lit\ =\ 3.13\ kgCO2eq/l$$

$$On\ road\ emissions\ =\ VDT * Petrol\ Emissions\ * Vehicular\ Efficiency * \ 1e-03 =\ 53.84\ Ton\ CO2\ eq$$

Table 4. 4. ICEV On-road Emissions

Emissions during **Operations**			**Units**			
			Ton CO_2eq.			
ICEV	**Running kms**					
	50K	**100K**	**150K**	**200K**	**250K**	**300K**
	8.972	17.945	26.917	35.89	44.862	**53.835**

4.4. BEV

The GHG emissions from cradle-to-gate and operations, with specific considerations given to both recycling and renewable energy for the BEV version, are reported herein. To comprehend the impact, the emissions correspond to vehicle alone and battery (alone) are presented separately in Sections 4.4.1 and 4.4.2 respectively.

4.4.1. Vehicle Alone Manufacturing (Cradle-To-Gate) Emissions

The data provided in Table 4. 5 are for vehicle emissions due to cradle-to-gate alone (sans battery emissions) for each stage of manufacturing i.e., Mining / recycling, Material Processing and Manufacturing and Assembly, in the cradle-to-gate pipeline for different percent recycling and renewable energy scenarios. As mentioned earlier (refer Section 4.3.1), recycling, as used here, pertains exclusively to materials that are recyclable. The emissions due to fossil fuel usage are colour coded in red, while the emissions when using electricity as energy source are colour coded as green. The total emission at each step is given in black. The details of these computations are in Appendix IV. c

Table 4. 5. BEV manufacturing (cradle-to-gate) Emissions, excluding battery

TOTAL MANUFACTURING GHG EMISSIONS – BEV (Unit: Ton-CO_2 eq.)												
Renewable Energy (%)	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	0.36 + 0.13	2.56 + 0.9	0.99 + 0.90	0.36 + 0.10	2.56 + 0.74	0.99 + 0.75	0.36 + 0.05	2.56 + 0.37	0.99 + 0.38	0.36 + 0.00	2.56 + 0.00	0.99 + 0.00
	3.91 + 1.93 (5.84)			3.91 + 1.59 (5.5)			3.91 + 0.8 (4.71)			3.91 + 0.00 (3.91)		
50	0.25 + 0.12	1.66 + 0.84	0.99 + 0.90	0.25 + 0.10	1.66 + 0.70	0.99 + 0.75	0.25 + 0.05	1.66 + 0.35	0.99 + 0.38	0.25 + 0.00	1.66 + 0.00	0.99 + 0.00
	2.9 + 1.85 (4.75)			2.9 + 1.54 (4.44)			2.9 + 0.77 (3.67)			2.9 + 0.00 (2.9)		
90	0.17 + 0.11	0.93 + 0.78	0.99 + 0.90	0.17 + 0.09	0.93 + 0.65	0.99 + 0.75	0.17 + 0.04	0.93 + 0.32	0.99 + 0.38	0.17 + 0.00	0.93 + 0.00	0.99 + 0.00
	2.09 + 1.79 (3.88)			2.09 + 1.49 (3.58)			2.09 + 0.74 (2.83)			2.09 + 0.00 (2.09)		
100	0.14 + 0.1	0.75 + 0.77	0.99 + 0.90	0.14 + 0.09	0.75 + 0.64	0.99 + 0.75	0.14 + 0.04	0.75 + 0.32	0.99 + 0.38	0.14 + 0.00	0.75 + 0.00	0.99 + 0.00
	1.89 + 1.77 (3.66)			1.89 + 1.48 (3.36)			1.89 + 0.74 (2.62)			1.89 + 0.00 (1.89)		

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Direct Fossil Usage Emission

Electricity Usage Emission

Total Emission

4.4.2. Battery Alone Manufacturing (Cradle-To-Gate) Emissions

LFP battery is considered for the chosen vehicle case scenario. Cradle-to-gate emissions for LFP Batteries vary significantly depending on energy sources and material usage. The computed data related to this stage are furnished in Table 4. *6*. The emissions due to fossil fuel usage are color coded in red, while the emissions when using electricity as energy source are color coded as green. The total emission at each step is given in black.

It may be noted that the proportions of the individual contributions due to Mining, Material Processing and Manufacturing for the battery towards the total emissions are selected by deliberate reasoning according to the data from a report on decarbonizing EVs by McKinsey & Co. [4]. The emission values reported in this section were determined based on inferences from the supplementary data provided with the PNAS Nexus report on the global impact of battery supply chain [5], providing a comprehensive look at the potential environmental benefits of cleaner production strategies[17]. This report has data for 2020 (which is termed as current) and projections for 2023, 2040, and 2050. The current year data have been calculated from the GREET 2021 model, EverBatt model and EcoInvent model, by considering the collective global supply chain. To determine the current renewable energy percentage, the collective contribution of each country was considered, which was found to be 30% in the global battery supply chain. The Circular Battery recycling scenario, along with the Direct Recycling standard is considered for this study. This ensures a complete ideal scenario, where the best possible projection for envisioning a Passenger battery circular ecosystem with respect to the recycling aspect of the battery. The projected values are based on the scenario wherein the Sustainable Development Scenario (SDS), stipulated by the International Energy Agency (IEA) is adopted [6]. The SDS scenario considers Research and Development in various technologies associated with reducing CO_2 emissions, being sped up due to multiple factors including the policies, implementation of policies, and technology development in one domain driving the technological advancement in another. The Direct Recycling technique is a technique wherein high yield of recovery of materials is possible, with 96% recovery rate for anodes and 85% recovery for cathodes [7].

The emissions are estimated for a 46.08 kWh battery, equivalent to the one found in the BEV model selected. The details of computations are in Appendix IV. d.

The need for battery replacement in electric vehicles is facing a downward trend thanks to advances in battery technologies. A new study by Stanford researchers shows that with dynamic cycling patterns with fluctuating current loads, pulses, and resting periods, thereby imitating real life driving conditions, improve battery life up to 38% over more standard constant current lab testing, showing that batteries perform considerably better under practical usage than was previously thought [8]. At the same time, detailed longevity research employing close to 300 million UK vehicle histories

[17] Refer Appendix IV. d. for reasoning behind each value and context of data selection

demonstrates that BEVs currently match or surpass the life of conventional petrol and diesel cars, averaging a life of 18.4 years and covering as much as about 200,000 kilometres, with newer BEVs registering an impressive 12% improvement in reliability per successive model year [9]. Another study by IEEE spectrum states that EV batteries might last 38% longer than previously known lab-based predictions, likely leaving drivers with up to 314,000 kilometres (195,000 miles) for one battery, lowering the requirement for battery replacement by a considerable margin [10]. These warrants prospective future wherein there is a reduced need for battery replacement, ultimately bringing down the emissions further. As a result, we have found that leading manufacturers of Electric Vehicles in India have started giving 200,000 kms or 8 years guarantee to the users. This is already a beginning, and we will see more of it in coming years. Essentially, the need to replace the battery during the lifetime of the vehicle will eventually disappear. When combined with the ability to recycle almost 90% of battery materials at end-of-life [7], future lifecycle analyses can account for scenarios wherein BEVs experience high material circularity and extended durability, with considerably lower overall emissions throughout their lifecycle.

Table 4. 6. LFP Battery Cradle-to-gate Emissions

TOTAL MANUFACTURING GHG EMISSIONS – LFP Battery (Unit: Ton-CO_2 eq.)												
Renewable Energy (%)	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	I	II	III	I	II	III	I	II	III	I	II	III
0	0.07 + 0.08	0.67 + 0.71	0.49 + 0.53	0.07 + 0.07	0.67 + 0.59	0.49 + 0.44	0.07 + 0.03	0.67 + 0.3	0.49 + 0.22	0.07 + 0.00	0.67 + 0.00	0.49 + 0.00
	1.24 + 1.32 (2.55)			1.24 + 1.1 (2.33)			1.24 + 0.55 (1.79)			1.24 + 0.00 (1.24)		
50	0.04 + 0.06	0.4 + 0.51	0.49 + 0.53	0.04 + 0.05	0.4 + 0.43	0.49 + 0.44	0.04 + 0.02	0.4 + 0.21	0.49 + 0.22	0.04 + 0.00	0.4 + 0.00	0.49 + 0.00
	0.94 + 1.1 (2.04)			0.94 + 0.92 (1.86)			0.94 + 0.46 (1.4)			0.94 + 0.00 (0.94)		
90	0.02 + 0.04	0.19 + 0.35	0.49 + 0.53	0.02 + 0.03	0.19 + 0.3	0.49 + 0.44	0.02 + 0.02	0.19 + 0.15	0.49 + 0.22	0.02 + 0.00	0.19 + 0.00	0.49 + 0.00
	0.71 + 0.92 (1.63)			0.71 + 0.77 (1.48)			0.71 + 0.38 (1.09)			0.71 + 0.00 (0.71)		
100	0.02 + 0.04	0.14 + 0.32	0.49 + 0.53	0.02 + 0.03	0.14 + 0.26	0.49 + 0.44	0.02 + 0.01	0.14 + 0.13	0.49 + 0.22	0.02 +0.00	0.14 + 0.00	0.49 + 0.00
	0.65 + 0.88 (1.53)			0.65 + 0.73 (1.38)			0.65 + 0.37 (1.02)			0.65 + 0.00 (0.65)		

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Direct Fossil Usage Emission

Electricity Usage Emission

Total Emission

4.4.3. BEV Manufacturing (Cradle-To-Gate) Emissions with Battery

This section presents the combined cradle-to-gate emissions for the BEV equipped with an integrated LFP battery. The corresponding data are provided in Table 4.7. Data in Tables (Table 4. 5 and Table 4. 6) are added to get this. At the current national scenario of 28% Renewable Energy, the emissions would be 8.39 ton-CO_2 eq. The emissions due to fossil fuel usage are colour coded in red, while the emissions when using electricity as energy source are colour coded as green. The total emission at each step is given in black.

Table 4.7. BEV with Integrated LFP Battery Cradle-to-gate Emissions

TOTAL EMISSIONS - BEV with Integrated Battery (Unit: Ton-CO_2 eq.)												
Renewable Energy (%)	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	0.43 + 0.21	3.23 + 1.61	1.48 + 1.43	0.43 + 0.17	3.23 + 1.33	1.48 + 1.19	0.43 + 0.09	3.23 + 0.67	1.48 + 0.6	0.43 + 0.00	3.23 + 0.00	1.48 + 0.00
	5.14 + 3.25 (8.39)			5.14 + 2.69 (7.83)			5.14 + 1.35 (6.49)			5.14 + 0.00 (5.14)		
50	0.3 + 0.17	2.06 + 1.35	1.48 + 1.43	0.3 + 0.14	2.06 + 1.13	1.48 + 1.19	0.3 + 0.07	2.06 + 0.56	1.48 + 0.6	0.3 + 0.00	2.06 + 0.00	1.48 + 0.00
	3.84 + 2.95 (6.79)			3.84 + 2.46 (6.3)			3.84 + 1.23 (5.07)			3.84 + 0.00 (3.84)		
90	0.19 + 0.15	1.13 + 1.13	1.48 + 1.43	0.19 + 0.12	1.13 + 0.95	1.48 + 1.19	0.19 + 0.06	1.13 + 0.47	1.48 + 0.6	0.19 + 0.00	1.13 + 0.00	1.48 + 0.00
	2.8 + 2.71 (5.51)			2.8 + 2.26 (5.06)			2.8 + 1.13 (3.93)			2.8 + 0.00 (2.8)		
100	0.16 + 0.14	0.9 + 1.08	1.48 + 1.43	0.16 + 0.12	0.9 + 0.9	1.48 + 1.19	0.16 + 0.06	0.9 + 0.45	1.48 + 0.6	0.16 + 0.00	0.9 + 0.00	1.48 + 0.00
	2.54 + 2.65 (5.19)			2.54 + 2.21 (4.74)			2.54 + 1.1 (3.64)			2.54 + 0.00 (2.54)		

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Direct Fossil Usage Emission

Electricity Usage Emission

Total Emission

4.4.4. BEV On-Road Emissions

Considering the worst-case scenario in the BEV usage, wherein the electricity used to power the vehicle is completely sourced from non-renewable energy sources [11] throughout its lifetime[18], the GHG emission is about 33.48 ton-CO_2 eq., as seen in Table 4.8.

Table 4.8. BEV On-road Emissions

Emissions during **Operations**			Units					
			Ton-CO_2 eq.					
BEV		**Running kms**						
		50K	**100K**	**150K**	**200K**	**250K**	**300K**
Renewable (%)	**28**	5.579	11.159	16.739	22.318	27.898	33.477
	40	4.650	9.301	13.951	18.602	23.252	27.903
	70	2.328	4.656	6.983	9.311	11.639	13.966
	100	0.005	0.010	0.015	0.020	0.025	**0.030**

4.5. Closure

The LCA model developed in-house, as per the details provided in Chapter 3, has been successfully applied in the context of both the ICEV and BEV variants of a 4-Wheeler passenger car. The GHG emission values in the lifetime of the vehicles are computed, providing absolute metrics by which the environmental impact of these vehicles can be gauged. In the next chapter we shall discuss the inferences obtained from the data presented in this chapter and do a detailed comparative assessment.

[18] As modern architecture tends to be implemented with renewable facilities as much as possible, the reliability on non-renewable sources is greatly reduced, thereby reducing the corresponding emissions, when the vehicle is charged in office buildings and other commercial complexes

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CHAPTER 5: RESULTS, DISCUSSIONS AND CONCLUSIONS

Having presented the computed GHG emissions for an ICE vehicle and an equivalent BEV in Chapter 4, we will now summarize the key results for ICE and Battery Electric vehicles, respectively in Section 5.1 and 5.2 followed by a detailed comparative assessment in Section 5.3.

In Section 5.1.1 and 5.1.2, respectively we will analyze the results of GHG emissions due to manufacturing (cradle-to-gate) and operations of ICEV. Subsequently, we perform the same exercises for the BEV in three parts: vehicle alone manufacturing emissions in Section 5.2.1; LFB battery manufacturing emissions in Section 5.2.2; and finally for BEV with an integrated battery in Section 5.2.3. Thereafter, we carry out a detailed comparative assessment of ICEV and BEV with a focus on manufacturing emissions in Section 5.3.1, followed by on-road emissions in Section 5.3.2. Finally, we introduce a comparative GHG index (CGHI) in Section 5.3.3 and assess the pros and cons of ICEV and BEV at both individual and combined phases of their lifecycle for several combinations of percent recycling and renewable energy without and with one battery replacement.

5.1. Results and Key Inferences for ICEV

5.1.1. ICEV Cradle-To-Gate Emissions

Figure 5.1 depicts the total emissions from manufacturing (cradle-to-gate) for ICEV, plotted as a function of increasing percentage of renewable energy and increasing recycling percent.

As seen in Figure 5.1, at the current scenario (i.e., 28% Renewable Energy), the emissions due to the manufacture of an ICEV are about 7.78 ton-CO_2 eq., if there is no recycling. If we were to switch to 100% Renewable energy and with no recycling, the emissions would fall to 5.52 ton-CO_2 eq., a 29% decrease. On the other hand, if we were to keep the current electricity mix as it is, and perform 100% recycling of all the recyclable materials, then the emissions drop to 4.95 ton-CO_2 eq., a 36% decrease. In the ideal world where there is 100% recycling and the electricity mix is 100% renewables, the emissions can drop to 2.89 ton-CO_2 eq.

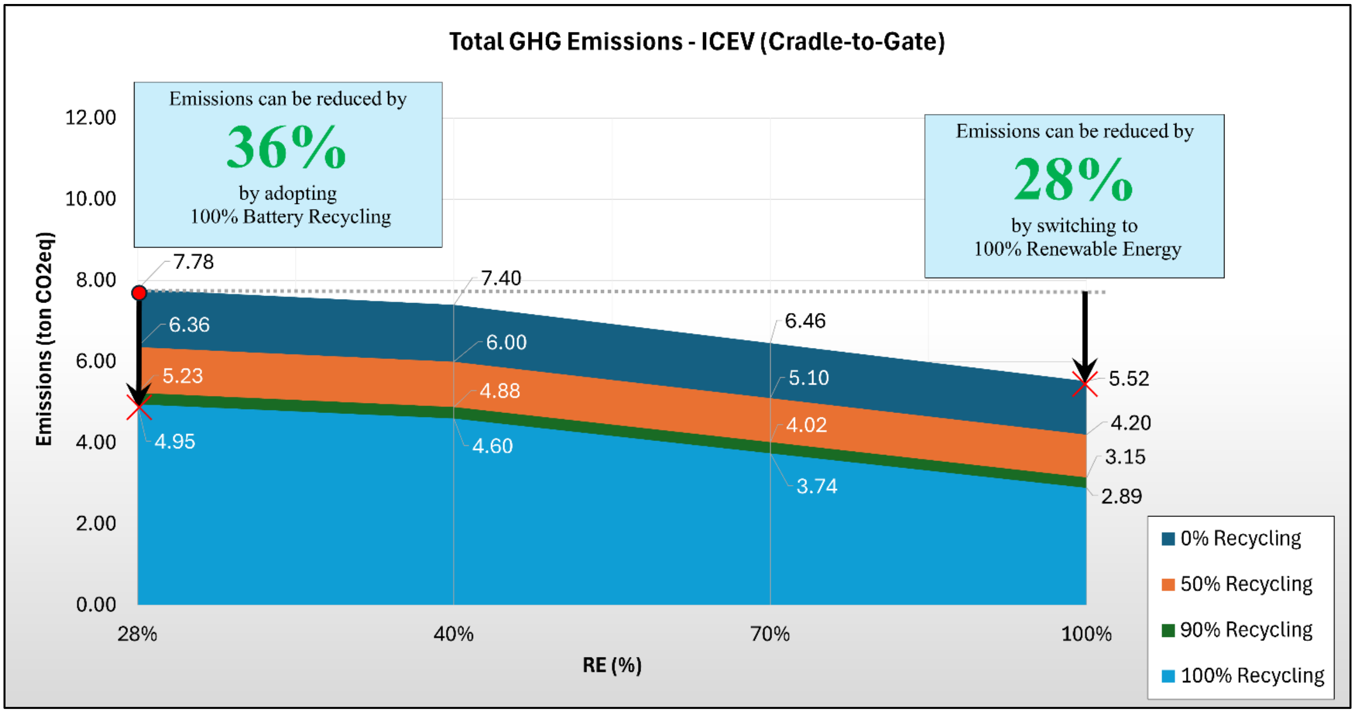

Figure 5.1. ICEV manufacturing (cradle-to-gate) Emissions

5.1.2. ICEV On-Road Emissions

Figure 5.2 summarizes the GHG emissions when the ICE vehicle is driven. Note that when the vehicle is driven even 50K miles, the emissions are just under 10 tons CO_2 eq. This is already higher than the emissions due to manufacturing in the current scenario. As shown in Figure 5.1, these emissions fall with higher renewable energy and higher recycling. With even 100,000 kms on board, the emissions are more than double of manufacturing emissions. This clearly implies that the primary contribution of GHG emissions form an ICE vehicle is from petrol, in its operational phase, with manufacturing contribution, relatively lesser. With 3 lakh kms (300,000 Kms) on board, the ICE vehicle emits 53.84 ton-CO_2 eq. whereas in the current 28% renewable energy scenario, the manufacturing emissions are only 7.78 ton-CO_2 eq. The emissions due to manufacturing are relatively smaller compared to operational emissions. It is petrol, during its operational phase, that is the main culprit for Global warming.

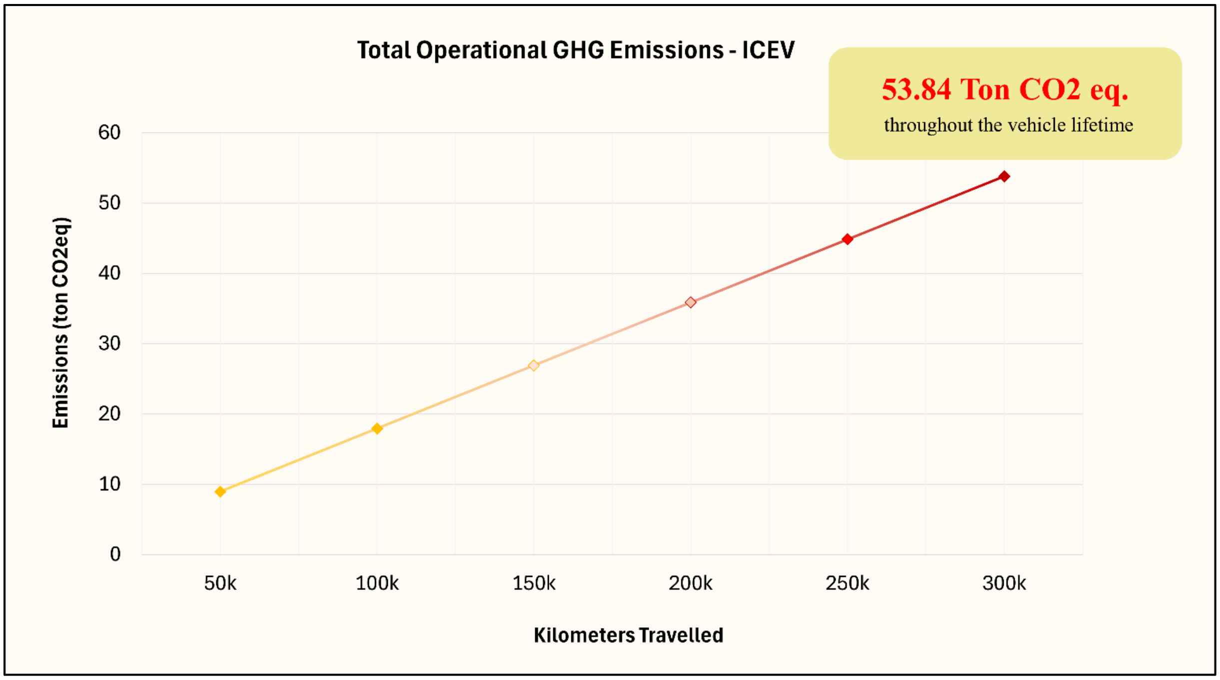

Figure 5.2. ICEV Operational Emissions

5.2. Results and Key Inferences for BEV

5.2.1. BEV Vehicle Alone Manufacturing (Cradle-To-Gate) Emissions

We now look at the total emissions from BEV vehicle alone (sans battery) during manufacturing (cradle-to-gate). This is plotted as a function of renewable energy share and recycling percentage in Figure 5.3.

As evident from Figure 5.3, the total greenhouse gas emissions associated with manufacturing a BEV are highest when relying entirely on virgin materials and a 28% renewable energy mix, reaching approximately 5.84 ton-CO_2 eq. If we were to shift fully to a renewable energy supply while recycling is still at 0%, the emissions would further decline to 3.91 ton-CO_2 eq., representing a decrease of 33%. Alternatively, if the electricity mix remains as it is today but we switch entirely to recycled materials, emissions would drop to 3.66 ton-CO_2 eq., which equates to a reduction of 37%. Thus, the effect of recycling on the mitigation of GHG emissions during cradle-to-gate processes in BEV is higher compared to that in ICEV. The most significant emission cuts can be achieved in an ideal scenario where both 100% renewable energy and 100% recycling are implemented, bringing emissions down to just 1.89 ton-CO_2 eq.

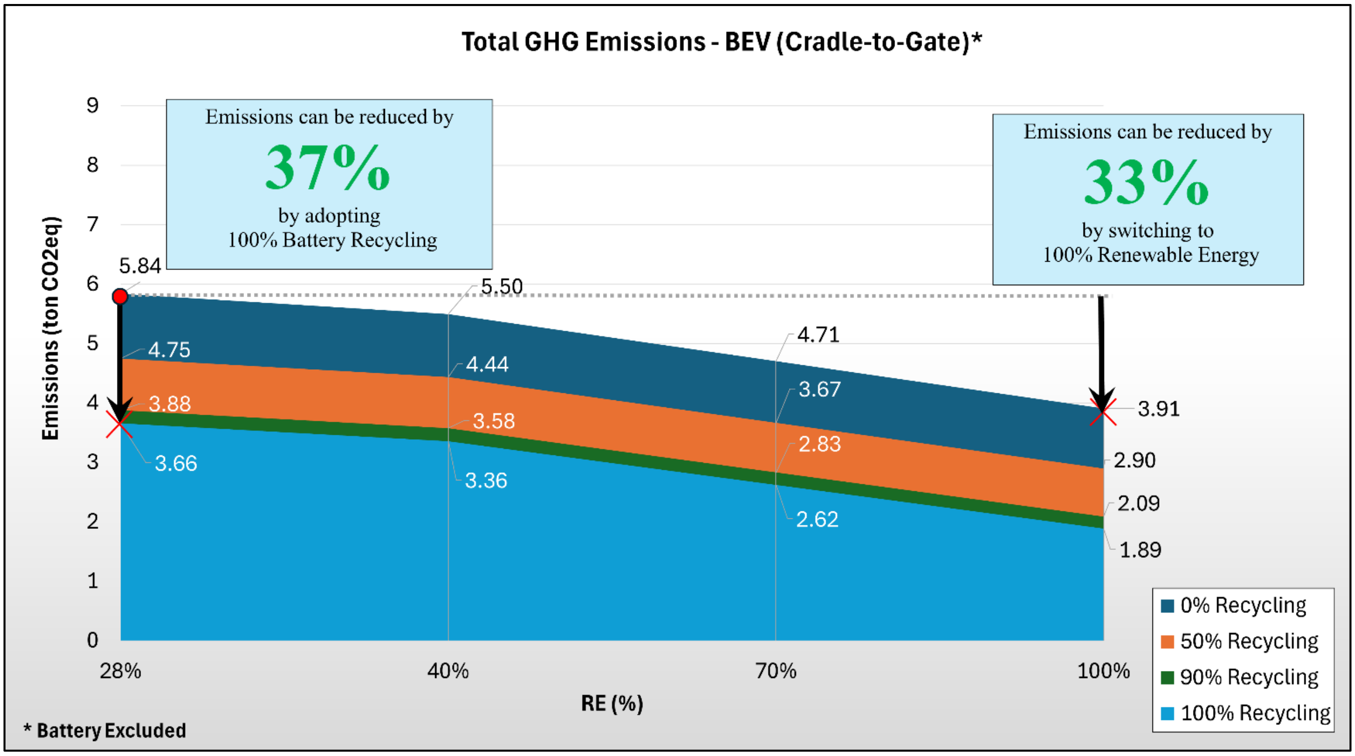

Figure 5.3. BEV manufacturing (cradle-to-gate) Emissions, excluding battery

5.2.2. LFP Battery Alone Manufacturing (Cradle-To-Gate) Emissions

The above computations were when battery was not included in the BEV. But battery is an integral part of such a vehicle. Therefore, now we look at emissions in a battery, used in BEV. Figure 5.4 shows the total manufacturing (cradle-to-gate) emissions from a battery (LFP), plotted as a function of renewable energy share and recycling percent.

The lowest emissions, 0.65 ton-CO_2 eq., occur when both renewable energy and full recycling are combined. As seen in Figure 5.4, the current reality, featuring 30% renewable energy (considering global battery supply chain), tends to be 2.55 ton-CO_2 eq. A complete transition to renewable electricity would cut emissions further to 1.24 ton-CO_2 eq., a reduction of 51%, indicating higher reliance on electricity for energy in the battery cradle-to-gate pipeline. On the other hand, adopting 100% recycling while retaining the current electricity mix would lower emissions to 1.53 ton-CO_2 eq., reflecting a 40% drop.

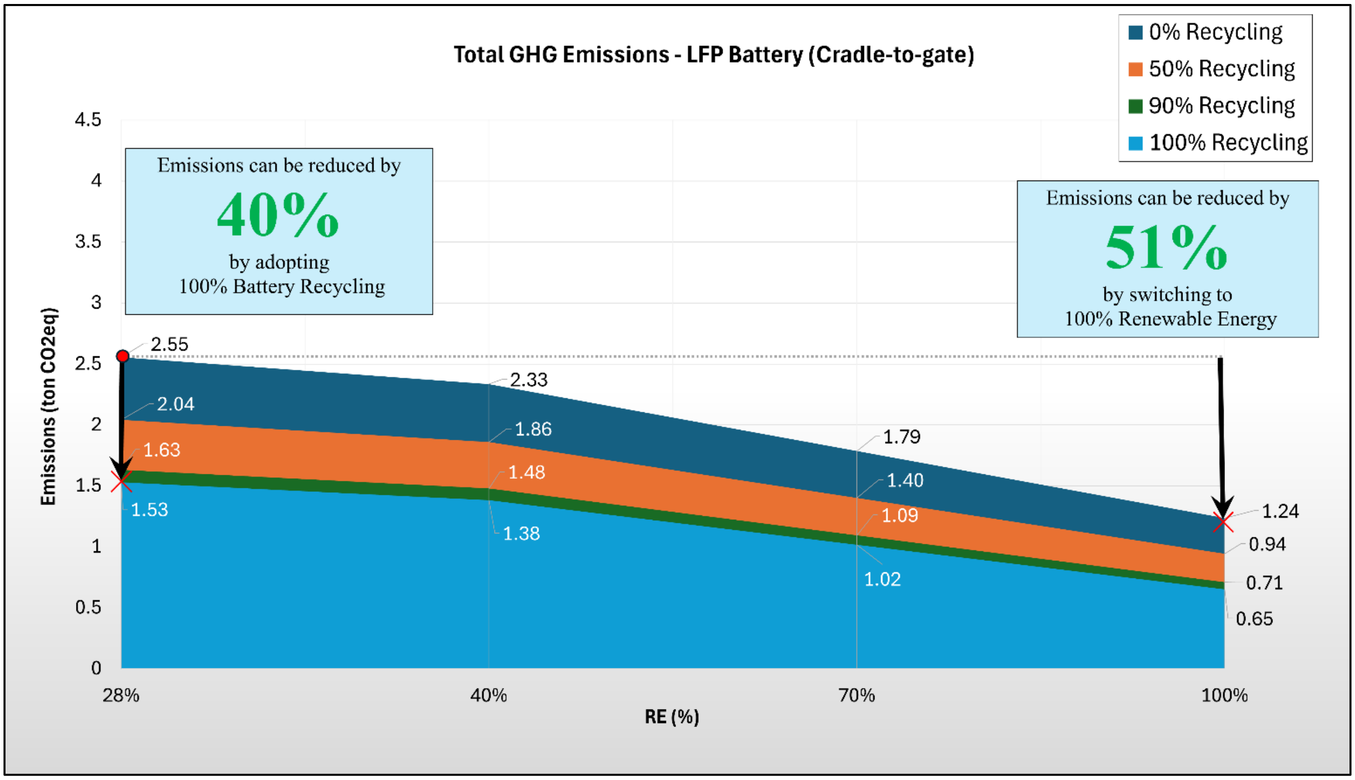

Figure 5.4. LFP Battery Cradle-to-gate Emissions

5.2.3. BEV Manufacturing (Cradle-To-Gate) Emissions with Integrated Battery

We now add the battery to the BEV and examine the emissions. Figure 5.5 depicts the total manufacturing (cradle-to-gate) emissions from BEV with an integrated battery, plotted as a function of renewable energy and recycling percent.

The lowest emissions, 2.54 ton-CO_2 eq., are achieved when both renewable energy and full material recycling are employed. As depicted in Figure 5.5, under the current national energy mix, which includes 28% renewable energy, emissions amount to roughly 8.39 ton-CO_2 eq. A full shift to renewable electricity would reduce emissions to 5.14 tons, a 39% decrease. Similarly, achieving 100% material recycling while maintaining the current energy mix would lower emissions to 5.19 ton-CO_2 eq., representing a 38% reduction from the present level.

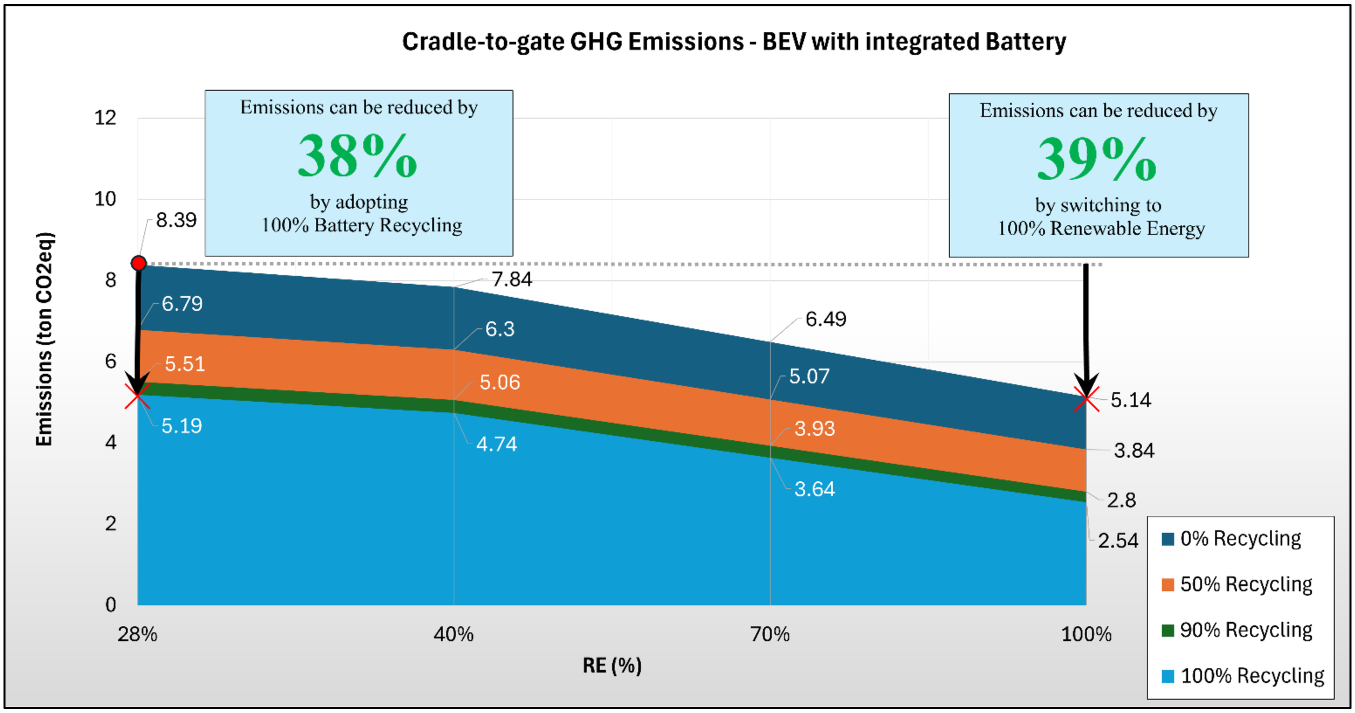

Figure 5.5. BEV with Integrated Battery Cradle-to-gate Emissions

5.2.4. BEV On-Road Emissions

Having examined the GHG emissions in a BEV with battery during its manufacturing phase, we now look at its emissions, when the vehicle is being driven. The GHG emissions from a BEV with battery are near ZERO, when electricity is 100% renewable. Assuming the current mix of electricity in India, 28% electricity from renewable sources, remain fixed and RE percentage do not grow, the total GHG emissions for vehicle being driven 300,000 kms would be about 33 ton-CO_2 eq., as shown in Figure 5.6. But as RE% in electricity is increasing rapidly in India, with 500 GWh target by 2030, this would drop drastically.

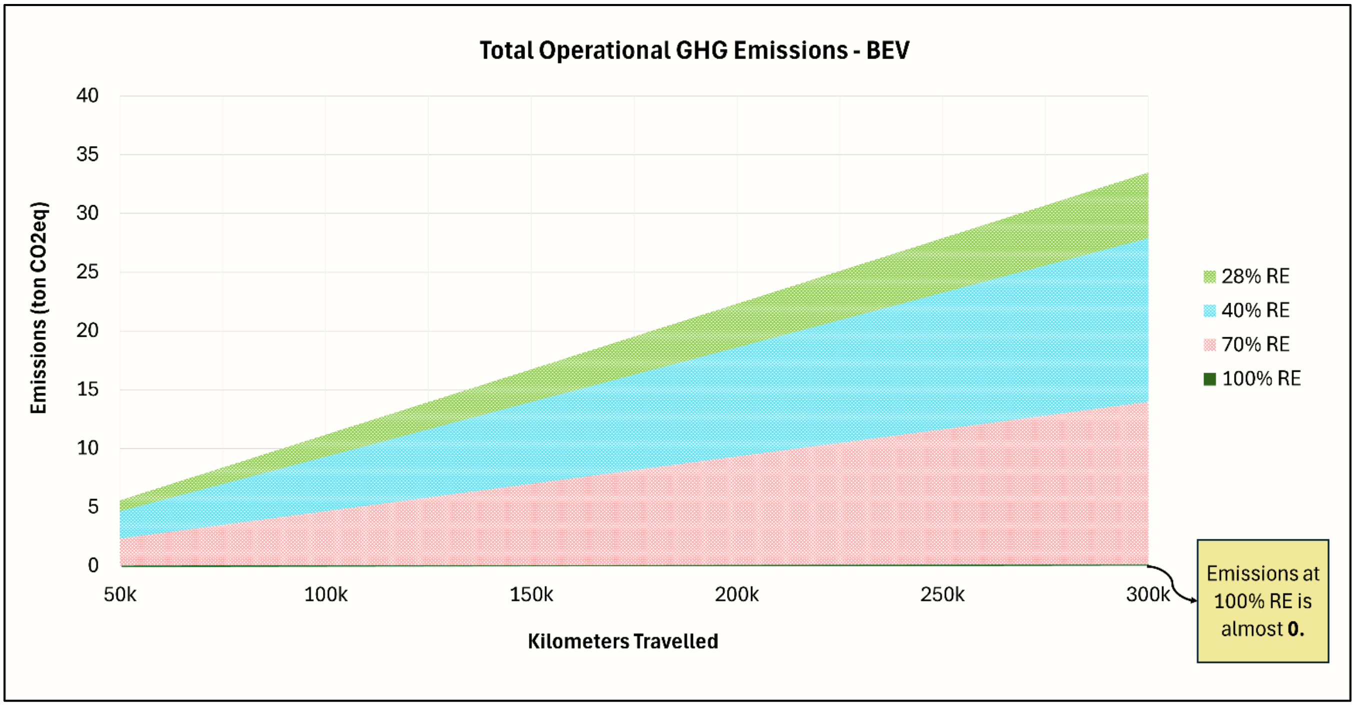

Figure 5.6. BEV Operational Emissions

5.3. Comparative GHG Assessments

We now present a comparative assessment of GHG emissions due to ICE vehicle and Battery Electric Vehicle. Manufacturing related emissions are compared in Section 5.3.1, followed by on-road emissions in Section 5.3.2.

5.3.1. Manufacturing Emissions (Cradle-to-Gate) Comparison

Table 5.1 presents the GHG emissions due to ICEV and BEV at the Cradle-to-Gate pipeline. As discussed earlier, this comparison is carried out, assuming renewable energy percentage in electricity production is 28% (the present value in India), 40%, 70% and 100%. Similarly, the comparison is made with increasing recycling from 0% to 100%. When the energy from electricity becomes fully renewable and the recyclable materials are completely recycled, the respective GHG emissions are 2.89 ton-CO_2 eq. from an ICE vehicle, and 2.54 ton-CO_2 eq. from a Battery Electric Vehicle. This implies that there is not much difference in emissions between the two in the manufacturing phase. Note that with 28% Renewables in electricity production and 0% recycling, the numbers for ICE and BEV becomes 7.78 and 8.39 respectively. It is obvious that greening the grid and increasing recycling will help reduce emissions in both ICE and BEV. We will now look at the GHG emissions during operations of the two vehicles.

Table 5.1. Cradle-to-Gate Emissions Comparison between ICEVs and BEVs

Emissions at **Cradle-to-Gate**			Units							
			Ton-CO_2 eq.							
Cradle-to-Gate	**ICEV vs. BEV***		**Renewable Energy (%)**							
			28%		**40%**		**70%**		**100%**	
			ICEV	**BEV**	**ICEV**	**BEV**	**ICEV**	**BEV**	**ICEV**	**BEV**
	Recycling (%)	**0%**	**7.78**	**8.39**	7.40	7.84	6.46	6.49	5.52	5.14
		50%	6.36	6.79	6.00	6.30	5.1	5.07	4.20	3.84
		90%	5.23	5.51	4.88	5.06	4.02	3.93	3.15	2.80
		100%	4.95	5.19	4.60	4.74	3.75	3.64	**2.89**	**2.54**

**BEV inclusive of integrated battery for its lifetime (no battery replacement required as it becomes irrelevant while considering current technological advancements[19]). Furthermore, in recent times, LFP batteries are starting to get available for 10,000 cycles and calendar life of 12 years.*

[19] Refer Section 4.4.2. for more details.

5.3.2. On-Road Emissions Comparison

It is the operational phase, the difference in emissions from an ICE vehicle and BEV becomes prominent, as shown in Table 5.2 and Figure 5.7. The ICE vehicle will emit 53.835 ton-CO_2 eq. in its lifetime (when the vehicle is run 3 lakh Kms (300,000 kms)). This contrasts with BEV, which will only emit about 33.48 ton-CO_2 eq. in its 300K kms journey, assuming the current percentage (28%) of renewables in India's electricity grid. As renewables in India's grid increase, the advantage will become increasingly more, with emissions from BEV falling to a minute value of 0.03 ton-CO_2 eq. if 100% RE is used. Note that India has committed to this journey and by as early as 2030, it expects us RE to increase to 500 GWh from 200 GWh today[20]. Moving the transport to RE and moving the grid to Renewables must go together.

Table 5.2. Vehicular On-road Emissions Comparison

Emissions during **Operations**		Units					
		Ton-CO_2 eq.					
ICEV		**Running kms**					
		50K	**100K**	**150K**	**200K**	**250K**	**300K**
		8.972	17.945	26.917	35.89	44.862	**53.835**
BEV		**Running kms**					
		50K	**100K**	**150K**	**200K**	**250K**	**300K**
Renewable (%)	**28**	5.579	11.159	16.739	22.318	27.898	**33.477**
	40	4.650	9.301	13.951	18.602	23.252	27.903
	70	2.328	4.656	6.983	9.311	11.639	13.966
	100	0.005	0.010	0.015	0.020	0.025	**0.030**

[20] As per National Electricity Plan (NEP 14) targets by 2030.

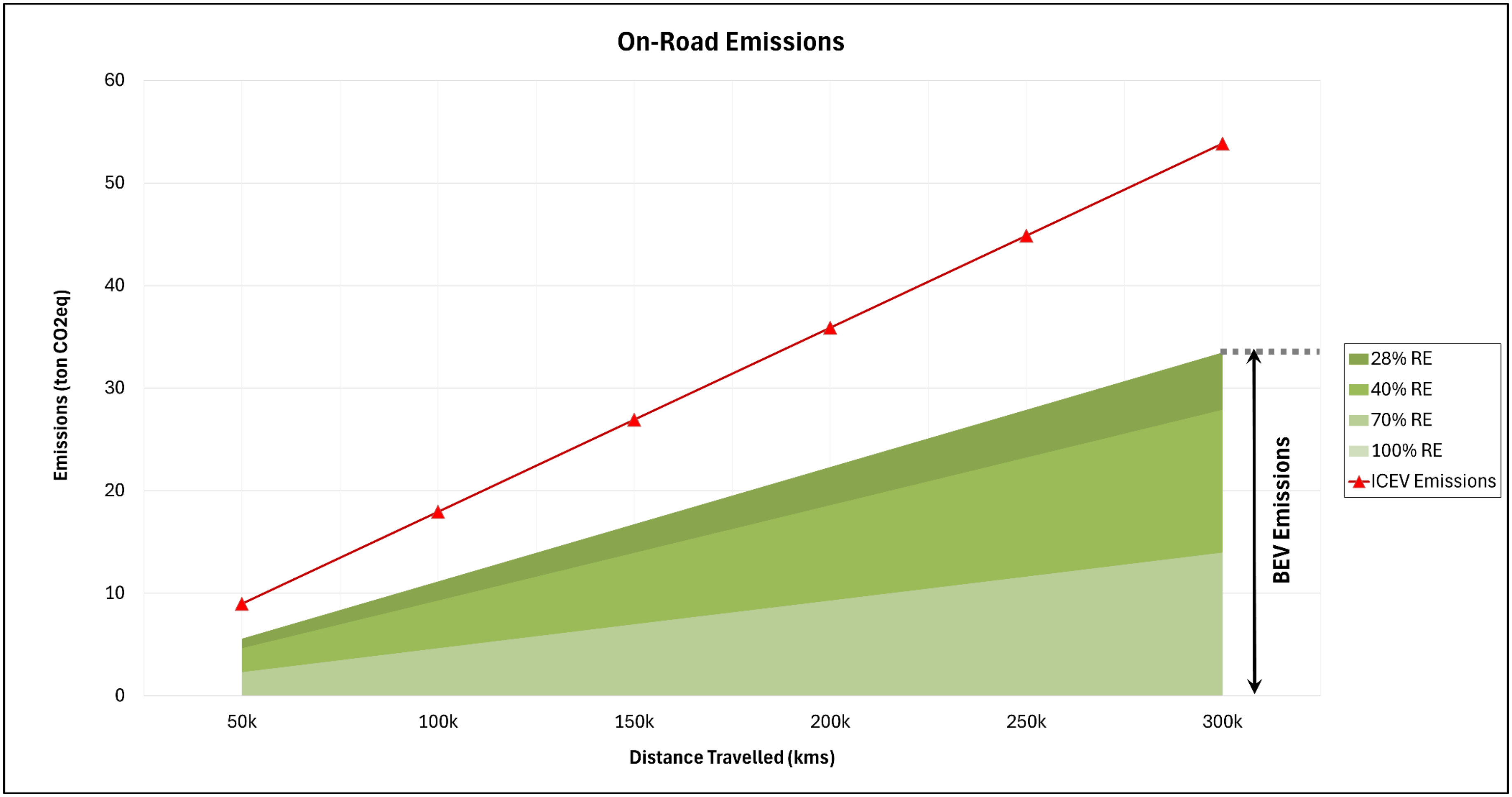

Figure 5.7. ICEV and BEV On-road Emissions Comparison

5.3.3. Life Cycle Emissions Comparison

Figure 5.8 shows the comparison between ICEVs and BEVs (with integrated battery) at various phases of their lifetime, assuming 100% RE and 100% recycling. The different phases shown here are the cradle-to-gate phases which include Mining/Recycling, Material Processing and Manufacturing and Assembly, and the on-road phase. It can be inferred BEV outscores in terms of GHG emissions in every phase of the vehicle lifetime. In Figure 5.9, we present the same comparison with 70% RE and 50% recycling, which India would hope to achieve within a decade. Even here, the BEV stands out as compared to an ICEV.

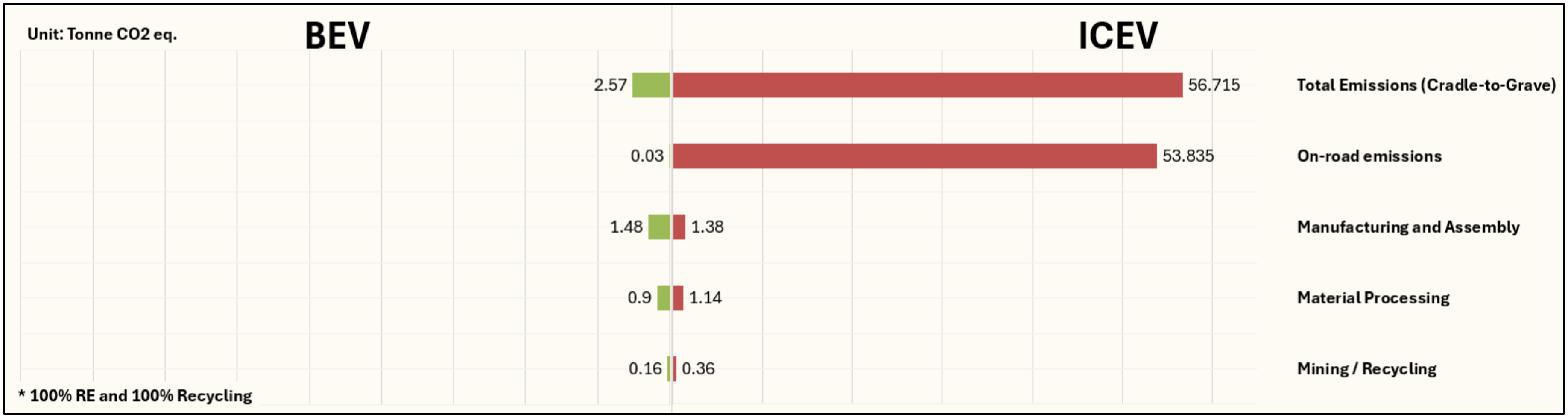

Figure 5.8. ICEV and BEV Emissions[21] Comparison at various phases of their life cycle

[21] The emission values correspond to an ambitious scenario of 100% Renewable Energy and 100% Recycling and are inclusive of integrated battery

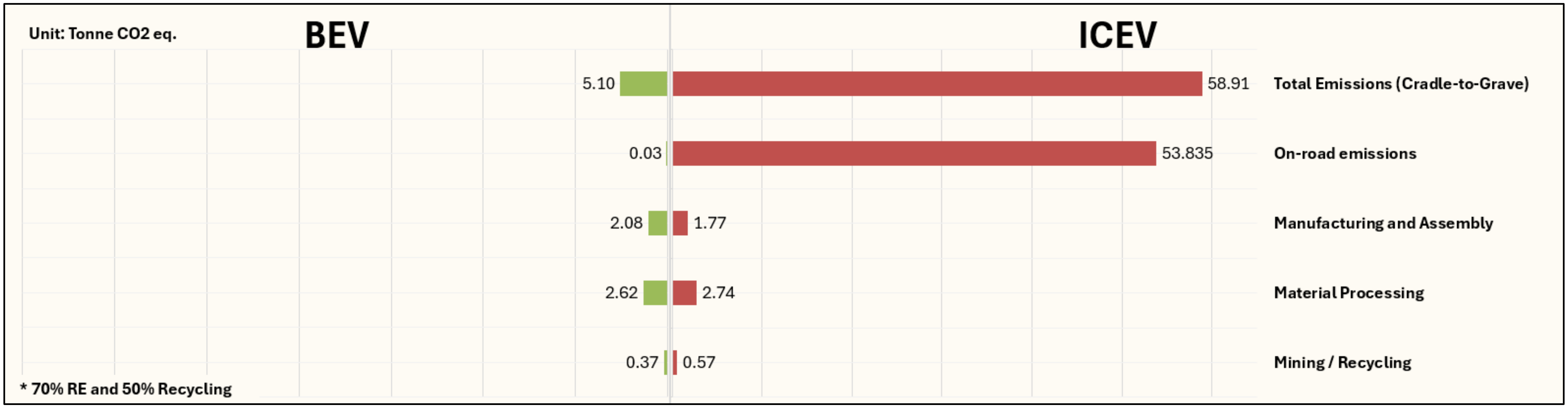

Figure 5.9. ICEV and BEV Emissions Comparison[22] at 70% RE and 50% Recycling

[22] The BEV emission values are inclusive of integrated battery

5.4. Conclusion

Before we conclude, we would like to emphasize, two other aspects of an electric vehicle, (i) an EV is far more energy efficient as compared to a ICE vehicle, (ii) as the cost of an EV falls, its upfront price becomes quite close to that of an ICE vehicle, and operations costs becomes much lower than that of an ICE vehicle throughout its lifetime.

5.4.1. Energy Efficiency of a BEV

The global transportation sector stands at a pivotal crossroads as the world confronts the urgent challenges of climate change, air pollution, and energy security. Battery electric vehicles (BEVs) have rapidly emerged as a transformative solution, offering a clean, efficient, and sustainable alternative to traditional internal combustion engine vehicles. Powered by rechargeable batteries and increasingly supported by renewable energy sources, BEVs produce zero tailpipe emissions, significantly reducing greenhouse gases and harmful air pollutants.

As discussed in Chapter 1, BEVs have high vehicle efficiency [1] compared to ICEVs, leading to lesser emissions, resulting in relatively lower emissions even when the electricity sourced to run the BEV throughout its lifetime is obtained from fossil sources[23] (Figure 5.10). As global warming looms upon us, we cannot afford to waste energy. Everything should become more energy efficient. The choice should be green electricity, full recycling and higher energy efficiency. Electric Vehicle stands out in all these dimensions.

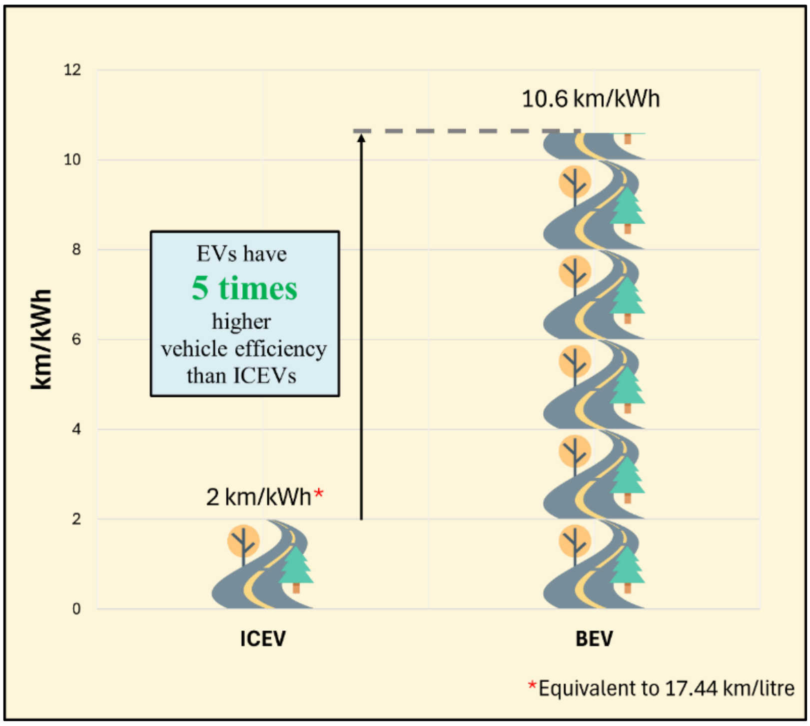

Figure 5.10. Vehicle efficiency comparison (BEV vs. ICEV)

[23] Vehicle efficiency is compared between the ICEV (Tata Nexon Creative + S 1.2 New - Petrol) and BEV (Tata Nexon EV Creative 45) models chosen for this study. Vehicle efficiency is the effective range of vehicle per 1 kWh equivalent of fuel.

5.4.2. Driving Down BEV Manufacturing Costs: Paving the Way for Affordable Electric Mobility

India's electric vehicle (EV) market is experiencing a pivotal transformation. Between October 2022 and September 2023, EVs made up approximately 5% of total vehicle sales. This figure is projected to surge, with EVs potentially comprising over 40% of all vehicle sales by 2030 [2], as shown on Figure 5.11.

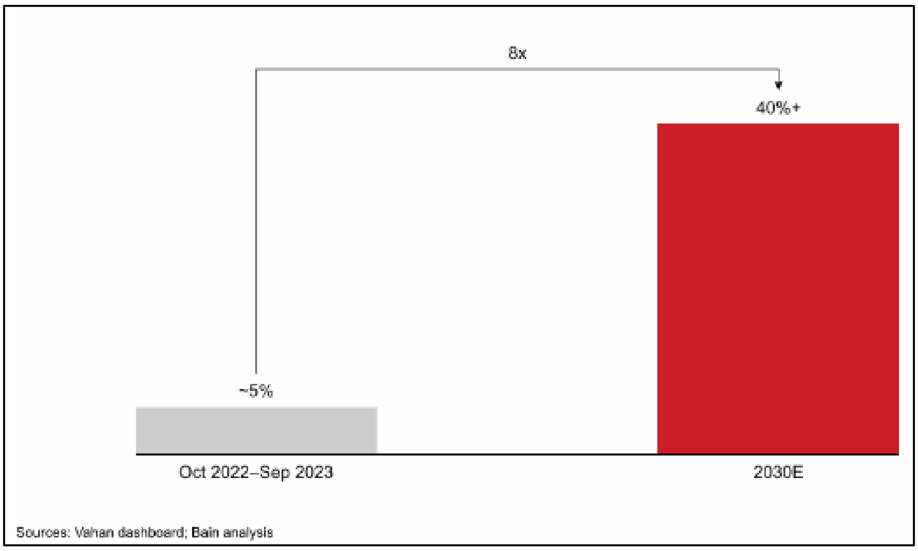

Figure 5.11. India's overall EV penetration is expected to grow over 40%

5.4.3. Today's Choice is Undoubtedly Electric Vehicle

The analysis carried out in this report clearly shows that BEV stands out as compared to ICEV in terms of total GHG emissions in its lifetime. The GHG emissions during manufacturing (Cradle-to-Gate) are comparable for the two vehicles. As we learn to recycle materials used and use higher percentage of Renewables in the electricity produced, the emissions during manufacturing will reduce significantly both for EV as well ICEV.

The difference comes from the emission during operations. This is far higher for ICEV as compared to that for EVs, even today. As the amount of Renewable Energy in India's electricity grid increases, the difference in emission between Electric and ICE Vehicles will become even more prominent. In fact, as the grid becomes close to 90% green, the emissions from EV will all but disappear. For petrol vehicles, it will just continue to remain the same year after year.

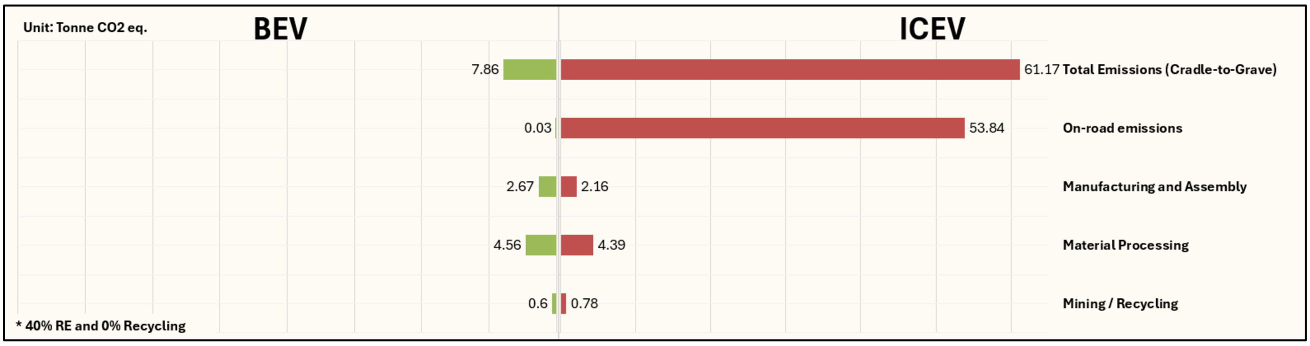

Figure 5.12. ICEV and BEV Emissions Comparison at various phases of their life cycle for the current scenario (38% RE and 0%Recycling)

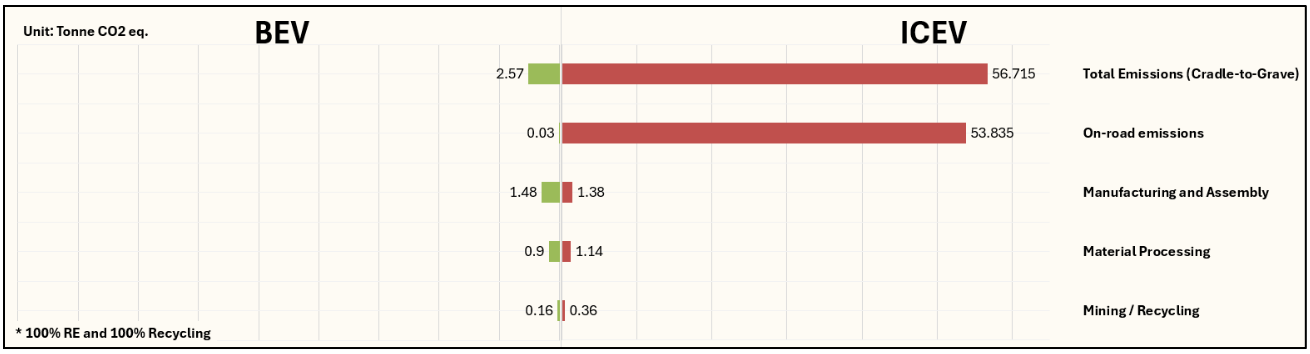

Figure 5.13. ICEV and BEV Emissions Comparison at various phases of their life cycle for the ambitious scenario (100% RE and 100%Recycling)

On the verge of completing the present study, we noticed that India has attained 38% renewable energy in July 2025, five years ahead of schedule [3], Accordingly, in the current scenario, a BEV deployed in the country is estimated to cause 7.8 times lesser lifetime emissions compared to ICEVs, with a BEV causing 35.7 ton-CO_2 eq. in its lifetime, while a similar ICEV is expected to emit 61.2 ton-CO_2 eq. of GHG emissions, as seen in Figure 5.12. In the ambitious scenario of 100% RE and 100% recycling, BEVs ought to emit up to 22 times less than an ICEV (Figure 5.13). It is obvious that the phaseout of ICEVs are not far as decarbonization of electricity mix complemented by emerging technologies in terms of materials, manufacturing and recycling along with aggressive EV policies can exponentially maximize the benefit of BEVs. Hence, the sooner we move away from all kinds of petrol cars to electric vehicles, better will it be for humanity.

Chapter 5 References

[1] Albatayneh, A., Assaf, M.N.., Alterman, D. & Jaradat, M. (2020). Comparison of the Overall Energy Efficiency for Internal Combustion Engine Vehicles and Electric Vehicles. Environmental and Climate Technologies, 24(1), 2020. 669-680. https://doi.org/10.2478/rtuect-2020-0041

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CHAPTER 6: CLOSURE

In this study, we set out to examine the greenhouse gas (GHG) emissions associated with the petrol-powered 4-Wheeler passenger ICE vehicle and an EV counterpart, in terms of the current scenario, and the future prospective sustainable technological developments in the transportation sector. By considering various levels of advancements in renewable energy and recycling technologies, we provide a dynamic comparative study, which accounts for changes in both directions. Through our analysis we conclude that, while EVs are not entirely free of GHG emissions when considering the full lifecycle of the vehicle from mining and manufacturing to end-of-life disposal, they consistently outperform the ICEV variants, overall. The reduction in emissions is even more amplified as the grid becomes greener, and more recycling is adopted.

Technological advancements are not isolated, as the innovation in one sector often drives the development of another. We believe that electrification of the transportation sector will accelerate the demand for progress in the renewable electricity generation sector and the reuse and recycling sector, thereby propelling us towards a sustainable safer future.

APPENDIX – I: GHG INCREASE AND ITS EFFECTS ON CLIMATE CHANGE – SOME RECENT EXAMPLES

Unprecedented heat waves

In 2024, Delhi experienced an unprecedented of 52.3°C, making it one of the hottest cities globally and causing severe heat stress for millions [1]. Lucknow's temperature peaked at 44.7°C in June 2023, disrupting agriculture and increasing heat-related illnesses [2]. Nagpur faced temperatures above 45°C in May 2024, resulting in increased electricity demand and health emergencies [3]. These rising temperatures worsen urban heat island effects, reduce water availability, and threaten food security. Urgent action is needed to manage heat risks and protect vulnerable communities across India.

Glacier melts

In October 2023, a glacial lake in Sikkim suddenly burst, causing heavy flooding along the Teesta River. The flood destroyed a major hydropower dam and many bridges, cutting off important connections. Over 90 people lost their lives, with many missing and thousands displaced. Homes and roads were severely damaged, isolating several areas. This event highlights the increasing dangers of glacier melt linked to climate change in the Himalayan region [4].

Urban flooding

In May 2025, Bengaluru saw intense flooding due to 157 mm of rain within two days, disrupting many neighbourhoods [5]. Rapid urban development has resulted in nearly 99% of the city being covered by impervious concrete surfaces. This growth also causes higher greenhouse gas emissions, which intensify heat and rainfall in the area. Even with a high budget aimed at infrastructure improvements, drainage issues and loss of natural water bodies continue to worsen flooding. To tackles these challenges, Bengaluru must focus on better urban planning and expanding green spaces to reduce both floods and emissions.

Damage to agriculture

In 2025, intensive farming in South India is causing soil damage and releasing methane, worsening climate change. Unpredictable rainfall has led to floods and droughts, destroying important crops like rice and cotton in areas such as Thanjavur. Rising temperatures are causing heat stress that reduces crop productivity, with rice yields falling significantly. These climate-driven challenges are putting financial strain on farmers and threatening food supplies. To address this, the Telangana government introduced a major solar irrigation program to promote sustainable farming practices [6].

Coastal erosion

Greenhouse gas emissions have raised global temperatures and sea levels, which intensify coastal erosion in cities like Mumbai and Kolkata [7]. Mumbai's coastline is increasingly vulnerable as stronger storms and rising seas erode beaches and damage infrastructure. Kolkata faces similar threats, with frequent flooding and tidal surges accelerating land loss near the Sundarbans. Land sinking combined with climate change effects worsens erosion, putting homes and ecosystems at risk in both cities. To protect these coastal zones, governments are focusing on restoring mangroves and building barriers to reduce erosion and protect communities [8].

Poor air quality

Delhi's air pollution remains critical, with vehicles, industries, and power plants contributing over 40% of the city's greenhouse gas emissions. In May 2025, Delhi's Air Quality Index (AQI) soared above 300, placing it in the 'very poor' category due to increased dust and emissions [9]. Studies reveal that vehicles emit up to 2–3 times more pollutants during real-world driving compared to lab tests, significantly worsening air quality. Industrial boilers and thermal power plants around Delhi NCR contribute nearly 7% of India's total greenhouse gas emissions, intensifying local pollution. To control pollution, the government deployed more than 500 anti-smog guns and sprinklers and enforced GRAP Stage-I restrictions across the city.

Climate Costs Uncovered

In 2024, greenhouse gas-driven climate disasters caused $417 billion in global damages, but only $137 billion was insured, leaving a vast financial gap [10]. India alone faced $228 billion in losses from just ten major climate events, with most of the population lacking insurance support [11]. Efforts like parametric insurance and targeted heatwave payouts have begun to offer relief, as seen in 2024 when 50,000 women in three Indian states received assistance during extreme temperatures [12].

The world is working hard to reduce greenhouse gas emissions by balancing what we emit with what we remove from the atmosphere, aiming for net zero to slow climate change. Many countries, including India, are investing heavily in renewable energy, clean technology, and natural carbon sinks to reach this goal, India plans to achieve net zero by 2070 with major projects in solar power and green hydrogen. Despite these efforts, global progress is still too slow, and current policies risk the planet warming by over 2°C unless actions are significantly sped up [13].

Table I.1 Recent India-specific environmental impact of GHG emissions

Event	Year and Location	Impact
Unprecedented heat waves	•2024, Delhi •June 2023, Lucknow •May 2024, Nagpur	•Temperature of 52.3°C, severe heat stress for millions. •Temperature peaked at 44.7°C, disrupting agriculture and increasing heat-related illnesses. •Temperatures above 45°C, increased electricity demand and health emergencies.
Glacier melts	•October 2023, Sikkim (Teesta River)	•Glacial lake burst, heavy flooding, destroyed hydropower dam and bridges resulted in loss of life and infrastructure.
Urban flooding	•May 2025, Bengaluru	•157 mm of rainfall was recorded in the Yelahanka area within six hours, resulting in the flooding of over 1,030 homes
Damage to agriculture	•2025, South India (e.g., Thanjavur)	•Soil damage, methane release, unpredictable rainfall leading to floods and droughts, destruction of crops (rice, cotton)
Coastal erosion	•Not specified (general), Mumbai and Kolkata	•Intensified by rising temperatures and sea levels which worsens GHG emissions and erosion
Poor air quality	• May 2025, Delhi	•AQI soared above 300 ('very poor'), increased dust and emissions, vehicles, industries, and power plants contributing to over 40% of GHG emissions.
Climate Costs Uncovered	• 2024, India	•$228 billion in losses from ten major climate events, most of population lacking insurance.

Thus, the escalating greenhouse gas emissions are driving drastic changes in the environment, resulting in extreme heat, severe flooding, and widespread damage across India, as summarized in the foregoing Table I.1. These impacts threaten public health, agriculture, infrastructure, and natural ecosystems, with vulnerable communities facing the greatest risks. Despite efforts to improve urban planning, reduce pollution, and promote sustainable energy, the pace of change remains insufficient to prevent further harm. Immediate and coordinated action is essential to cut emissions, protect natural resources, and build resilience against the growing climate challenges threatening both people and the planet.

Appendix – I References

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APPENDIX – II: Are hybrids Electric Vehicles?

IC Engine vehicles are energy inefficient using just above 20% of the energy of the fuel to drive the vehicle. Also, these fossil fuel vehicles are pollution and contribute heavily to GHG emission. Over the last 50 years, petrol vehicle manufacturers have been working to improve the energy efficiency of the petrol vehicles. The efforts have been credit-worthy. It has led to whole series of improvements, and the strong hybrids of today have energy efficiency in excess of 30%. However, they continue to use petrol, continue to emit pollution and impact global warming, even though to a lesser extent than they did earlier. Then there are plug-in hybrid electric vehicles (PHEVs), where a smaller size battery drives an electric motor for traction. However, as the battery is small, the range is small. Once the battery gets discharged, petrol is used to generate electricity and drive the vehicle. As the battery drives small range, the customers often avoid the hassle of charging the battery and continue to run the vehicle on petrol. As a result, their greenhouse gas emissions may approach those of conventional vehicles. Moreover, recent studies from European and international environmental agencies have shown that PHEVs emit significantly more CO_2 under actual driving conditions than in laboratory tests—sometimes two to four times higher.

Given all this, one wonder why not switch to electric vehicles completely? Batteries are becoming less expensive, charging network is expanding rapidly and fast charging is also increasingly available. The EVs will never use petrol and not contribute to either pollution or to GHG emissions. Governments around the world are promoting these EVs by providing some kind of incentives. It appears that some ICE vehicle manufacturers, who have not yet switched to EVs want to take these incentives for their vehicles, which use petrol, by calling them equivalent to EVs. They have this named them PHEVs. The accompanying articles discusses this in greater detail.

We therefore decided not to take up with any kind of hybrid vehicles for analysis in this report. We have taken up only ICE vehicles of BEVs. As shown in the report, the GHG emissions in ICE vehicles (especially during operations) is very high as compared to the EVs. Even if these petrol vehicles called hybrids, reduce the emission a bit, they continue to contribute to pollution, as well as GHG emissions. It is time they get replaced by EVs.

We now provide some references which discuss these issues in greater details. We also reproduce photocopies of some of the recent articles in this regard.

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Hybrids as a fake proxy for EV—a roadblock on India's path to clean air

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ASHOK JHUNJHUNWALA

By promoting petrol-based hybrid vehicles, policymakers risk using hybrids as a fake proxy for EV. While hybrids may be slightly more fuel-efficient than other petrol cars, they still run on petrol, still emit harmful NOx and PM2.5, and still contribute to the very pollution crisis the country is trying to solve.(for representational purposes only)

Every winter, Delhi's skies turn into a toxic haze, reminding us of the urgent need to break free from the grip of fossil fuels. Use of these fuels for transport is one of the major pollutants. These fuels also power our electricity and industries; the GHG emissions from all these is causing global warming and slowly but surely destroying life on earth. The erratic rainfalls is just a sign. The science is clear: to save our cities and our planet, we must end our reliance on fossil fuels as soon as possible.

Fortunately, the technology for transition is ready. Electricity generated from solar and wind are now cheaper than that from fossil fuels. Electric vehicles (EVs) for two-wheelers, three-wheelers, and cars are rapidly maturing. The price gap with petrol vehicles is narrowing, and EVs offer a direct route to slashing pollution, while getting rid of fossil fuel. They are not just a vision for tomorrow—they are a present-day solution for cleaner air and a healthier future.

Yet, at this pivotal moment, the Delhi government is considering a policy that threatens to undermine this progress. By promoting petrol-based hybrid vehicles, policymakers risk using hybrids as a fake proxy for EV. While hybrids may be slightly more fuel-efficient than other petrol cars, they still run on petrol, still emit harmful NOx and PM2.5, and still contribute to the very pollution crisis we are trying to solve. Granting them concessions and incentives is a dangerous sleight of hand—one that confuses consumers and slows the adoption of genuine electric vehicles.

The Government of India deserves praise for its clear policy to promote electric vehicles, which has already spurred rapid growth in the EV sector. However, by allowing hybrids as a fake proxy for EV, and offering them subsidies, we risk reversing this momentum. This is not just a policy misstep—it is a step backward in India's march toward its net-zero emission targets.

India's commitment to net-zero emissions is bold and necessary. Achieving this goal requires us to reject false-measures and embrace true electrification. We must not be misled by hybrids and equate them to EVs. The path forward is clear: rapid, unwavering support for genuine electric vehicles.

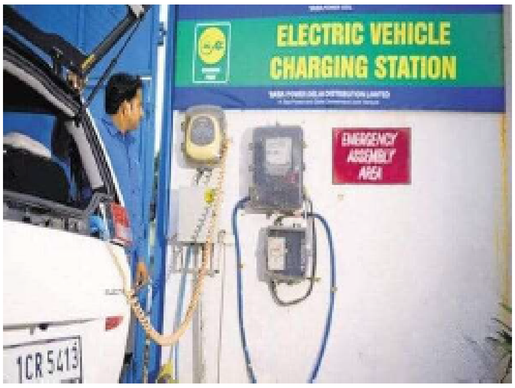
The time for ambiguity is over. We must reject policies that prolong our dependence on fossil fuels and instead focus on accelerating the adoption of real elect[illegible] vehicles. For the sake of our children, our cities, and our planet, let us accelerate our efforts to move fully to renewable electricity and fully to electric vehicles.

(The writer is Institute Professor, IIT Madras and Chairman, ITEL)

Figure II. 1. The Hindu, July 29, 2025 mint Premium Opinion

Don't let hybrids muddle our path to net-zero: EVs must prevail

Ashok Jhunjhunwala 4 min read 11 Mar 2024, 12:19 AM IST



EV-sceptics point out that the batteries used in EVs today could become big polluters tomorrow.

Summary: Hybrid advocacy seems aimed at prolonging the ICE age of unclean vehicles while we urgently need pollution-free transport.

An Economist article on 7 February 2024 by Elizabeth Lees presented a pictorial representation of the world's heat map over the past 60 years as compared to pre-Industrial Age temperatures. The latter half of 2023 showed a 2° Celsius heating above the pre-industrial level, and while it was an El Niño year of additional warming, this illustrates the climate-change disaster that we are facing today. The only way the earth will survive is if we stop using fossil fuels as a source of energy at the earliest. Electricity generation has started moving from coal, oil and gas to solar, wind and hydro power; nuclear energy will also become another major source of fossil-free power generation in the future. A promising aspect is that the replacement of fossil fuels with renewable energy sources reduces the cost of electricity. The only hurdle here is that solar and wind-based green electricity generation does not take place 24x7 and cannot be controlled to match instantaneous demand; one would need energy storage to balance supply and demand. This adds to the overall cost of electricity use, but power-storage costs are also falling rapidly with emerging solutions.

While electricity at homes, offices and industries could witness a quick shift to green and renewable sources, transportation will continue to depend on fossil fuels. Most vehicles use petrol and diesel. This also pollutes the environment severely, making the air unbreathable in many cities across the world during busy hours. Fortunately, electric vehicles (EVs), which do not pollute and could use green electricity for battery charging, are becoming economically viable as an alternative to combustion-engine vehicles. The shift to EVs is real.

In India, it already makes economic sense to use electric two-wheelers and three-wheelers. Electric four-wheelers are slightly more expensive to purchase than equivalent-category vehicles that use petrol or diesel; but, as the cost of electricity is much lower than that of petrol, an EV four-wheeler can make up for its higher upfront price in a year or two. This applies to electric pick-up trucks as well. However, this is not the case with long-distance heavy vehicles like trucks and buses, as these require large and costly batteries, making them more expensive than their diesel counterparts (and commercially unviable as a result). This scenario could change in another five years, as economical and higher-density batteries and hydrogen-fuelled vehicles emerge.

Taking note of the emergence of EVs, many petrol vehicle manufacturers initiated research and development around 2012 aimed at a transition to clean vehicles. But not everyone did. Caught off-guard by automobiles going electric, some naysayers have sought to run a campaign that maligns EVs. The first argument made is that the electricity available today results in greenhouse gas emissions, as it is largely generated from fossil fuels (which include coal, apart from hydrocarbons). This is true, of course, as of today. But solar and wind-based electricity is fast becoming economically viable. It is only a matter of time before we transition to clean electricity. Critics are welcome to demand that this transformation of the electricity grid be speeded up, as it would allow zero- or low-emission EV charging.

EV-sceptics also point out that the batteries used in EVs today could become big polluters tomorrow. This would indeed be so if each battery, whether in an EV, cellphone or laptop, is not recycled fully. This, however, need not be the case. Recycling technologies have attained maturity and can be scaled up. A circular economy, which reuses everything that can be reused, needs to be the future.

The third argument, voiced most vociferously, is in favour of hybrid vehicles instead of EVs. The proposition is to have an electric propulsion motor as well as an internal combustion engine (ICE) in every vehicle. If the battery runs down, then the ICE takes over. As vehicular motion can generate electricity, a hybrid can also recharge its battery while it is being driven. The rationale is that such a dual arrangement can overcome 'range anxiety': i.e., the fear of running out of charge midway. How long EV batteries take to charge has also been brought up in this context.

These appear to be arguments to prolong the life of ICE vehicles, in which huge investments have been made over the past century. Having both an electric and combustion engine in a single vehicle is a huge waste of resources. When a hybrid runs on its combustion engine, it burns a fossil fuel that emits a carbon-rich exhaust, so it cannot claim to be a clean vehicle. As for an EV's range anxiety, it could be overcome by larger or faster-charging batteries. Fairly soon, we are likely to get advanced power-packs that could be charged 80% in just 10-12 minutes. This development would be the final blow to hybrids. Till then, unfortunately, hybrids might continue to muddle the transport sector's transition.

The replacement of fossil-fuel vehicles with EVs is an important and necessary step towards attaining net-zero emissions. However, EVs will not solve the problem of urban traffic congestion. Today, in India's major cities, one could spend upwards of two hours driving to and from office. It takes a toll on people's health and wastes their time. This cannot be the future, and requires alternative ideas as solutions. IIT-M Research Park, for example, has come up with one such alternate called High-Speed Autonomous Sustainable Human Transport, or Hashtic. Technology along these lines would complement the EVs of tomorrow.

Figure II. 2. Mint, 11 March, 2024

● ELECTRIC VEHICLES

Hybrids are fine, but the real focus has to be on EVs

The 20th century was the age of hybrids, but with EVs having arrived, the hybrid argument doesn't make sense

■ **ASHOK JHUNJHUNWALA**

DONALD TRUMP, the EV-basher-in-chief, complains that they "cost too much and don't go far." Many others join him in complaining that the electricity grid in India is dirty and mostly uses coal as fuel; thus, EVs use coal-based electricity. Others complain that charging infrastructure doesn't exist, and batteries and solar panels will create huge waste at the end of their life. All these statements are half-truths.

Let's start with cost. In China, EV costs have already gone down vis-à-vis ICE cars, and are going down elsewhere also. We should be able to do this in India as well, provided we don't declare a war on EVs.

The argument "does not go far" is based on the fact that batteries are large and heavy, and expensive compared to petrol tanks. In fact, a battery is about 40 times heavier and larger as compared to a petrol tank to carry the same energy. It's not going to change in the near future. But this battery uses energy four times more efficiently (ICE cars waste most of the energy and use only about 20% of the energy for traction). Using energy efficiently is critical in our fight against greenhouse gas (GHG) emissions. Also, the extra vehicle weight due to the battery for a two-, three- or four-wheeler with 250-km range would barely be 10-15% more. The extra energy consumed due to weight is more than compensated by the fact that EVs do not waste energy during idling (say, at traffic lights) and recover energy via regeneration.

The argument of "not enough charging infrastructure" is linked to "does not go far." The question is, how much do we drive on a typical day? When we drive within a city in India, we rarely do even 100 km in a day. Over 95% of daily household travel would fall under the given range. If the battery provides a range of 200-250 km, overnight charging at home is adequate for most days. For the days when we do travel long distance (between cities), we anyway take a break every 3-4 hours, and top-up fast charging is now there on most highways. I've counted five such fast chargers between Chennai and Bengaluru.

What about electricity being dirty? Today, electricity generated using solar or wind costs ₹2-3 per unit, whereas electricity from a new coal powerplant incorporating pollution-control equipment, required by law, would be more than ₹4 per unit. So, there is no reason to continue using dirty, expensive electricity. The government has anyway set a 500-GW electricity generation target for renewables by 2030. One would welcome a campaign to get there faster. But to not switch from petrol to electricity for transport would be foolish and retrograde.

The concern around waste from batteries and solar panels is genuine. But recycling them has started making economic sense. Cell phone batteries are generating enough waste for profitable recycling, and to use the "waste" argument against EVs is like demanding a relay race runner run the last lap first.

Finally, some people think hybrids are a better option. It's difficult to understand this argument. Hybrid vehicles use petrol instead of electricity as a source of energy. This neither solves the problem of pollution nor helps us combat GHG emissions. An argument is being made that hybrids use petrol more efficiently. So what? For decades, automakers have been working to reduce fuel consumption, and hybrid is another such effort. Hybrids were fine in the 20th century, but now that EVs are already here, the hybrid argument doesn't make sense. If people are falling for it, it means they don't understand.

Then there are arguments about different kinds of hybrid technologies (mild, strong, plug-in parallel, and plug-in series). The last lot has some merit, but that calls for another article, another discussion. But overall, we've to make sure that we don't slow down EVs.

IN SHORT

- EV battery uses energy four times more efficiently than petrol engines;
- EVs don't waste energy during idling (say, at traffic lights or in traffic jams);
- Every electric car sold comes with a home charger;
- Technologies to recycle EV batteries have started making economic sense;
- EVs operate quietly, reducing noise pollution.

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Figure II. 3. Financial Express, August 24, 2024 livemint.com **Encouraging hybrid vehicles will make climate change harder to fight | Mint**

mint

6–8 minutes

Electric Vehicles (EVs) replace petrol as a source of energy used in petrol vehicles (PVs) with electricity. While electricity can be generated from fully renewable sources, such as the sun and wind, and can be completely green, petrol comes from fossil fuels, which results in air pollution and greenhouse gas (GHG) emissions.

As climate change caused by these emissions increasingly threatens life on Earth, the world needs to replace fossil fuels with green sources of energy and PVs with EVs. This was not possible some years ago, as green electricity and EVs were very expensive. However, things have changed and green electricity now costs less than the electricity generated using fossil fuels such as coal, gas and diesel. At the same time, EVs are becoming cost-competitive vis-a-vis PVs.

Manufacturers of PVs that have failed to carry out sufficient R&D in time to switch over to EV-making seem to have embarked on a campaign to run down and slow the emergence of EVs.

First, they claimed that EVs are not green, as the power used is sourced from fossil fuels, that they cost too much, do not go long distances, and that they lack charging infrastructure. These half-truths did not stop EVs from selling.

Then, to prolong the life of their PVs, they came up with hybrids and tried to portray them as part-EVs. Let us examine what these hybrids are.

Ever since the use of petrol grew, auto-makers have been carrying out R&D to enhance the efficiency of their vehicles and reduce the amount of petrol used per kilometre. As petrol costs rose, fuel efficiency arose as a marketing edge. This was indeed welcome.

Energy in a vehicle is wasted when brakes are applied while descending a slope or slowing down. As power electronics advanced and EVs emerged, researchers developed a mechanism called regeneration to recover part of this energy and convert it back into electricity to charge the vehicle's battery. This made these vehicles more efficient.

Makers of PVs seized upon this technology to stretch the life of their product portfolios. They inducted regeneration into their vehicles and started charging auxiliary batteries to deliver better fuel economy. They called these vehicles hybrids.

But, as they could derive only a small advantage through regeneration, they started doing more. Recognizing that petrol engines reach peak efficiency only when these vehicles are driven at a particular speed, torque and power, they came with another form of hybrid.

They added an electric drive-train with a small battery and motor to be used while starting the vehicle and to increase speed; the petrol engine would turn on only once its speed reached a certain level.

To differentiate between these and vehicles using only regeneration, they rechristened the former as 'mild hybrids' and these new ones as 'strong hybrids.' The latter assured higher energy efficiency, using less petrol per kilometre, and resulted in less GHG emissions.

This led PV makers to project such hybrids as EV equivalents. The fact that these vehicles still use a fossil fuel as their energy source has largely been obfuscated.

As regulators refused to accept strong hybrids as EV equivalents, PV makers came up with yet another version: plug-in hybrids (PHEVs). These would indeed have an electric drive-train, but with a small battery to be charged using electricity from the grid.

PHEVs operate as EVs for a limited range (say, the first 60km), but to go further, they have a petrol fuel tank and a generator that converts petrol to electricity and charges the battery.

The argument was that since most vehicles travel only a small distance on most days, they would be driven with grid electricity. Only if they needed to go longer distances would petrol be used for range extension. PV makers have used these arguments to lobby for green incentives for PHEVs of the kind that EVs are given (with success in some places).

However, the experience of some European countries shows that PHEV users usually do not plug their vehicles in for grid charging and mostly use just the petrol engine to drive their vehicles. The plug-in apparatus then looks like just a façade to get incentives.

Manufacturers have also come up with parallel PHEVs, with an internal combustion engine (ICE) and electric motor designed to work in parallel. Confusing? It sure is.

The primary purpose of these so-called hybrid variants appears to be largely to obtained EV-like incentives. It is unfortunate that some governments are falling for such tricks that extend PVs' lease of life and slow down the adoption of EVs.

In Series PHEVs, an internal combustion engine cannot drive the vehicle directly, but only charge the battery. Such vehicles have a real-life driving range of 100km with air-conditioning (equivalent to a 140km certified range) and could be useful if they use GPS technology to stay strictly off ICE in geo-tagged urban centres, so as to restrain emissions.

If these conditions are satisfied without exception, incentives provided to Series PHEVs will not go waste and could perhaps be used till such time that our charging infrastructure gets strengthened.

Else, incentives for hybrids could hurt the climate by prolonging the life of ICE in the name of going green. The planet's future depends on fully replacing energy from fossil fuels with renewable electricity and the latter's use for transport. This transition is what people and governments need to support.

Figure II. 4. Mint, September 2024

GUEST VIEW

Spark a charging-facility boom to hasten EV adoption

ASHOK JHUNJHUNWALA

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A large variety of electric vehicles (EVs) have emerged in India. Their costs have been dropping rapidly, thanks to a fall in battery prices. At the same time, their quality is improving, making them more comfortable and easier to drive as compared to petrol vehicles. The focus of policy now needs to be on ensuring sufficient charging infrastructure. While this is being built, India needs it to grow at a much faster pace to keep up with the growth of EVs in the country.

To get the best life from batteries, it is desirable to charge them slowly (in three to six hours), and this can be done at places where vehicles are parked for a long time. Overnight charging at home and in office parking slots during daytime would, therefore, not only be the most convenient but also the best.

This is done using alternate current (AC) chargers with a power rating of 3 kilowatts (kW), 7kW, 11kW or 22k. While two- and three-wheelers may require only 3kW chargers, cars and larger vehicles would require higher-rate chargers. Most Indian cars use 7kW or 11kW chargers today and this may go up to 22kW in the near future.

On the other hand, for long-distance travel or when one is in a hurry, one needs fast chargers of an even higher power-rating to charge cars and larger vehicles, which can juice-up a vehicle in 30 to 60 minutes. Using these only occasionally does not hurt the life of batteries.

A reasonable number of direct current (DC) fast chargers, charging at a rate between 30kW and 120kW, are already deployed on 85% of Indian highways. These fast chargers have also been deployed in various cities at locations like malls and parking buildings. What one requires is a single mobile app that can tell EV drivers where these chargers are placed, regardless of which operator they may belong to, and allow drivers to reserve them. Such apps are becoming available.

The question is whether the deployment of public chargers is financially viable today. While it is getting better, a viability gap still exists. This gap will disappear as the number of EVs on the roads increases.

Current incentive schemes to deploy fast chargers in public places are likely to see this through. The issue, however, is a bit more complicated for AC slow chargers. Here are different ways of incentivizing their deployment.

First, as noted earlier, the best place to use an EV charger is at home. If a customer wishes to deploy it at his or her dedicated parking space, s/he could purchase and install low-cost 3kW charging equipment, as a vehicle would likely be parked long enough to charge.

Second, for residential housing complexes, the builder or welfare association of the complex should mandatorily install some chargers for residents.

A mix of 3/7/11kW AC chargers could be installed, and EV users can be asked to pay at a rate determined by the electricity used as well as the time span of charging. The system of payments should be such that it enables the builder or association to recover the capital expenditure incurred on installing the charging facility within 12 to 15 months. At the same time, this should incentivize the user to detach the vehicle from the charger as soon as its battery is fully charged, so that others can use it. Office and commercial complexes should also mandatorily install such public chargers. Users can be charged similar tariffs.

Dedicated power lines and sensible tariffs for EV charging could help crack a chicken and egg problem

Three, it is important to use an appropriate source of electricity. If one uses the common area power line for the purpose of EV charging, the electricity rates (including demand charges) would be high. This is where electricity distribution companies (discoms) come in, as they also have a role to play in promoting the adoption of EVs. It would be best if a discom provides a separate and special EV power line (EVPL) with special tariffs for residential and commercial complexes. These lines are to be used exclusively for low-power EV chargers (3/7/11kW installations), complete with electricity meters and the capacity to communicate directly with the discom over wireless 4G/5G telecom networks. When the total electricity drawn on the EVPL at any time exceeds what the meters on connected EV chargers show, the line can be simply cut off.

Four, it may be desirable for EVPL chargers to have a simple electricity tariff structure—say of ₹4 and ₹6 per unit (kWh) during off-peak and peak hours, respectively, and zero demand charges. Such a system could have a provision that enables the discom to send a message to all connected chargers to reduce the maximum charging rate whenever it faces a shortage of electricity (and is purchasing power at high rates). This variability would help the discom balance its supply and demand of electricity in peak hours.

While many states have a policy of providing special power lines for charging EVs, their approach falls short of what is needed. It is advisable to take a new approach to providing dedicated EV charging lines through a single-window system at residential and commercial complexes.

This could help accelerate the installation of EV chargers at such complexes and thereby the adoption of EVs in the country. It would not overburden electricity discoms, but will surely help customers.

Policy action in this direction is highly desirable.

Figure II. 5. Mint, 18th March, 2025

APPENDIX – III: LIFE CYCLE ASSESSMENT OF ROAD TRANSPORTATION TECHNOLOGY AND REVIEW

The appendix explains the LCA approach, system boundaries (like cradle-to-grave), methodology, assumptions, and sensitivity analysis. It also includes a short summary and inferences of key reports and literature on LCA of ICEV's and BEV's.

III. a. LCA Methodology and Framework

Life Cycle Assessment represents a structured analytical approach to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction through materials processing, manufacturing, distribution, use, repair and maintenance, to disposal or recycling. For transportation technologies, this comprehensive approach is particularly valuable as impacts occur across multiple stages and geographical locations.

The LCA methodology generally follows the four main phases outlined in ISO 14040 and ISO 14044 standards:

- **Goal and scope definition:** Establishing the intended application, reasons for carrying out the study, target audience, and system boundaries
- **Inventory analysis:** Compiling and quantifying inputs and outputs throughout the life cycle
- **Impact assessment:** Evaluating potential environmental impacts associated with inventory
- **Interpretation:** Analyzing results and forming conclusions and recommendations

System Boundaries in Transportation LCA

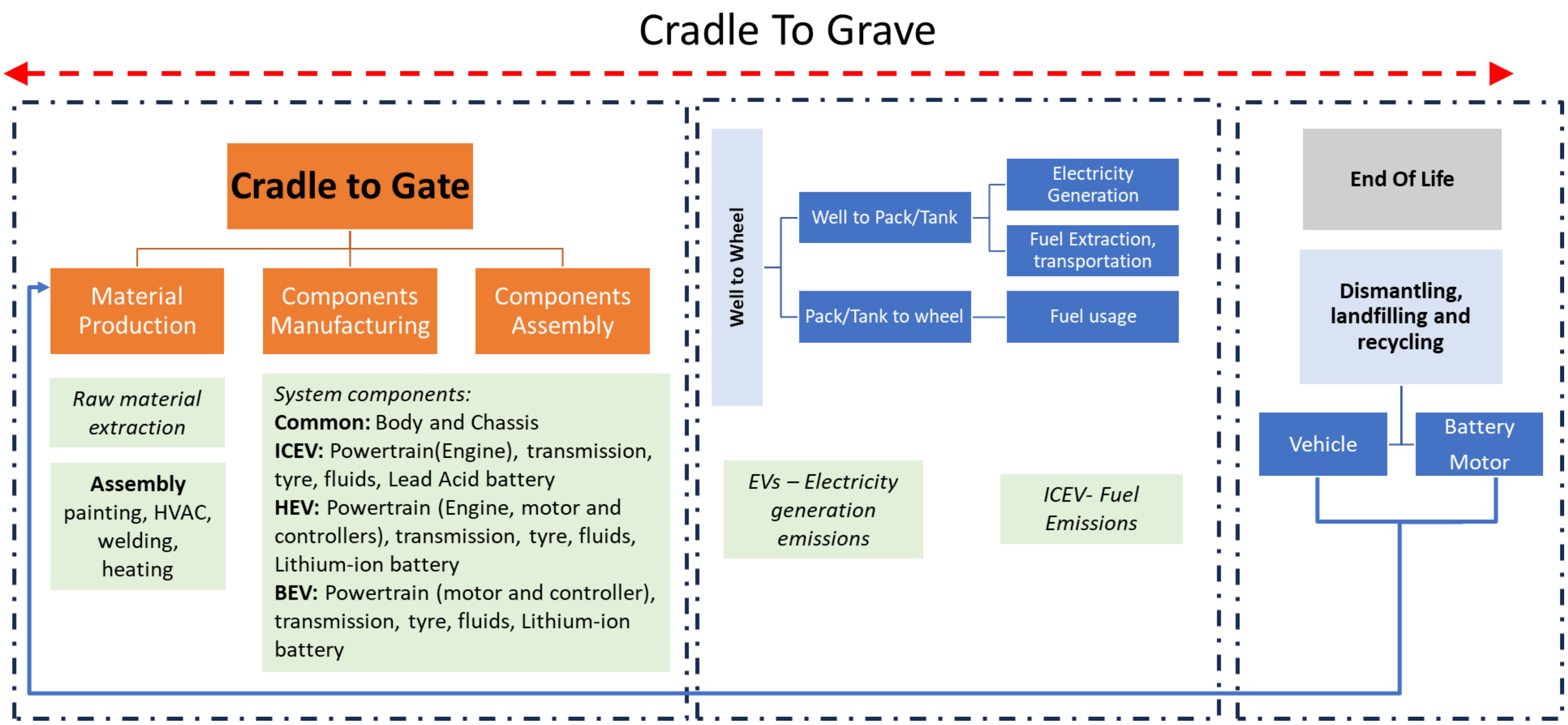

Figure III. 1. System boundary flowchart from Cradle to Grave

A critical aspect of LCA methodology is defining appropriate system boundaries. For road transportation technologies, several common system boundary definitions appear across studies:

Cradle-to-Gate (C2G)

This boundary encompasses processes from raw material extraction through vehicle manufacturing and assembly. This includes:

- Raw material extraction and processing
- Transportation of materials
- Vehicle Manufacturing
- Assembly processes

Well-to-Wheel (W2W)

This boundary focuses on the energy carrier, encompassing:

- Well-to-Tank (W2T): Fuel extraction, processing, and transportation; electricity generation and transmission
- Tank-to-Wheel (T2W): Energy consumption during vehicle operation

End-of-Life (EOL)

This boundary covers the final stage of the vehicle life cycle:

- Dismantling and disassembly
- Recycling processes
- Landfilling of non-recyclable components
- Incineration, where applicable

Complete Cradle-to-Grave

The comprehensive boundary integrates all three previous boundaries [C2G, W2W, and EOL] to provide a holistic view of environmental impacts throughout the entire life cycle. This approach allows for the most complete comparison between different transportation technologies and is increasingly being adopted as the standard for policy-relevant LCA studies.

Figure III.1. illustrates the complete system boundary for BEVs, showing all processes from raw material extraction through end-of-life management, including detailed considerations for the vehicle powertrain system.

Functional Unit

The selection of an appropriate functional unit is crucial for meaningful comparisons between different transportation technologies. Common functional units observed across the studies include:

- Grams of CO_2 equivalent per kilometre travelled (gCO_2 eq./km): Most frequently used for vehicle comparison
- Kilograms of CO_2 equivalent per kilowatt-hour (kg CO_2 eq./kWh): Often used for battery-specific assessments
- Total lifecycle emissions (e.g., tons of CO_2 equivalent): Used to express absolute emissions over vehicle lifetime

Key Assumptions and Methodological Considerations

Several critical assumptions significantly influence LCA outcomes for transportation technologies:

- Vehicle Lifetime Distance
- Electricity Generation Mix
- Recycling Rates
- Battery Replacement
- Manufacturing Scope (full vehicle vs component level)

The comprehensive approach of LCA methodology demonstrates its value for transportation technology assessment. By capturing environmental impacts across all life cycle stages and considering multiple impact categories, LCA provides a holistic evaluation framework essential for informed decision-making by policymakers, academics, and industry professionals.

III. b. Summary and Inferences of Key Reports and Literature on LCA for ICE and EVs

This section synthesizes findings from major reports on LCA for ICEVs and EVs, highlighting methodological differences, key outcomes, and critical insights. Additionally, it examines specific considerations that significantly influence LCA results: recycling processes and electricity mix variations.

Recent years have seen several comprehensive LCA studies specifically examining Indian transportation contexts. Four key detailed studies were analyzed, and inferences are drawn along with the limitations in this report. The studies included are:

1. **Article 1.** Comparative life cycle GHG emission analysis of conventional and electric vehicles in India **–** Dr. Jani Das, Muthoot Institute of Technology and Science, 2021 (Springer) **Error! Reference source not found.**
2. **Article 2**. Should India Move Toward Vehicle Electrification? Assessing Life Cycle Greenhouse Gas and Criteria Air Pollutant Emissions of Alternative and Conventional Fuel Vehicles in India – Stanford University, 2022 (ACS) **Error! Reference source not found.**
3. **Report 1.** LCA and TCO Analysis of BEVs, HEVs, and ICEVs –Dr. Avinash Kumar Agarwal, IIT Kanpur, March 2023 **Error! Reference source not found.**
4. **Report 2.** Comparative Analysis of Electric Vehicles and Internal Combustion Engine Vehicles from Resource Efficiency Perspective, NITI Aayog, Jul 2023 (TERI Energy and Research Institute) **Error! Reference source not found.**

Article 1: Kerala Institute Study (2021)

This study compared the Mercedes A-class (ICEV) and Hyundai Kona EV (BEV) with three battery chemistries (NMC, LFP, LMO) under Indian conditions.

Key Findings:

- Lifecycle emissions: ICEV (270 gCO_2 eq./km), BEV (370 gCO_2 eq./km)
- Battery chemistry significantly affected emissions: LFP showed the highest GHG emissions
- Battery contribution to total BEV emissions varied by chemistry: LFP (62%), NMC (43%), LMO (26%)
- Well-to-wheel phase dominated emissions for both vehicle types: ICEV (80-83%), BEV (67.3-78.5%)

Sensitivity Analysis:

- Increasing renewable mix from current levels to 27% would reduce electricity GHG footprint from 1.4 to 0.9 kgCO_2 eq./kWh
- Manufacturing batteries in India with imported raw materials could reduce transportation-related emissions by 0.4-0.5%

Limitations:

- End-of-life stage contributed minimally (0.7-1.1% for EVs)
- Battery second life is mentioned but not quantified
- Some inconsistencies in material-level GHG emissions calculations

Article 2: Stanford University Study (2022)

This study analyzed GHG and criteria air pollutant (CAP) emissions for passenger vehicles across multiple vehicle types and technologies, with particular attention to regional variations within India.

Key Findings:

- National average emissions: ICEV (216 gCO_2 eq. /km), HEV (198 gCO_2 eq./km), PHEV (213 gCO_2 eq./km), BEV (185 gCO_2 eq./km)
- Significant regional variations:
- States with high coal dependency showed higher emissions for BEVs than conventional vehicles
- 11 states/UTs showed lower GHG emissions for BEVs but still experienced higher SO_2 emissions
- Rajasthan, Puducherry, and Tamil Nadu showed very high SO_2 emissions from BEVs due to coal-dominated electricity

Sensitivity Analysis:

- Temperature effects showed substantial energy consumption increases for BEVs at extreme temperatures: +89% at 20°F, +33% at 95°F
- BEV 4W emissions become lower than gasoline compact vehicles at grid emission factors around 350 kgCO_2 eq. /MWh
- Afternoon charging (2-6 pm) showed decreases in both CO_2 and SO_2 emissions across heavily populated states

Limitations:

- Battery recycling and second-life applications are not considered
- Battery replacement is assumed but not explicitly modeled in the results
- Followed conservative electricity mix (80.6% fossil)

Report 1: IIT Kanpur Report (March 2023)

IIT Kanpur examined Indian brand vehicles including ICEV (Tata Nexon Petrol), HEV (Maruti Grand Vitara), and BEV (Tata Nexon EV) across production, usage, and end-of-life stages.

Key Findings:

- Lifecycle GHG emissions: ICEV (244 gCO_2 eq./km), HEV (167 gCO_2 eq./km), BEV (187 gCO_2 eq./km)
- HEVs performed best, with emissions 10.69% lower than BEVs and 31.55% lower than ICEVs
- BEVs showed 23.36% lower emissions than ICEVs, attributed to shorter range (312 km vs. 550 km)

Sensitivity Analysis:

- One-time battery replacement increased lifecycle emissions for BEVs by 6.9% and HEVs by 1.2%
- BEVs showed higher emissions than ICEVs for lifetime distances below 33,000 km
- Regional variations showed HEVs consistently outperforming both BEVs and ICEVs

Limitations:

- Adopted conservative electricity mix (79% fossil, 21% non-fossil)
- End-of-life management details not provided
- Second-life battery applications have not been explored

Report 2: TERI Report (July 2023)

The TERI report conducted a detailed LCA of TATA Nexon vehicles across three variants: BEV, ICEV-Diesel, and ICEV-Petrol, with a comprehensive system boundary encompassing raw material extraction through end-of-life management.

Key Findings:

- Lifecycle GHG emissions: BEVs (24.8 tons), Diesel ICEVs (27.2 tons), Petrol ICEVs (30.2 tons)
- Per-kilometre emissions: BEVs (150.8 gCO_2 eq./km), Diesel ICEVs (170 gCO_2 eq./km), Petrol ICEVs (189 gCO_2 eq./km)
- EVs outperformed ICEVs in GWP, ozone depletion, and ecotoxicity.
- However, EVs performed worse in water consumption (1.5x more), particulate matter formation, and resource utilization.

Sensitivity Analysis:

- 50% renewable electricity could reduce BEV emissions by 22%
- E20 fuel instead of E5 showed minor improvements for ICEVs

Limitations:

- Northern India grid used for electricity mix calculations (year not specified)
- Recycling contributions are limited to 2.5% of total GHG emissions despite high assumed recovery rates (93% for batteries, 75% for motors)
- Component wear and tears are not considered.

Table III. 1. GHG emissions were reported in four different studies included in this analysis.

GHG Emissions (eq grams CO_2 / km)																
	Reported by															
	IIT K (2023)				TERI (2023)				Stanford (2022)				Kerala Institute (2021)			
LCA Metrics	ICEV	HEV	PHEV	BEV	ICEV	HEV	PHEV	BEV	ICEV	HEV	PHEV	BEV	ICEV	HEV	PHEV	BEV
C-Grave	244	167	N/A	187	189	N/A	N/A	150	216	198	213	185	270	N/A	N/A	370
W-W	205	127	N/A	140	188	N/A	N/A	148	172	112	127	103	221	N/A	N/A	252
W-T/P	N/A	N/A	N/A	N/A	37	N/A	N/A	134	32	25	75	103	N/A	N/A	N/A	N/A
T/P-W	N/A	N/A	N/A	N/A	151	N/A	N/A	14	140	87	52	0	N/A	N/A	N/A	N/A
C-Gate	39	40	N/A	47	2	N/A	N/A	6	38	76	74	75	46	N/A	N/A	118
EoL	N/A	N/A	N/A	N/A	1	N/A	N/A	-4	6	10	12	7	0.81	N/A	N/A	2.96
Vehicles	Tata Nexon ICEV, BEV, and Maruti Grand Vitara HEV				TATA Nexon (BEV, ICEV-Petrol, ICEV-Diesel)				Maruti Suzuki, Prius hybrid, Toyota Prius - Prime, Mahindra E-20				Mercedes Class A, Hyundai Kona EV			
Cradle to Gate	Whole vehicle				Power Train				Whole vehicle				Whole vehicle			
Electricity mix	79% Fossil, 21% non-fossil (2020)				62% Fossil, 38% Renewable				81% Fossil, 18% non-fossil (2019, BP statistical review)				78% Fossil, 22% non-fossil (2020)			

III. c. Specific Considerations in LCA - Recycling

Two key LCA studies related to BEV recycling are investigated, and the essence of the work is captured in the following.

Article 1: Life Cycle Assessment of Lithium–ion Battery Materials in Production and Recycling Phase: Evaluation of Global Greenhouse Gas Emissions and Environmental Impacts, Beijing Institute of Technology (Dec 2024), Social Science Research Network **Error! Reference source not found.**

This study specifically examines the carbon footprints, greenhouse gas emissions, and ecological indicators of Lithium-ion battery production for NCM, NCA, and LFP chemistries, and assesses the life cycle of recycled graphite from spent LIBs.

The results of Article 1 show that magnesium–sulphur batteries exhibit the lowest environmental footprint due to their minimal resource demands, while LFP chemistries demonstrate the best overall greenhouse gas emissions performance, followed by NCM and NCA. The cathode alone contributes significantly, accounting for 30% to 60% of a battery's total emissions.

Article 2: Impact of electric vehicle battery recycling on reducing raw material demand and battery life-cycle carbon emissions in China – 2025, Scientific reports (Nature), 2025 **Error! Reference source not found.**

In this article, an LCA was performed on LFP and NCM batteries for road transportation, analyzing material demand based on market trends between 2020 and 2060. The study encompassed battery production, use, and end-of-life (EOL) phases, considering BEVs, including cars, buses, taxis, and trucks, with a second-use battery life set at 10 years.

Four scenarios were explored:

- Scenario 1 assumed an average battery life of 8 years with NCM dominating the market over LFP.
- Scenario 2 extended the battery life to 10 years, building upon Scenario 1.
- Scenario 3 saw LFP becoming dominant over NCM, building on Scenario 2.
- Scenario 4, building on Scenario 3, explored a high-nickel-oriented path for NCM technology development.

Sensitivity analyses were conducted on EOL strategies, specifically comparing pyrometallurgy, hydrometallurgy, and two direct cathode recycling methods, and these EOL strategies were assessed to include the impact of second-use battery life.

When excluding EOL techniques, the battery use phase accounts for more than 80% of cumulative carbon emissions, making it the primary contributor. The possibility for reducing carbon emissions by recycling alone, without a second use, is low; across the four scenarios, the average is only 3.4% for DCR-C, 2.8% for DCR-B, 2.1% for HR, and 0.8% for PR. This demonstrates that the advantages of conventional recycling and remanufacturing are still outweighed by the second usage. On the other hand, combining recycling with 100% second use retired LFP batteries greatly increases the average possible decrease in carbon emissions to 37.9% with DCR-C, 37.5% with DCR-B, 37.1% with HR, and 36.0% with PR.

III. d. Takeaway from Earlier Studies on Recycling and Electricity Mix Considerations

Recycling

Vehicle and component recycling represent critical aspects of transportation LCA that can significantly influence results. The studies reviewed reveal several important insights regarding recycling processes, benefits, and limitations.

Recycling Processes and Technologies:

The studies mention several approaches to battery recycling:

1. Pyrometallurgy (PR): A high-temperature process that recovers cobalt, nickel, and copper but typically loses lithium and aluminium. This process is energy-intensive, releasing VOCs during thermal decomposition.
2. Hydrometallurgy (HR): Chemical leaching processes that can recover more materials than pyrometallurgy but produce acidic solutions with environmental impacts.
3. Direct Cathode Recycling (DCR): Advanced processes that attempt to recover cathode materials directly, preserving their structure and requiring less energy.
4. Combined Approaches: The Beijing Institute study noted that hydrometallurgy combined with pyrometallurgy yields the best recovery rates for raw materials.

Environmental Benefits:

The studies quantified several environmental benefits of recycling:

- TERI reported a net recycling contribution of - 619 kg CO_2 eq. for BEVs, representing approximately 2.5% of total lifecycle emissions.
- The Nature study (2025) indicated recycling alone contributes to approximately 3.5% GHG reduction, which increases to 38% when combined with second-life applications.
- Recovery rates were reported at up to 93% for batteries and 75% for motors in the TERI study.

Challenges and Limitations:

Despite its benefits, recycling faces several challenges:

- The Beijing Institute study revealed wide variations in GHG values for graphite recovery, ranging from 5.69 to 1199.94 kg CO_2/kg of recovered graphite, sometimes exceeding emissions from virgin graphite production.
- Economic considerations often limit lithium recovery in pyrometallurgical processes.
- The Kerala Institute study showed end-of-life contributions to only about 0.3% for ICEVs and 0.7-1.1% for EVs, suggesting limited current impact.
- Most studies applied theoretical recycling rates rather than actual industry practices, potentially overestimating benefits.

Prospects:

The studies suggest several promising developments:

- Direct Cathode Recycling shows the most significant potential for reducing raw material demand but requires further technological maturation.
- Recycling with 100% second use of retired LFPs could boost carbon emission reduction potential to 36-38%.
- Calcination combined with leaching processes shows promise for anode recycling.

Electricity Mix data

India currently has a demand for 464 GW of power production capacity, out of which 45% is coming from renewable sources, which includes 22% solar, 11% wind, 2% biomass, and 10% hydro. Currently, coal remains the dominant source of grid emissions, contributing about 95.4% of the total emissions. It is projected that the power production capacity will increase 4 times by the year 2050, with a total requirement of 2110 GW, with renewables contributing a total of 63% in the overall capacity requirements.

Table III. 2. Decade-wise power generation distribution projection

Sources Category	Year (Distribution)	2025 (CEA) Error! Reference source not found.	2030 (CEA) Error! Reference source not found.	2040 (IFA)	2050 (TERI)	Total
Renewables: According to CEA and IEA	%Solar	22%	34%	42%	35%	**63%**
	%Wind	11%	17%	15%	25%	
	%Biomass	2%	2%	2%	1%	
	%Hydro	10%	9%	7%	2%	
Fossil Fuel	%Coal/ (Coal + Oil)	48%	33%	29%	33%	**36%**
	%Natural Gas	5%	3%	3%	3%	
Non-Fossil Fuel	%Nuclear	2%	2%	2%	1%	**1%**
Capacity (GW)	Installed Capacity	**464**	**817**	**1466**	**2110**	**100%**

Renewable energy capacity sees over a 57% increase from 2025 to 2030. Then, for each decade, we notice only a 3% increase each year. It is important to note that the average CO_2 emission must drop to 300g CO_2/kWh for a 50% reduction from EVs. There is a decreasing trend in Hydroelectricity, yet the installed capacity continues to increase overall capacity. Complete reliance on Renewable accounts to electricity deficit, accounting for BESS-related emissions not mentioned. Emission is completely dependent on the electricity mix and not the capacity installed.

Appendix – III References

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APPENDIX – IV: INHOUSE LCA MODEL DEVELOPMENT AND DATA GENERATION

Appendix – IV presents the GHG emission calculation process and context behind the values chosen, in the case of both ICEV and BEV, for each vehicle component chosen. Information and assumptions associated with the LFP battery cradle-to-gate emission data collection are also discussed.

IV. a. CO_2 eq. emission calculation and Vehicle Component Proportions for the LCA Model

CO_2 Equivalent (CO_2 eq.) GHG Emissions Formula

The influence of various greenhouse gases (GHGs) is expressed using a standardized metric called CO_2 equivalent (CO_2 eq.), which measures how much CO_2 would have the same global warming effect.

Formula:

The general formula for calculating CO_2 equivalent emissions is:

$$\boldsymbol{CO2\ eq.} = \sum_{\boldsymbol{i}} (\boldsymbol{Mass\ of\ GHG_i} \times \boldsymbol{GWP_i})$$

where:

Mass of GHG_i is the amount (typically in tonnes or kilograms) of the specific greenhouse gas emitted.

GWP_i is the global warming potential of that gas over a specified time horizon (usually 100 years), relative to CO_2 (which has a GWP of 1).

GWP Values used: CO_2: 1, CH_4 (methane): 29.8, N_2O (nitrous oxide): 273 **Error! Reference source not found.**.

Vehicle Components

The individual components of the 4-Wheeler passenger cars and their respective percentage division into the 3M processes is given in **Error! Reference source not found.**.

Table IV. 1. Vehicle Components considered

S. No.	Components	ICEV	BEV	Mining/Recycling (%)	Material Processes (%)	Manufacturing (%)
1	Vehicle Body	YES	YES	9	81	10
2	Powertrain System (Engine)	YES	NO	5	75	20
3	Powertrain (Motor and Controller)	NO	YES	7	63	30
4	Transmission System/gearbox	YES	YES	8	68	25
5	Chassis - w/o battery	YES	YES	8	73	19
6	Vehicle tire replacement	YES	YES	13	52	35
7	Others (Engine Oil, Brake fluid, Transmission fluid, Engine/powertrain coolant, Windshield Fluid, Adhesives, Lead Acid Battery)	YES	YES	32.5	32.5	35
8	Assembly, Disposal and Recycling	YES	YES	0	0	100
9	Traction Battery Bill of Material and Assembly	NO	YES	0	0	100

The justification for the percentage contribution of individual elements throughout the cradle-to-gate process is provided below in sections IV. b and IV. c.

IV. b. ICEV Vehicle Manufacturing Data

1. Vehicle Body: The body is primarily made of steel, aluminium, glass, and plastics. Mining and recycling contribute a small share of emissions because extracting raw materials like iron ore and bauxite is less carbon-intensive compared to subsequent stages. The bulk of emissions (81%) arise during material processing and refining, as steel and aluminium production are highly energy-intensive, particularly in smelting and reduction processes. Manufacturing, which includes forming and assembling the body, contributes the remaining emissions due to energy use in shaping and joining materials. **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**
2. Powertrain System (Engine): The powertrain is largely composed of cast iron, steel, and aluminium alloys. Mining and recycling account for 5% of emissions, as this stage involves extraction and basic preparation. Material processing, including smelting, alloying, and heat treatment, is the most GHG-intensive (75%) due to the high energy demand and chemical reactions involved. Manufacturing (20%) covers machining, casting, and assembly, which are less energy-intensive but still significant. **Error! Reference source not found.**
3. Transmission System/Gearbox: The logic is similar to the powertrain, as transmissions are made from steel and cast iron. Mining/recycling (8%) and manufacturing (25%) are less intensive, while material processing (68%) dominates due to the complexity of producing high-strength alloys and precise components. **Error! Reference source not found.**
4. Chassis (without battery): The chassis uses mainly steel (80%) and aluminium (10%). Mining/recycling (8%) and manufacturing (19%) are relatively minor contributors, dominated by refining and material processing (73%) because of the energy required for alloy production and forming structural components. **Error! Reference source not found.Error! Reference source not found.Error! Reference source not found.**
5. Assembly, Disposal, and Recycling: For this category, 100% of emissions are attributed to the manufacturing stage, as these activities are entirely process-driven and involve assembling, disassembling, or recycling finished components, often using electric power.
6. Vehicle Tire Replacement: Tire production involves mining/recycling (13%) for natural and synthetic rubber and fillers, but major emissions (52%) come from compounding and processing materials, which are energy intensive. Manufacturing (35%) includes mixing, forming, vulcanizing, and final assembly, all of which require significant energy input. **Error! Reference source not found.**

7. Others (Fluids, Adhesives, etc.): Since no specific distribution was provided in the literature, and the contribution from these components in overall GHG emissions is significantly less, the total GHG emissions are approximately divided equally among the three segments.

Table IV. 2. ICEV Vehicle Body Emissions

1. Vehicle body - 640 kg				Unit: kg CO_2 eq.								
RE (%)	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**2374.21**			**2258.28**			**1969.66**			**1680.77**		
	213.68	1923.11	237.42	203.25	1829.21	225.83	176.28	1586.51	195.87	151.27	1361.43	168.08
50	**1825.50**			**1716.14**			**1443.87**			**1171.35**		
	158.81	1429.27	237.42	149.03	1341.28	225.83	123.76	1113.87	195.87	100.33	902.95	168.08
100	**1276.79**			**1173.99**			**918.08**			**661.93**		
	103.94	935.43	237.42	94.82	853.35	225.83	71.25	641.22	195.87	49.39	444.47	168.08

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 3. ICEV Powertrain emissions

2. Powertrain - 151kg				Unit: kg CO_2 eq.								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	I	II	III	I	II	III	I	II	III	I	II	III
0	**799.11**			**767.25**			**687.93**			**608.54**		
	63.93	575.36	159.82	61.38	552.42	153.45	54.79	493.14	136.98	48.68	438.15	121.71
50	**577.26**			**547.14**			**488.23**			**426.07**		
	41.74	375.69	159.82	39.37	354.32	153.45	34.89	313.98	136.98	30.44	273.93	121.71
100	**373.09**			**344.14**			**272.06**			**199.91**		
	21.33	191.94	159.82	19.07	171.62	153.45	13.23	119.09	136.98	7.82	70.38	121.71

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 4. ICEV Transmission System Emissions

3. Transmission System - 92 kg												
	Unit: kg CO_2 eq.											
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**399.85**			**387.03**			**355.12**			**323.18**		
	29.99	269.90	99.96	29.03	261.25	96.76	26.54	238.88	88.47	24.24	218.14	80.79
50	**292.46**			**280.28**			**249.93**			**219.56**		
	19.25	173.25	99.96	18.35	165.17	96.76	16.03	144.27	88.47	13.88	124.89	80.79
100	**185.08**			**173.52**			**144.75**			**115.95**		
	8.51	76.61	99.96	7.68	69.09	96.76	5.52	49.66	88.47	3.52	31.64	80.79

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 5. ICEV Chassis (W/o Battery) Emissions

4. Chassis W/o Battery - 325kg				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**1430.59**			**1375.03**			**1236.71**			**1098.26**		
	115.88	1042.90	271.81	111.38	1002.40	261.26	99.75	897.72	233.97	88.96	800.63	208.67
50	**1011.14**			**960.50**			**834.42**			**708.22**		
	73.93	665.40	271.81	69.92	629.32	261.26	59.56	536.07	233.97	49.95	449.59	208.67
100	**591.69**			**545.97**			**432.13**			**318.18**		
	31.99	287.89	271.81	28.47	256.24	261.26	19.38	174.43	233.97	10.95	98.56	208.67

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 6. ICEV Assembly Disposal and Recycling Emissions

5. Assembly Disposal and Recycling				Unit: kg CO_2 eq.								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**920.31**			**813.20**			**546.57**			**279.68**		
	0.00	0.00	920.31	0.00	0.00	813.20	0.00	0.00	536.40	0.00	0.00	279.68
50	**920.31**			**813.20**			**546.56**			**279.68**		
	0.00	0.00	920.31	0.00	0.00	813.20	0.00	0.00	536.40	0.00	0.00	279.68
100	**920.31**			**813.20**			**546.57**			**279.68**		
	0.00	0.00	920.31	0.00	0.00	813.20	0.00	0.00	536.40	0.00	0.00	279.68

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 7. ICEV Vehicle Tire (with Replacement) Emissions

6. Vehicle Tire with Replacement - 256kg				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**987.24**			**955.71**			**877.19**			**798.59**		
	128.34	513.37	345.54	124.24	496.97	334.50	113.65	454.58	305.97	103.82	415.27	279.51
50	**886.16**			**855.94**			**780.69**			**705.37**		
	108.13	432.50	345.54	104.29	417.15	334.50	94.37	377.48	305.97	85.17	340.69	279.51
100	**785.08**			**756.17**			**684.19**			**612.15**		
	87.91	351.64	345.54	84.33	337.34	334.50	75.10	300.39	305.97	66.53	266.11	279.51

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 8. ICEV Miscellaneous Emissions

7. Others (Fluids + Lead Acid Battery)- 380 kg				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**787.55**			**771.60**			**731.88**			**692.12**		
	255.96	255.96	275.64	250.77	250.77	270.06	237.37	237.37	255.63	224.94	224.94	242.24
50	**778.86**			**764.66**			**729.30**			**693.92**		
	251.61	251.61	275.64	247.30	247.30	270.06	236.17	236.17	255.63	225.84	225.84	242.24
100	**770.17**			**757.72**			**726.73**			**695.71**		
	247.26	247.26	275.64	243.83	243.83	270.06	234.96	234.96	255.63	226.73	226.73	242.24

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

IV. c. BEV Vehicle Manufacturing Data

1. Vehicle Body, Transmission, Chassis, Assembly, Tire Replacement, Others: For these components, the logic and distribution of emissions mirror those of ICEVs, as the material composition and manufacturing processes remain largely unchanged between the two vehicle types.
2. Powertrain (Traction Motor + Controller): In BEVs, the powertrain is simpler but still involves significant emissions from mining (5%), material processing (75%), and manufacturing (20%) due to the use of copper, steel, and rare earth materials in motors and controllers.
3. LFP Battery Pack: The battery pack is unique to BEVs and has a distinct emissions profile. Mining and recycling (15%) are significant due to the extraction of lithium, iron, phosphate, and other battery materials. Material processing (50%) is the most GHG-intensive, as refining and synthesizing battery-grade materials require substantial energy, often from fossil sources. Manufacturing (35%) covers cell assembly, module integration, and pack assembly, all of which are energy-demanding operations. **Error! Reference source not found.**

Table IV. 9. BEV Vehicle body Emissions

1. Vehicle body - 557kg				Unit: kg CO_2 eq.								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**2072.91**			**1963.91**			**1717.94**			**1467.67**		
	186.56	1679.05	207.29	176.75	1590.77	196.39	154.62	1391.54	171.79	132.09	1188.82	146.77
50	**1593.19**			**1497.74**			**1260.13**			**1022.29**		
	138.59	1247.31	207.29	130.14	1171.22	196.39	108.83	979.50	171.79	87.55	787.97	146.77
100	**1114.31**			**1024.59**			**800.05**			**577.70**		
	90.70	816.31	207.29	82.82	745.38	196.39	62.83	565.43	171.79	43.09	387.84	146.77

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 10. BEV Powertrain Emissions

2. Powertrain - 22.22kg				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**89.56**			**83.26**			**69.04**			**54.58**		
	7.17	64.48	17.91	6.66	59.95	16.65	5.52	49.71	13.81	4.37	39.30	10.92
50	**77.26**			**71.58**			**57.42**			**43.25**		
	5.94	53.42	17.91	5.49	49.43	16.65	4.36	39.25	13.81	3.23	29.10	10.92
100	**64.97**			**59.44**			**45.68**			**31.91**		
	4.71	42.35	17.91	4.28	38.51	16.65	3.19	28.69	13.81	2.10	18.89	10.92

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 11. BEV Transmission System Emissions

3. Transmission System - 16.66 kg				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**83.30**			**78.84**			**68.79**			**58.57**		
	6.25	56.23	20.83	5.91	53.22	19.71	5.16	46.44	17.20	4.39	39.53	14.64
50	**61.65**			**57.70**			**47.86**			**38.02**		
	4.08	36.74	20.83	3.80	34.19	19.71	3.07	27.60	17.20	2.34	21.04	14.64
100	**40.17**			**36.40**			**27.02**			**17.63**		
	1.93	17.41	20.83	1.67	15.02	19.71	0.98	8.84	17.20	0.30	2.69	14.64

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 12. BEV Chassis (W/o Battery) Emissions

4. Chassis W/o Battery - 290.98kg				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**1279.30**			**1229.63**			**1105.95**			**982.16**		
	103.62	932.61	243.07	99.60	896.40	233.63	89.58	806.24	210.13	79.56	716.00	186.61
50	**904.02**			**858.74**			**746.02**			**633.19**		
	66.10	594.86	243.07	62.51	562.60	233.63	53.59	482.30	210.13	44.66	401.92	186.61
100	**529.01**			**488.12**			**386.35**			**284.47**		
	28.59	257.35	243.07	25.45	229.05	233.63	17.62	158.59	210.13	9.79	88.07	186.61

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 13. BEV Traction Motor and Electronics Controller Emissions

5. Traction Motor, Electronics Controller - 57.33kg				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	I	II	III	I	II	III	I	II	III	I	II	III
0	**383.8**			**368.5**			**333.8**			**298.5**		
	26.9	241.8	115.1	25.8	232.1	110.5	23.4	210.3	100.1	20.9	188.1	89.6
50	**268.2**			**255.0**			**222.1**			**189.2**		
	15.3	137.7	115.1	14.4	130.0	110.5	12.2	109.8	100.1	10.0	89.7	89.6
100	**153.2**			**141.1**			**110.3**			**79.6**		
	3.8	34.2	115.1	3.1	27.5	110.5	1.0	9.1	100.1	-1.0*	-9.0*	89.6

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

* The negative values are a result of calculation integrity/consistency, as the total emission value (79.6 kgCo$_2$ eq.) is obtained from the GREET model, while the three process breakup (I, II and III) are calculated as a function of their respective percentages: ***Not to be taken literally,*** as in, an indication/suggestion of negative emissions.

Table IV. 14. BEV Vehicle Tire (With Replacement) Emissions

6. Vehicle Tire with Replacement - 226kg				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**874.72**			**796.90**			**765.26**			**707.57**		
	113.71	454.85	306.15	103.60	414.39	278.92	99.48	397.93	267.84	91.98	367.94	247.65
50	**785.16**			**758.38**			**691.70**			**624.97**		
	95.80	383.20	306.15	95.89	383.57	278.92	84.77	339.09	267.84	75.46	301.86	247.65
100	**695.60**			**669.98**			**606.21**			**542.37**		
	77.89	311.56	306.15	78.21	312.85	278.92	67.67	270.69	267.84	58.95	235.78	247.65

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 15. BEV Miscellaneous Emissions

7. Others - 170 kg				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**137.48**			128.49			108.23			87.61		
	44.68	44.68	48.12	41.76	41.76	44.97	35.17	35.17	37.88	28.47	28.47	30.66
50	**132.29**			**125.00**			**106.85**			**88.68**		
	42.09	42.09	48.12	40.01	40.01	44.97	34.48	34.48	37.88	29.01	29.01	30.66
100	**127.11**			**120.86**			**105.31**			**89.75**		
	39.50	39.50	48.12	37.94	37.94	44.97	33.72	33.72	37.88	29.54	29.54	30.66

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

Table IV. 16. BEV Assembly Disposal and Recycling Emissions

8. Assembly Disposal and Recycling				**Unit: kg CO_2 eq.**								
RE%	**28%**			**40%**			**70%**			**100%**		
Recycling (%)	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**	**I**	**II**	**III**
0	**938.40**			**825.97**			**546.07**			**265.90**		
	0.00	0.00	938.40	0.00	0.00	825.97	0.00	0.00	546.07	0.00	0.00	265.90
50	**938.40**			**825.97**			**546.07**			**265.90**		
	0.00	0.00	938.40	0.00	0.00	825.97	0.00	0.00	546.07	0.00	0.00	265.90
100	**938.40**			**825.97**			**546.07**			**265.90**		
	0.00	0.00	938.40	0.00	0.00	825.97	0.00	0.00	546.07	0.00	0.00	265.90

I – Mining/ Recycling

II – Material Processing

III – Manufacturing and Assembly

IV. d. LFP Battery Manufacturing data

Battery manufacturing data was obtained from the supplementary Excel files accompanying the PNAS Nexus report published by the Oxford University Press **Error! Reference source not found.**.

The Nexus report has electricity mix data for 2020 (which is termed as current) and projections for 2023, 2040, and 2050.

Electricity mix of countries in LIB supply chain
Reference Year: 2020

	Argentina	*Australia*	*Bahrain*	*Belgium*	*Brazil*	*Canada*	*Chile*	*China*	*Cote d'Ivoire*	*Cuba*	*DRC*	*Finland*	*Gabon*	*Germany*	*Ghana*	*Guatemala*
Coal	1.36%	54.88%	0.00%	2.07%	2.82%	4.87%	31.14%	64.13%	0.00%	0.00%	0.00%	7.96%	0.00%	25.46%	0.00%	15.40%
Natural gas	60.89%	20.82%	99.99%	29.97%	8.61%	11.06%	17.98%	2.80%	68.97%	12.65%	0.02%	5.37%	50.35%	17.11%	58.79%	0.05%
Oil	4.64%	1.70%	0.01%	0.10%	1.73%	0.80%	3.72%	0.14%	0.08%	83.71%	0.05%	0.39%	9.98%	0.84%	3.93%	10.00%
Nuclear	7.39%	0.00%	0.00%	38.92%	2.26%	15.32%	0.00%	4.70%	0.00%	0.00%	0.00%	33.78%	0.00%	11.06%	0.00%	0.00%
Hydro	16.74%	5.71%	0.00%	1.49%	63.80%	60.03%	25.31%	17.12%	30.19%	0.70%	99.58%	23.00%	39.11%	4.27%	36.99%	47.22%
Biofuels	1.56%	1.26%	0.00%	4.89%	9.46%	1.54%	5.49%	1.46%	0.59%	2.13%	0.26%	15.95%	0.48%	7.69%	0.00%	20.50%
Wind	6.49%	7.69%	0.00%	14.55%	9.18%	5.63%	6.75%	6.04%	0.00%	0.10%	0.00%	11.51%	0.00%	22.50%	0.00%	2.49%
Solar pv	0.93%	7.93%	0.00%	5.62%	1.73%	0.67%	9.31%	3.46%	0.16%	0.71%	0.09%	0.37%	0.09%	8.69%	0.29%	1.75%
Geothermal	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.30%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.04%	0.00%	2.59%
Solar thermal	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Tide	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other sources	0.00%	0.00%	0.00%	0.36%	0.04%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.38%	0.00%	0.20%	0.00%	0.00%
Waste	0.00%	0.00%	0.00%	2.03%	0.37%	0.05%	0.00%	0.14%	0.00%	0.00%	0.00%	1.29%	0.00%	2.13%	0.00%	0.00%
T&D loss	15.00%	5.00%	4.00%	5.00%	16.00%	9.00%	7.00%	5.00%	14.00%	15.00%	21.00%	4.00%	28.00%	4.00%	23.00%	9.00%

Sources:
[1] Electricity mix: IEA Data and Statistics
https://www.iea.org/data-and-statistics/data-tables
[2] Electricity T&D losses: The World Data Bank
https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS

Figure IV. 1. LIB supply chain countries Electricity Mix – 2020 [15]

The current year data have been calculated from the GREET 2021 model, Everbatt model, and Ecoinvent model, by considering the collective global supply chain.

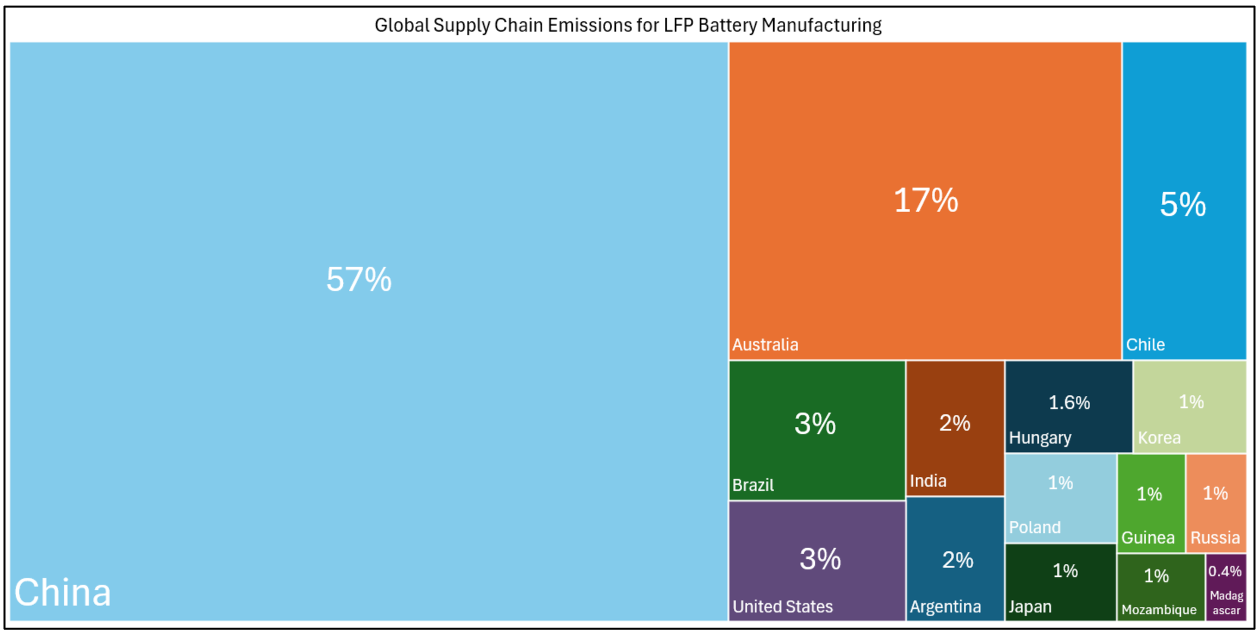


Figure IV. 2. LIB Supply chain country-wise GHG Emissions contribution

Estimates of electricity mix for two different scenarios, namely, the stated policies scenario (SPS) and Sustainable Development Scenario (SDS), can be seen in **Error! Reference source not found.**.

Sustainable Development Scenario (SDS)																
Country	Argentina			Australia			Bahrain			Belgium			Brazil			C
Energy Source	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030
Coal	0.32%	0.05%	0.00%	27.88%	9.00%	0.14%	0.72%	0.50%	0.01%	1.08%	0.86%	0.02%	0.00%	0.00%	0.00%	1.43%
Natural gas	10.77%	4.91%	2.50%	13.58%	10.68%	3.68%	60.71%	33.04%	7.85%	14.28%	8.04%	0.62%	3.80%	0.70%	1.86%	30.29%
Oil	1.14%	0.49%	0.22%	0.53%	0.25%	0.10%	8.58%	3.02%	0.98%	0.44%	0.13%	0.06%	0.42%	0.00%	0.00%	0.21%
coal with CCUS	0.00%	0.00%	0.00%	0.00%	0.00%	3.57%	0.00%	0.00%	0.19%	0.00%	0.00%	0.40%	0.00%	0.00%	0.00%	0.00%
natural gas with CCUS	0.00%	0.00%	0.93%	0.00%	0.00%	1.36%	0.00%	0.00%	2.90%	0.00%	0.00%	0.23%	0.00%	0.00%	0.69%	0.00%
Nuclear	2.28%	4.02%	3.07%	8.74%	10.30%	8.59%	2.88%	6.59%	4.25%	19.51%	15.86%	12.94%	3.66%	5.47%	3.96%	16.93%
Hydro	57.48%	54.47%	31.97%	15.12%	15.24%	8.31%	2.52%	2.18%	0.91%	12.47%	10.41%	6.17%	61.27%	58.79%	34.33%	15.31%
Biofuels	6.27%	6.13%	4.12%	3.96%	5.45%	3.40%	0.94%	1.54%	0.74%	8.15%	8.19%	5.56%	9.30%	7.80%	5.22%	2.73%
Biofuels with BECCS	0.00%	0.00%	0.76%	0.00%	0.00%	0.63%	0.00%	0.00%	0.14%	0.00%	0.00%	1.03%	0.00%	0.00%	0.97%	0.00%
Wind	11.53%	14.82%	33.32%	13.05%	19.63%	30.03%	9.88%	21.30%	29.63%	29.09%	39.30%	56.03%	14.08%	16.41%	33.25%	17.89%
Solar pv	8.94%	12.66%	21.15%	15.94%	26.69%	38.10%	11.90%	20.26%	44.75%	14.09%	15.02%	15.07%	7.32%	10.36%	19.31%	13.72%
Geothermal	0.89%	1.52%	1.09%	0.91%	1.39%	0.93%	0.00%	0.00%	0.00%	0.32%	0.45%	0.33%	0.00%	0.00%	0.00%	0.82%
Solar thermal	0.38%	0.88%	0.82%	0.26%	1.27%	1.10%	1.87%	11.59%	7.66%	0.41%	0.86%	0.80%	0.14%	0.47%	0.43%	0.61%
Tide	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%	0%	0%	0%	0%

Figure IV. 3. Future Electricity Mix Projections for 2030, 2040, 2050 [15]

To determine the current renewable energy percentage, the collective contribution of each country was considered, and their weighted average was considered as the current electricity mix. The proportional contribution of the countries can be seen in **Error! Reference source not found.**. According to this calculation, the current renewable energy percentage is 30%.

Global Supply Chain of Total LFP Battery

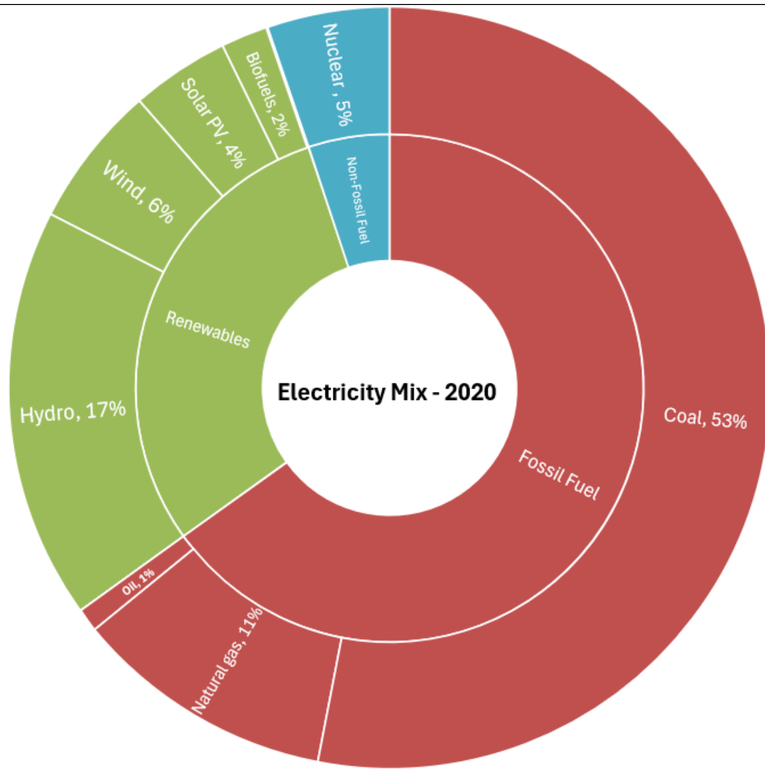
Emissions in *kg CO_2 eq/ kWh*

Other emissions include: Binder, Electrolytes (LiPF6, Ethylene Carbonate, Dimethyl Carbonate), Plastics (polypropylene, polyethylene, polyethylene te

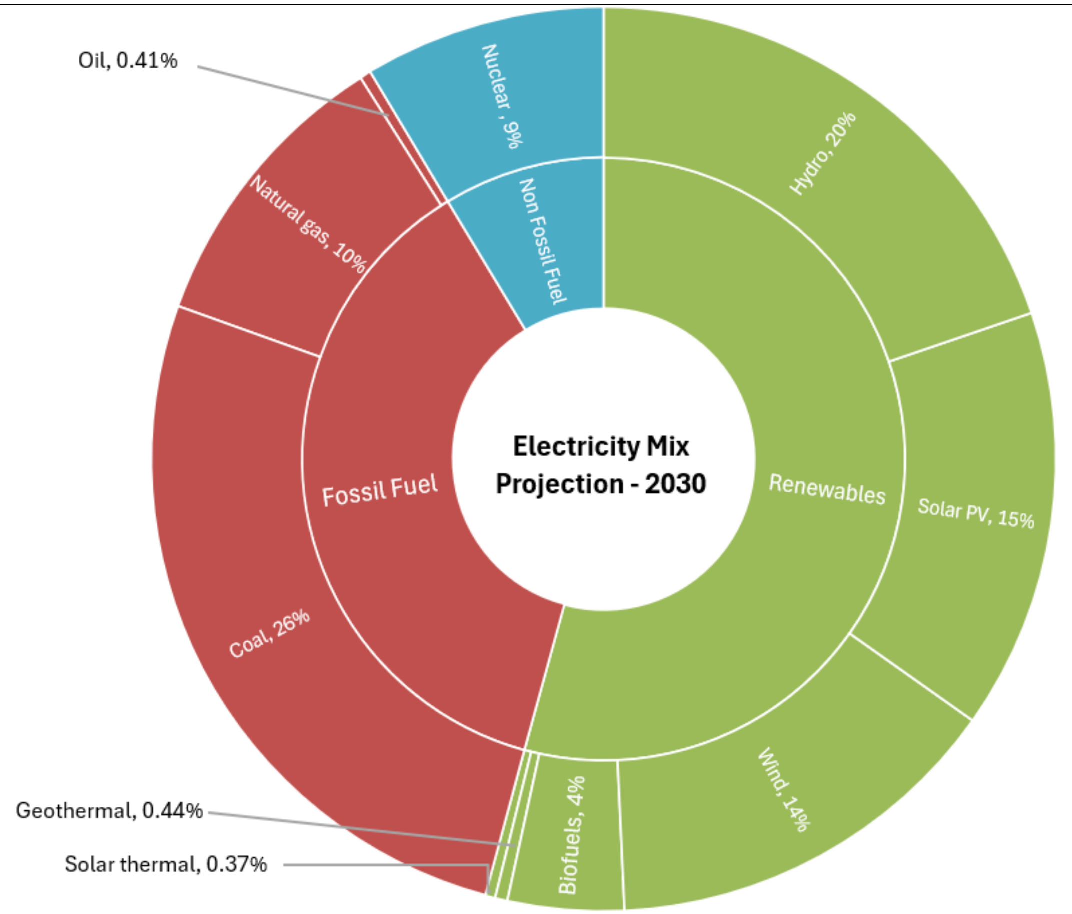
LFP	Active Material	Graphite	Copper	Wrought Aluminium	Battery Assembly	*Total*	*Country Percentage*
China	5.52	2.60	0.66	7.13	13.02	***28.93***	***0.57***
Australia	6.15	0.00	0.03	2.52	0.00	***8.70***	***0.17***
Chile	2.64	0.00	0.14	0.00	0.00	***2.77***	***0.05***
Brazil	0.35	0.36	0.00	1.03	0.00	***1.73***	***0.03***
United States	0.40	0.00	0.06	0.00	1.03	***1.49***	***0.03***
India	0.00	0.12	0.02	0.78	0.00	***0.93***	***0.02***
Argentina	0.86	0.00	0.00	0.00	0.00	***0.86***	***0.02***

Figure IV. 4. Global Supply Chain Contribution by Individual Countries (Top 7) [15]

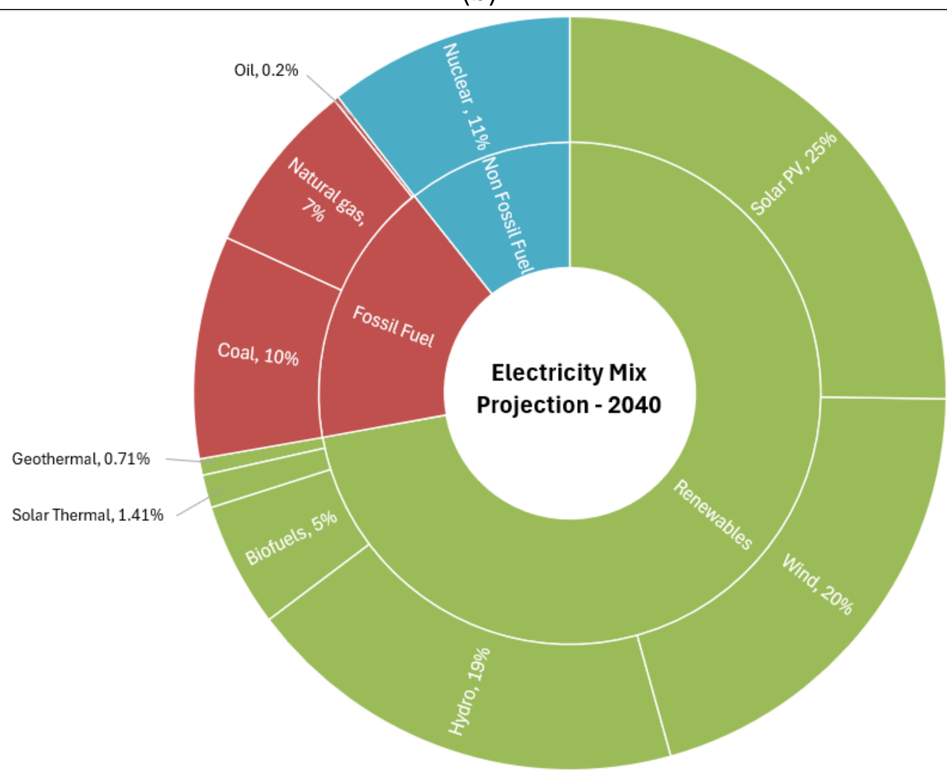
Similarly, calculating for the other years' projections, the distribution seen in **Error! Reference source not found.** is obtained.


Electricity Mix - 2020
Fossil Fuel
Renewables
Non-Fossil Fuel
Coal, 53%
Natural gas, 11%
Oil, 1%
Hydro, 17%
Wind, 6%
Solar PV, 4%
Biofuels, 2%
Nuclear , 5%

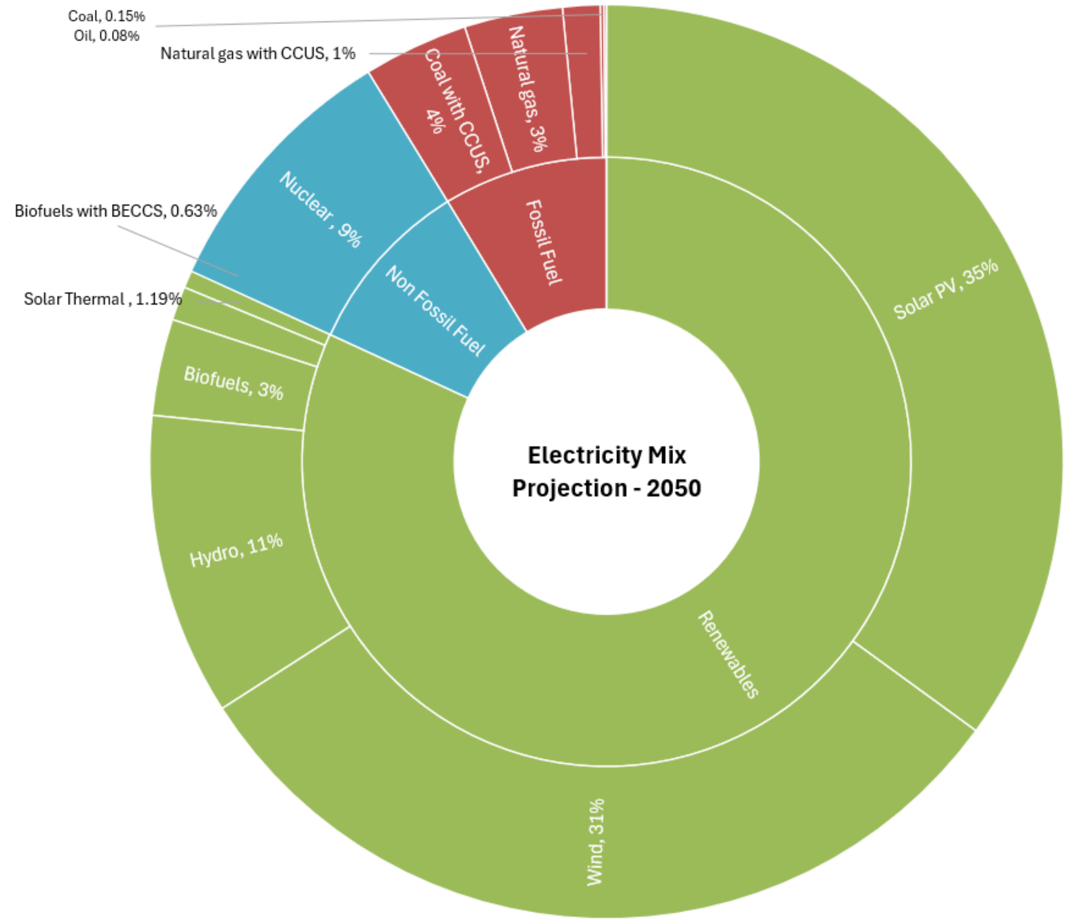
(a)


Electricity Mix
Projection - 2030
Oil, 0.41%
Nuclear , 9%
Non Fossil Fuel
Hydro, 20%
Natural gas, 10%
Fossil Fuel
Renewables
Solar PV, 15%
Coal, 26%
Wind, 14%
Biofuels, 4%
Geothermal, 0.44%
Solar thermal, 0.37%

(b)


Electricity Mix
Projection - 2040
Oil, 0.2%
Nuclear , 11%
Non Fossil Fuel
Solar PV, 25%
Natural gas, 7%
Fossil Fuel
Coal, 10%
Renewables
Geothermal, 0.71%
Solar Thermal, 1.41%
Biofuels, 5%
Wind, 20%
Hydro, 19%

(c)



(d)

Figure IV. 5. Global LIB (LFP) supply chain Electricity Mix (2020, 2030, 2040, 2050)

Another assumption is that the current battery manufacturing scenario uses 0% recycling. This is because recycling was excluded while making projections using the global supply chain in the original study.

The data is presented as two different procedures: stated policies scenario (SPS), and sustainability development scenario (SDS). The sustainability development scenario (SDS) is considered in this study, as it considers the ideal scenario wherein the optimal probable course of action towards sustainability is taken.

The recycling process is studied in terms of three types of procedures stated for battery recycling, namely, the pyro, hydro, and direct procedures. The direct procedure, in which the battery active materials are structurally restored as they are and reused, is considered in this study. In these procedures, two closed-loop recycling scenarios are followed, namely the EU and CB. CB considers a scenario wherein most of the battery materials are recycled, which aligns with the circularity vision.

The study considers SDS, with direct recycling procedures, performed on CB standards.

The three main processes in the manufacturing of a battery pack are: Mining and Refining, Material Processing, and Manufacturing. The emissions from these processes involve gauging the exact usage of fossil fuels in each procedure involved in these processes. The mining and refining process is said to consume 6% of all the emissions from the manufacturing process, and Material Processing and Manufacturing contribute 54% and 40%, respectively. After getting these values for 0% Recycling, the absolute values of emissions for the other recycling percentages are kept the same, as in the manufacturing processes, recycling does not make a difference, while the renewable energy percentage is the one contributing to the reduction in emissions in this step. For the remaining recycling percentages, the mining-refining to Material processing ratio is kept at 1:9.

The LFP pack is considered as 46.08 kWh, which is the specification of a Tata Nexon EV battery pack.

IV. e. BEV and LFP Battery Combined Data

Table IV. 17. BEV Total emissions (BEV Vehicle Manufacturing + LFP Battery Manufacturing)

TOTAL EMISSIONS* – BEV Manufacturing + LFP Battery	**Renewable Energy (%)**			
Recycling (%)	**28%**	**40%**	**70%**	**100%**
0	5.84 + 2.55 (8.39)	5.5 + 2.33 (7.84)	4.71 + 1.79 (6.49)	3.91 + 1.24 (5.14)
50	4.75 + 2.04 (6.79)	4.44 + 1.86 (6.3)	3.67 + 1.40 (5.07)	2.9 + 0.94 (3.84)
90	3.88 + 1.63 (5.51)	3.58 + 1.48 (5.06)	2.83 + 1.09 (3.93)	2.09 + 0.71 (2.8)
100	3.66 + 1.53 (5.19)	3.36 + 1.38 (4.74)	2.62 + 1.02 (3.64)	1.89 + 0.65 (2.54)

***Unit: Ton-CO_2 eq.**

BEV Manufacturing
Battery Manufacturing

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