LCA and TCO Assessment for CBG, CNG, and Petrol Fuelled ICEVs vis-à-vis BEVs

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Executive Summary

This study aims to assess the Lifecycle Emissions Analysis (LCA) and Total Cost of Ownership (TCO) for Battery Electric Vehicles (BEVs), Compressed Natural Gas (CNG), Compressed Biogas (CBG), and Gasoline-fuelled Internal Combustion Engine Vehicle (ICEV) powertrain options available in India. Two combinations of comparable BEV, CNG-ICEV, CBG-ICEV, and Gasoline-ICEV, were chosen for analysis from the vehicles currently sold in India for this study. Vehicles manufactured by Indian companies are called Set-1, and vehicles manufactured by foreign companies are called Set-2. A comprehensive "Well-to-Pump", "Well-to-Wheel", and "Cradle-to-Grave" analysis was done. Sensitivity analysis for LCA was performed for (i) one-time battery replacement during vehicle lifetime, (ii) power generation region-wise, (iii) use of different gasohol blends, and (iv) distance travelled during vehicle lifetime.

A new model was developed and used for the TCO analysis. The sensitivity analysis for TCO was performed for (i) the price of a one-time replacement of battery pack, (ii) distance travelled per year, (iii) possible vehicle purchase price changes, and (iv) possible fuel and electricity price changes. The well-to-pump GHG emissions for CBG was ~ (-) 61 gCO_2-

eq/MJ, while the WTP GHG emissions for CNG was ~26 gCO_2-eq/MJ. In this WTP GHG emissions, ~9 gCO_2-eq/MJ was contributed by domestic CNG, which was 52% of the total CNG consumed in India. The imported CNG contributed the remaining 17 gCO_2-eq/MJ, which constituted ~48% of the total CNG consumed in India. The GHG emissions during the production of CBG in India were 249 gCO_2-eq/MJ, but 26 gCO_2-eq GHG emission was avoided on account of displacing an equivalent CNG, 48 gCO_2-eq was avoided by avoiding natural composting of cow dung in the open environment, and 234 gCO_2-eq was avoided on account of displacing imported inorganic NPK (15-15-15) fertiliser. The GHG emissions for electricity generation in India differ in different regions because of variations in the feedstock for electricity generation. The Lifecycle GHG emissions for CBG-ICEV were lower than BEVs, E10-ICEVs and CNG-ICEV for Foreign and Indian brand vehicles. The lifecycle GHG emissions for all cases of sensitivity analysis were the lowest for CBG-ICEVs. The GHG emissions for ICEVs were lower than BEVs during the vehicle production stage; however, after a certain distance travelled, the emissions become lower for BEVs than ICEVs. CBG-powered ICEVs emerged as a strong candidate for sustainable transport in India. The TCO of CBG-ICEV was the lowest for Set-1 vehicles.

In the technology mature phase (S3) and intermediate phase (S2), the TCO of Tiago-BEV for all vehicle purchase price categories was higher than CNG and CBG-powered Baleno-ICEV. As the scenario changed from the Promotion Phase (S1) to the Matured Phase (S3) via the Intermediate Phase (S2), the TCO of MG ZS-BEV in ₹/km increased significantly. The CBG-powered ICEVs emerged as the most economically viable vehicle powertrain option among the considered options.

CBG-powered ICEV powertrains emerged to be the most environment-friendly and pocket-friendly to the end user. They can reduce the nation's dependency on imported crude, LNG, lithium-ion batteries, and other major BEV components, a step in the right direction for '**Sustainable and Atma-Nirbhar Bharat**'.

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Chapter 1
Project Description

The main objective of this study was to identify the net greenhouse gas (GHG) emissions and the global warming potential (GWP) because of net emissions, along with the economic feasibility of different vehicle powertrain technology options, by conducting a Lifecycle Assessment (LCA) and Total Cost of Ownership (TCO) analysis of two sets of four-wheeler (4W) vehicles, powered by compressed natural gas (CNG), compressed biogas (CBG), and gasoline-fuelled ICEVs and BEVs.

The specific objectives of the LCA and TCO analysis in this study were as follows:

1.1. Objectives of Lifecycle Assessment (LCA) Analysis

i. To conduct the LCA analysis according to the principles, framework, requirements, and guidelines prescribed by ISO 14040 and ISO 14044.

ii. To evaluate and compare the impact of BEV, CNG-ICEV, CBG-ICEV and P-ICEV powertrains on the environment by evaluating net GHG emissions.

iii. To identify the variations in the GHG emissions from various powertrains by sensitivities analyses accounting for:

- ❑ Variations in electricity mix in different Indian regions.
- ❑ Battery Replacement Frequency.
- ❑ Distance Travelled
- ❑ Variations in gasoline composition due to ethanol blending.

1.2. Objectives of Total Cost of Ownership Analysis

i. Compare CNG-ICEVs, CBG-ICEVs, P-ICEVs and BEVs for TCO at an average annual distance travelled.

ii. Compare TCO variations of these powertrains for different distances travelled.

iii. Assess whether the battery replacement in BEVs affects the TCO significantly or not?

iv. Calculate the TCO of BEVs and assess how much battery cost reduction affects the TCO?

v. By changing the vehicle's initial purchase price, assess the TCO changes for CNG-ICEVs, CBG-ICEVs, P-ICEVs and BEVs.

vi. Assess the effect of changing fuel/ electricity prices on the TCO for different powertrain options.

vii. BEVs to be compared for a scenario without the government incentives vis-a-vis CNG-ICEVs, CBG-ICEVs, and P-ICEVs. Also compare them for incentivised cases, as per government policy today.

viii. Sensitivity Analysis:

- ❑ TCO changes for varying annual distances travelled (5000, 10000, 15000, 20000, and 25000 km/ year for 4W)
- ❑ TCO changes by battery pack replacement (no replacement and one-time replacement over the vehicle lifetime)
- ❑ TCO changes because of varying replacement battery costs ($160, $140, $120 and $100/kWh)
- ❑ TCO changes due to changes in the base price of the vehicles (-10%, +10% and +20%)
- ❑ TCO changes due to changes in fuel/ electricity prices (+20% and -20%)
- ❑ For BEV, all the above calculations have been done for three scenarios (no tax + subsidy; Tax + subsidy; and tax + no subsidy)

The overall objectives of this project are shown in Figure 1.

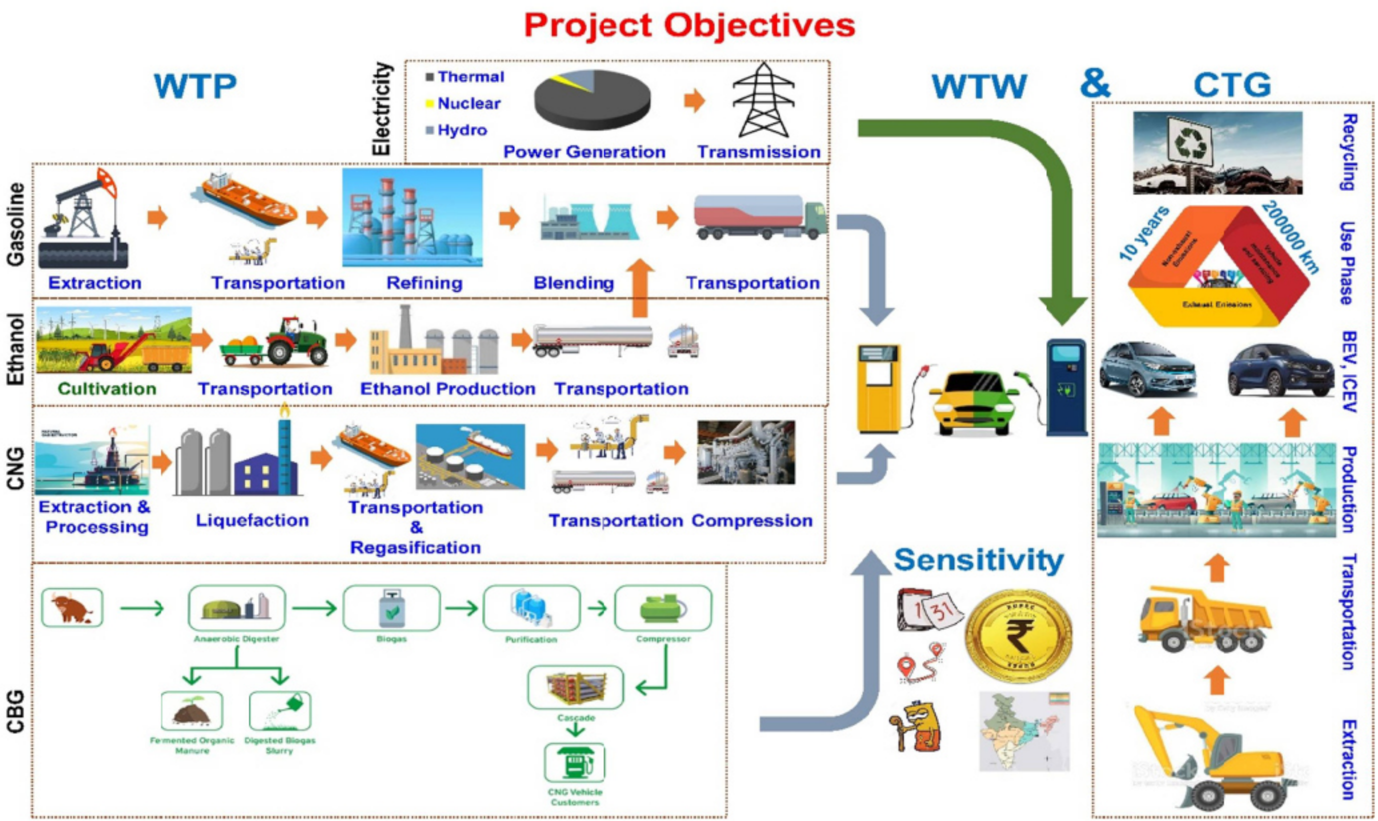


Figure 1: Overall Project Objectives

1.3. Vehicles Chosen for the Study

The NEDO recommended the following comparable vehicles for this study. Technical specifications required for LCA and TCO analyses of these vehicle sets were given in Tables 1 and 2.

Table 1: Vehicle Set 1 (Indian Small Cars)

Vehicle	**TATA Tiago_XZ+Tech Lux LR [1,2]**	**Maruti Baleno Zeta (MT) [3]**	**Maruti Baleno Zeta (MT)[3]**
Energy Type	Electric	CNG/ CBG	Gasoline
Power Source Type	PMSM	1.2 l, 4-cylinder, BS6 Engine	1.2 l, 4-cylinder, BS6 Engine
Max Power (kW)	55	57 @ 6000 rpm	66 @ 6000 rpm
Max Torque (Nm)	114	98.5 @ 4300 rpm	113 @ 4400 rpm
Capacity	24 kWh	9.6 kg CNG @ 200 bar at 15°C	37 l
Mileage	-	30.6 km/kg	19.01 kmpl
Range (km)	315	293 in CNG/ CBG	706
Kerb Weight (kg)	1235	1030	955
Ex-Showroom Price @ New Delhi (₹) as on 1st November 2023	12,03,999/-	9,28,000/-	8,38,000/-

Table 1 includes the comparable Indian small cars (Set-1), and Table 2 includes the comparable Foreign Multi Utility Vehicles (MUV) (Set-2) for the three powertrain options considered in this study. Since there are no separate CBG vehicles, in the market yet, the vehicles sold for CNG powertrain option were considered for CBG analysis.

Table 2: Vehicle Set 2 (Foreign MUVs)

Vehicle	**MG ZS EV_EXCLUSIVE PRO[4,5]**	**Toyota Urban Cruiser Hyryder G CNG[6]**	**Toyota Urban Cruiser Hyryder G[6]**
Energy Type	Electric	CNG/ CBG	Gasoline
Power Source Type	PMSM	1462 cc Gasoline Engine	1462 cc Gasoline Engine
Max Power (kW)	130	64.6 @ 5500 rpm	74 @ 6000 rpm
Max Torque (Nm)	280	121.5 @ 4200 rpm	136 @ 4400 rpm
Capacity	50.3 kWh	9.6 kg CNG @ 200 bar at 15°C	45 l
Mileage	-	26.6 km/kg	21.11 kmpl
Range (km)	461	255	950
Kerb Weight (kg)	1528	1245	1185
Ex-Showroom Price @ New Delhi (₹) as on 1st November 2023	25,89,800/-	15,44,000/-	14,49,000/-

Chapter 2
Methodology

The Lifecycle Assesment (LCA) is a tool to identify the effects of any product, process or service on the environment. In LCA analysis, emissions from 'Well-to-Pump', 'Well-to-Wheel', 'Cradle-to-Gate', 'Cradle-to-Grave', or 'Cradle-to-Cradle' can be assessed.

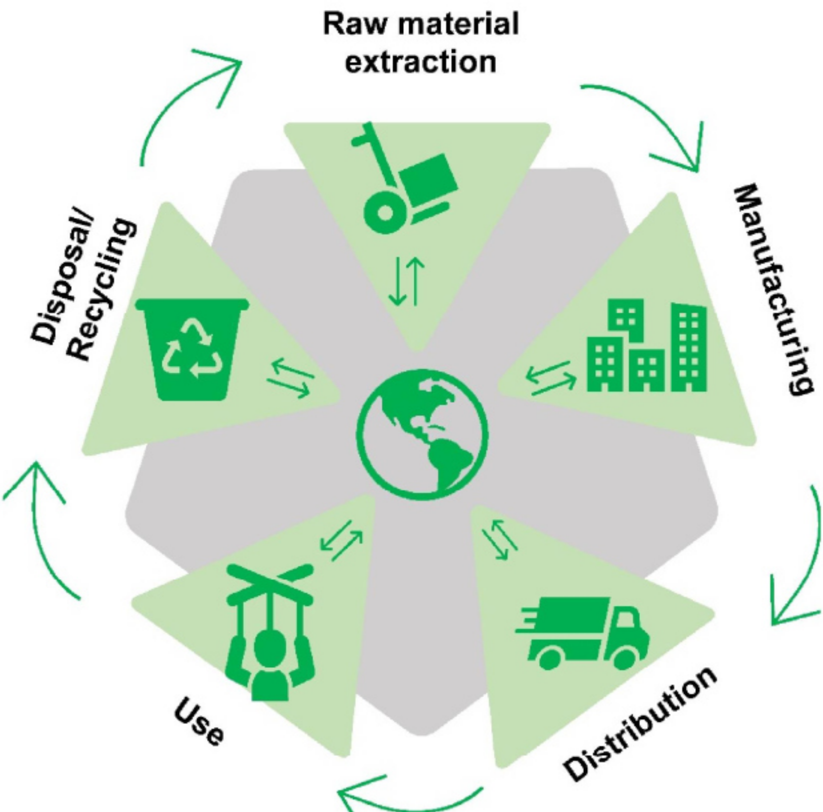


Figure 2: LCA Phases

This analysis assesses global warming potential, global temperature potential, human and environmental toxicity, and resource depletion. To reach net zero, each organisation must become a net-zero emitter. Hence, LCA analysis is a primary tool for identifying the environmental sustainability of any product, process or service. The product's lifecycle, as shown in Figure 2, consists of the following phases:

(i) Extraction phase of materials from nature;

(ii) The production phase;

(iii) The use phase;

(iv) The after-use phase.

Using LCA, we can evaluate the environmental impact of any product, process or service from the first lifecycle stage to the last or any lifecycle stage in-between. On the other hand, the **Total Cost of Ownership** analysis reveals the actual cost to the end user.

2.1. LCA Methodology

This LCA analysis was conducted according to the guidelines and principles framed by the International Organization for Standardization (ISO), namely, ISO 14040 and 14044. In ISO 14040, the 'Principles and Framework for LCA' are described. In ISO 14044, 'Requirements and Guidelines for LCA' are specified. Figure 3 shows different steps of the LCA analysis.

2.1.1. Goal and Scope Definitions

Goal:

'Well-to-Wheel' and 'Cradle-to-Grave' LCA was conducted to assess the Lifecycle GHG emissions for the recommended BEVs and ICEVs fuelled with ethanol-blended gasoline, CNG, and cow dung-based CBG.

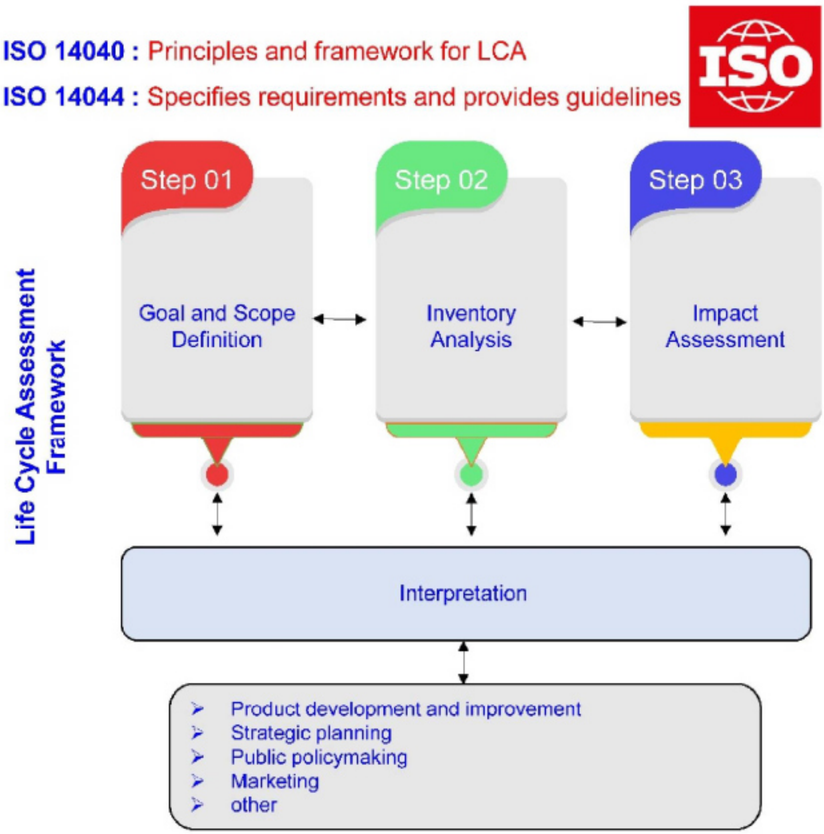


Figure 3: LCA Analysis Steps

Scope:

This study evaluated and compared the impact of four-wheeler passenger vehicles on the environment. The comparison was made on a 'Well-to-Wheel' and 'Cradle-to-Grave' basis to assess the environmental impacts of vehicle powertrain/ fuel options. Vehicles belonging to the same class or segment, defined in terms of vehicle weight/ size and vehicle powertrain, were compared.

This study included 4W- ICEVs (CNG and Gasoline) and BEVs [2 Models each], one for a comparable Foreign MUV set and the other for an Indian Small Car Set. The functional unit for this study was 'per km', derived from the distance travelled by the vehicle till the end of its life.

System Boundary:

The following system boundaries were considered in the LCA analysis (Figure 4):

- ❑ Fuel Extraction Production, and Transportation.
- ❑ Electricity Generation and Transmission.
- ❑ Vehicle Production and Recycling.
- ❑ Vehicle Maintenance.

The lifetime of the vehicles was assumed to be 200,000 km, covered over ten years.

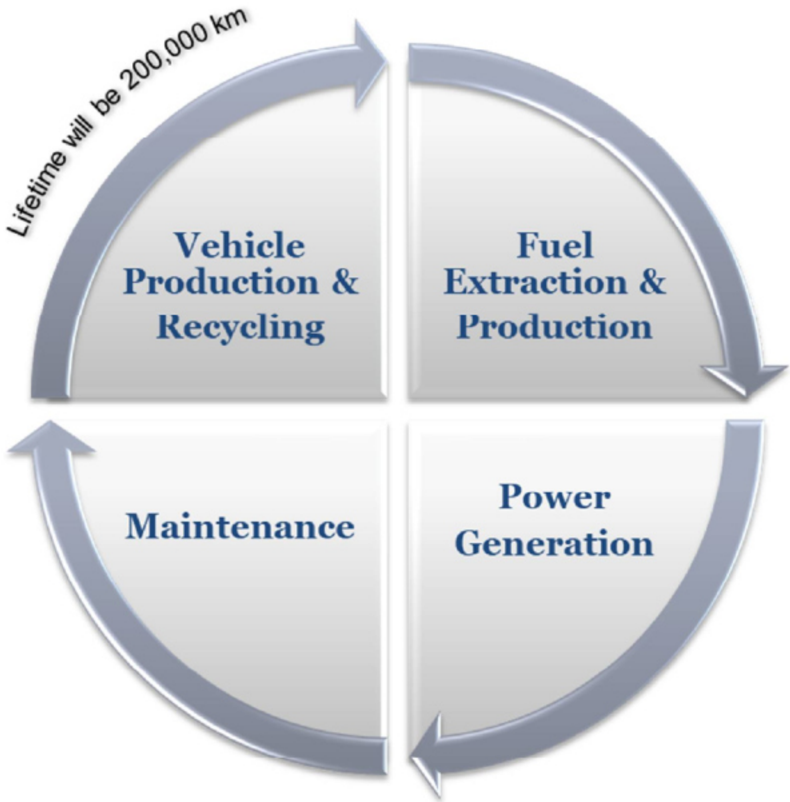


Figure 4: System Boundary

2.1.2. Lifecycle Inventory Analysis:

The Lifecycle Inventory Analysis (LCIA) mainly has three components: 'Cradle-to-Grave' analysis, 'Well-to-Pump' analysis, and 'Well-to-Wheel' analysis.

I. <u>'Cradle-to-Grave' inventory analysis:</u>

'Cradle-to-Grave' inventory analysis is a comprehensive method to assess the environmental impact. This analyses the emissions from various stages of a product throughout its lifecycle, starting from raw material extraction to production, transportation, usage, and eventual disposal/ recycling. When applied to a car, this analysis provides valuable insights into the environmental footprint associated with a vehicle's entire lifespan. The lifecycle analysis begins with extracting raw materials such as metals, plastics, and rubber for car manufacturing. Mining and processing these materials contributes to environmental impacts, including habitat destruction and energy consumption. The manufacturing phase involves machining, assembling the components, painting, and other processes. The transportation of raw materials to manufacturing facilities and the distribution of finished cars to dealerships also contribute to their carbon footprint.

This study took the combined effect of the carbon footprint by all these steps from the Greenhouse gases, Regulated Emissions, and Energy use in Technologies, an LCA package from Argonne National Laboratory, USA (GREET) background emission database, based on the weight of various components of the recommended cars. The usage phase represents a substantial portion of the car's lifecycle emission impact. Fuel consumption, emissions, and maintenance requirements contributed to the overall environmental footprint of each vehicle. Background emissions from fuel/electricity production were analysed for different pathways in the Well-to-Pump inventory analysis. The disposal and recycling of a car at the end of its useful life were critical considerations. The environmental impact also depends on how efficiently recycled materials and disposal methods were used. Car disposal in landfills contribute to environmental pollution and waste generation. However, recycling reduces the demand for new raw materials.

Advances in technology and design can significantly reduce the environmental impact of cars. For example, using lightweight materials, improving fuel efficiency, and adopting hybrid technologies could reduce the overall emission footprint of the vehicles. This analysis is, therefore, essential for making informed decisions about sustainable practices in the automotive industry. As the industry evolves, focusing on reducing the environmental footprint at every stage of a car's lifecycle becomes increasingly important for manufacturers and consumers.

'GREET Vehicle Cycle Model' gives the weight distributions of various components in a vehicle, which are used in this study for the calculations. It was assumed that the weight distribution of the components was the same for Indian and US-made vehicles having identical powertrains, with reasonable accuracy. Table 3 shows the list of the components in BEVs and ICEVs, as specified in the GREET vehicle Lifecycle model[7].

Table 3: List of the Components in the Vehicles, as Specified in the GREET Vehicle Lifecycle Model.

S. N.	System	BEV	ICEV
1	**Body System**	√	√
2	**Powertrain System**	√	√
3	**Transmission System**	√	√
4	**Chassis System**	√	√
5	**Traction Motor**	√	X
6	**Generator**	X	X
7	**Electronic Controller**	√	X
8	**Batteries**	√	√
9	**Fluids**	√	√

The vehicles' total weight was categorised into four sub-sections, i.e., Vehicle components, Fluid and tires, Batteries, and Assembly-disposal-recycling (ADR), as shown in Figure 5. The data for vehicle components was as per the 'GREET vehicle cycle model'. Fluid and tire weight distribution were the same as available in the GREET database. The calculation of the weight of batteries in the vehicle was done separately. Data from recently published literature was taken to calculate the battery weight (160 Wh/kg)[8]. The percentage weight distribution of components for BEVs and ICEVs, as defined in the GREET vehicle cycle model, is given in Table 4. This model was applied to the vehicles selected for this study. Some fluid replacements differed for different sensitivities, such as distance travelled. Table 5 describes the number of replacements of such fluids in the usage phase.

Table 4: Weight (%) Distribution of Vehicle Components

SN.	Component	BEV (%)	ICEV (%)
1	**Body System**	53.50	44.1
2	**Powertrain System**	1.7	25.7
3	**Transmission System**	3.3	6.3
4	**Chassis System**	28.9	23.9
5	**Traction Motor**	6.7	0
6	**Generator**	0	0
7	**Electronic Controller**	5.9	0

Table 5: Number of Replacements of Fluids over Vehicle Lifespan

Distance Travelled (km/year)	**25,000**	**20,000**	**15,000**	**10,000**	**5,000**
Engine Oil	25	20	15	10	5
Brake Fluid	3	3	3	3	3
Transmission Fluid	2	2	1	1	0
Powertrain Coolant	5	4	3	2	1

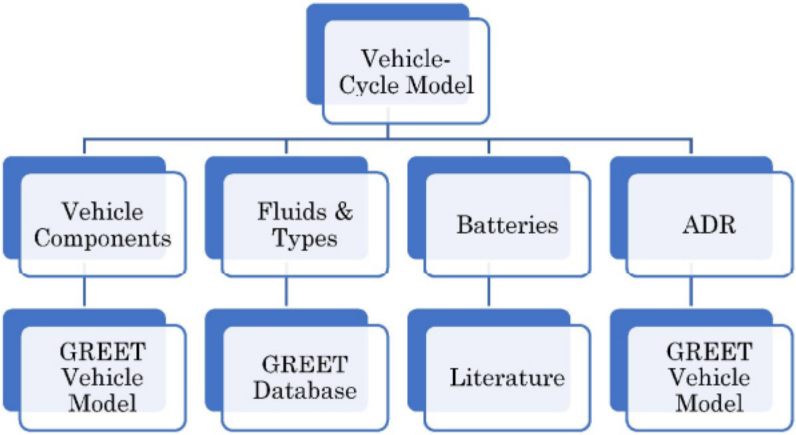


Figure 5: Vehicle-Cycle Model and Data Sources

Tailpipe and Non-Exhaust Emissions:

For different powertrains, GREET used different tailpipe and non-exhaust emission factors (EFs), as listed by EPA's Motor Vehicle Emission Simulator (MOVES3) model [9]. These EFs are given in Tables 6 and 7.

Table 6. MOVES3 Tailpipe Vehicle Operation Emission Factors

SN.	Type	BEV	CNG-ICEV	P-ICEV
1	**VOC (µg/m)**	0	24.7	24.7
2	**CO (mg/m)**	0	0.9	0.9
3	**NO_x (µg/m)**	0	24.4	20.5
4	**PM_{10} (µg/m)**	0	2.8	2.8
5	**$PM_{2.5}$ (µg/m)**	0	2.5	2.5
6	**CH_4 (µg/m)**	0	49	49
7	**N_2O (µg/m)**	0	2.4	2.4
8	**BC (µg/m)**	0	1.7	1.7
9	***POC (µg/m)***	*0*	*0.6*	*0.6*

Table 7. MOVES3 Non-Exhaust Vehicle Operation Emission Factors

SN.	Type	BEV	CNG-ICEV	P-ICEV
1	**VOC Evap. (mg/km)**	0	0	70.6
2	**PM_{10} TBW (mg/km)**	19.1	19.1	19.1
3	**$PM_{2.5}$ TBW (mg/km)**	2.5	2.5	2.5
4	**BC TBW (µg/m)**	0.4	0.4	0.4
5	**POC TBW (µg/m)**	0.5	0.5	0.5

The equation used in GREET by Argonne National Laboratory, USA for the calculation of EFs in the MOVES3 model is as follows:

$$EF_{i,j,MY} \frac{\sum_{CY}^{CY+30}(VMT_{i,CY} \times EF_{i,j,CY})}{\sum_{CY}^{CY+30} VMT_{i,CY}}$$

Where, $EF_{i,j,MY}$ is the vehicle miles travelled (VMT)-weighted lifetime emission factor of pollutant *j* from vehicle type *i* for Model Year (MY); $VMT_{i,CY}$ is the VMT of vehicle type *i* for each Calender Year (CY) during the lifetime of the MY vehicle; $EF_{i,j,CY}$ is the emission factor of pollutant *j* from vehicle type *i* for each CY during the lifetime of the MY vehicle.

Simulation Logic for GREET Vehicle-Cycle Analysis:

Figure 6 shows the layout of simulation logic for GREET vehicle-cycle analysis [10]. The first step was to estimate the weight of the components in a vehicle. The major components for which weight estimation was done included the body, chassis, powertrain, batteries, fluids, transmission, motor, controller, and generator, depending on the vehicle powertrain type. In the second step, the model divided the weight of major components into their material composition, e.g. steel, aluminium, iron, plastics, rubber, and other materials. The model then applied the components requiring replacement, such as fluids, tires, and batteries, during the vehicle's lifetime. In the last step, for disposal and recycling of the vehicles, the model considered the energy required and emissions generated during their recycling. To account for recycling, the model returns those values to its original materials for reuse. The LCIA data was procured from different sources, including the websites of Original Equipment Manufacturers (OEMs), the Government of India databases, Literature and the database available in GREET.

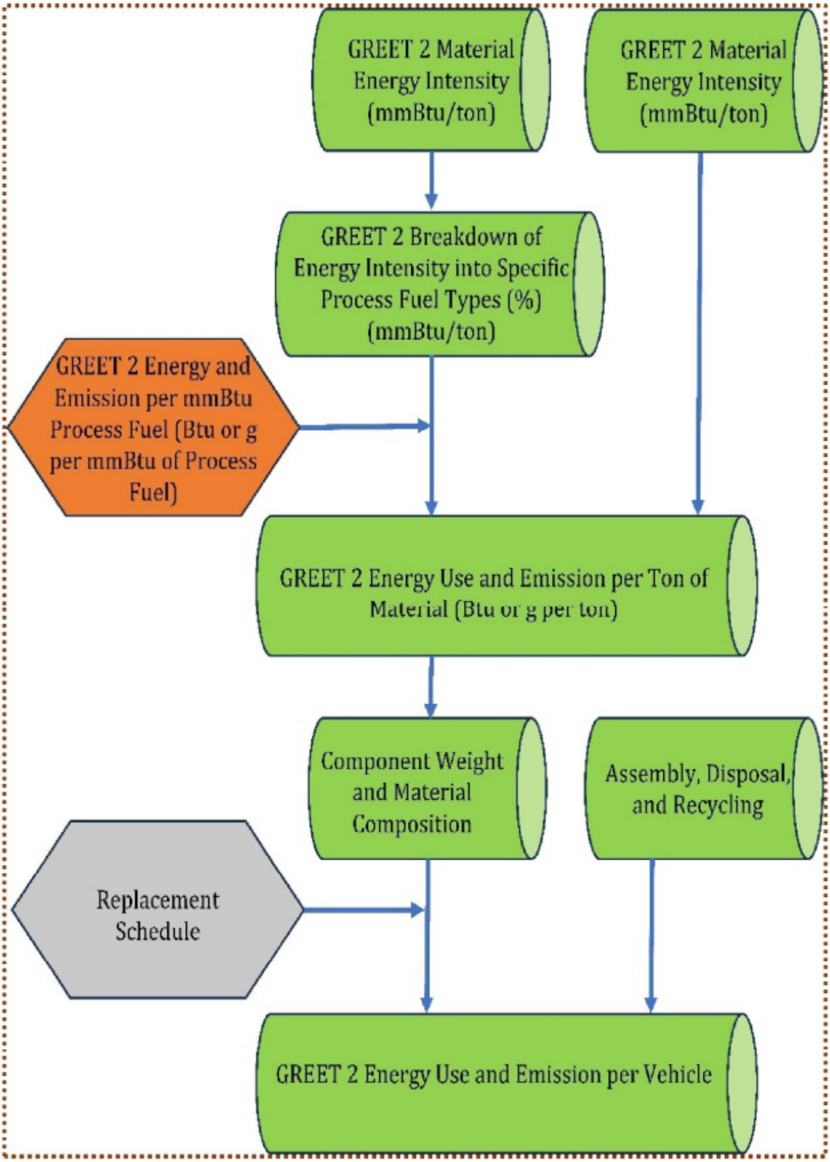


Figure 6: Simulation Logic for GREET Vehicle-Cycle Analysis

II. Well-to-Pump (WTP) inventory analysis

WTP inventory analysis is a methodology used to assess the environmental impacts associated with the production and transportation of fuel/electricity for vehicle application, from the extraction of raw materials to the point of distribution. This analysis is particularly relevant in evaluating the Lifecycle emissions of various fuels, providing insights into the energy and environmental implications of different fuel sources. Critical components of WTP inventory analysis include (i) Extraction of Raw Materials: WTP considers the entire process of extracting and processing raw materials of fuel production. This includes activities such as drilling for oil, mining for coal, or cultivating biofuel feedstocks. The environmental impact of these extraction processes, including habitat disruption and energy consumption, is assessed. (ii) Transportation of Raw Materials: The energy and emissions of transporting raw materials/ crude oil from extraction sites to refineries or processing plants are considered. Transportation modes, distances, and energy sources influence this phase. (iii) Refining and Production: The energy-intensive process of refining crude oil or converting raw materials into usable fuel significantly contributes to the overall environmental impact. The type of technology used, energy efficiency, and the energy sources employed during refining are crucial considerations. (iv) Distribution: The transportation of the finished fuel from refineries to distribution points, such as fueling stations, is an integral part of the WTP analysis. The mode of transportation and the distance covered play a role in determining the environmental impact of this phase. This analysis was particularly relevant in evaluating alternative fuels, as it helps stakeholders make informed decisions regarding the sustainability and environmental performance of different energy sources. WTP analysis becomes a valuable tool for policy-makers, industry professionals, and consumers seeking to promote and adopt environmentally friendly fuels to mitigate the impact of transportation on the environment.

In this study, four fuels/energy sources were considered: Compressed Biogas (CBG), Compressed Natural Gas (CNG), Ethanol-Blended Gasoline (EBP), and electricity.

Pathway for CBG Production in India

Figure 7 shows the pathways of CBG production from animal manure (Cow dung). The pathway created in GREET is shown in Figure 8.

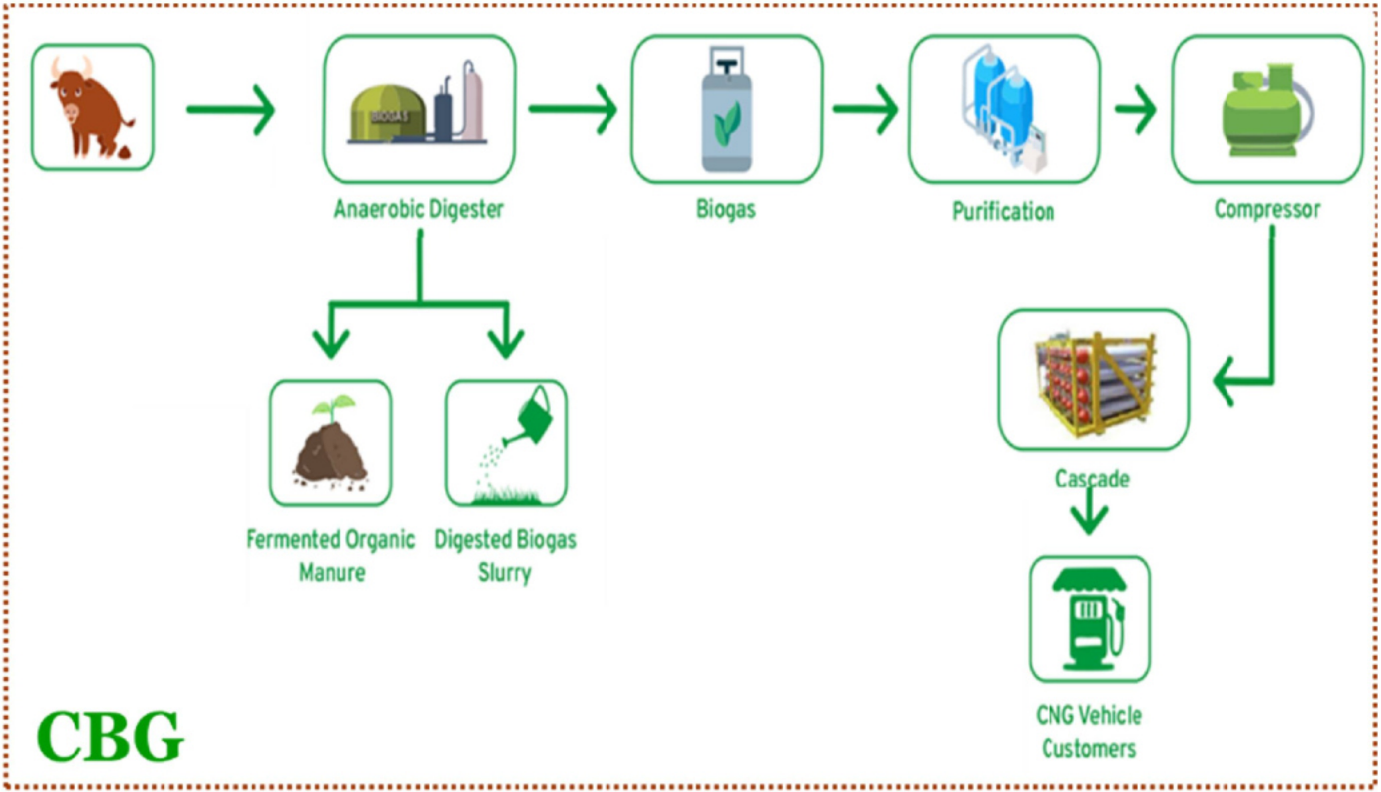


Figure 7: CBG Production Pathway

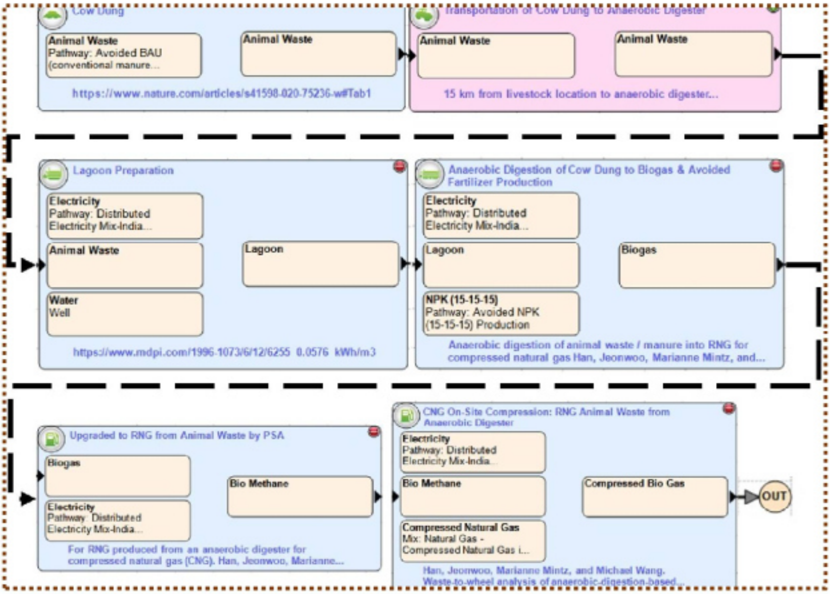


Figure 8: CBG Production Pathway Created in GREET.

As per a report of the Banas Biogas plant [11], the production pathway of biogas from cow-dung was considered. The pathway reported in this study was mass-balanced. The details on each step of the biogas production are as follows:

a. Collection and Transportation of Cow Dung: It was assumed that the cow dung was collected from the nearby village (Figure 9) within an average distance of 15 km using a tractor trolly. The considered weighing capacity of the tractor trolly was 3 tons/ trolly [12]. In this case study, it was assumed that 40 tons of cow dung was collected in a day. The natural composting of cow dung is a potential emitter of various GHGs. Hence, by using cow dung for biogas production, the natural composting of the cow dung and, hence, releasing these GHGs into the environment was avoided.

Figure 9: Collection of Cow Dung and Transporting it to the Biogas Plant

b. Slurry Preparation: In this process (Figure 10), 40 tons of cow dung was mixed with water in a 1:1 ratio, and a slurry was made using electrical motor-driven agitators. The energy consumed in this process was ~ 350 kWh. At the end of this stage, 80 tons of slurry was prepared. The slurry was stored here for a long time; hence, the direct emissions in this stage were assumed to be negligible.

c. Anaerobic Digestion in Biogas Digester: The slurry prepared in the previous stage was the primary input to the anaerobic digester (Figure 11). The energy input here was 316 kWh of electricity. By anaerobic digestion, 80 tons of slurry would produce approximately ~2000 m^3 (2344 kg) of biogas. It was assumed that the significant constituents of the biogas thus produced are 60% (v/v) CH_4, 35% (v/v) CO_2, and 5% (v/v) other gasses. The byproducts of this process are very critical in calculating net emissions.

Figure 10: Slurry Preparation [11]

After extracting 2344 kg of biogas from 80 tons of slurry, 77.474 tons of digestate is left as a byproduct of this process. Much of this is liquid, which can be used directly as 34ertilizer. The solid digestate could go through vermicomposting to produce natural 35ertilizer or can be directly used in organic farming. The use of both liquid and solid fertilisers would avoid the use of inorganic fertilisers. A study reported that 800 kg of NPK (15-15-15) equals 5.5 tons of cow dung [13]. Since the water was mixed in the previous process in a 1:1 ratio, 77.474 tons of organic fertiliser equals 38.737 tons of cow dung-based fertiliser, which has the potential to avoid the use of 5.634 tons of inorganic NPK (15-15-15) fertilisers and hence avoid associated emissions in producing the same in fertiliser plants. This would also reduce the national dependence on imported fertilisers and benefit the environment.

Figure 11: Biogas Digester [11]

d. <u>Purification of Biogas for Methane Enrichment:</u> The biogas produced from the previous step need to be purified for upgrade to vehicle-grade fuel in this step (Figure 12). We assumed the pressure swing adsorption technique could be used for this upgrade. This technique is cost-effective for industrial-scale application, though it has a disadvantage of losing ~20% methane (v/v) during purification. However, the output biogas can be purified up to 93% (v/v) CH_4, 4% (v/v) CO_2 and 3% (v/v) other gases. To do this, ~667 kWh of electricity is drawn from the grid. Finally, ~800 kg of biomethane (93% purity) could be produced from the 2000 m^3 (2344 kg) of biogas generated.

Figure 12: Biogas Purification System

e. <u>Biogas Compression at Fueling Station:</u> In this stage, the purified biomethane is compressed to 200 bar and stored in a cascade (Figure 13). For compressing purified

800 kg biomethane, the compressor consumes ~667 kWh of electricity.

Figure 13: CBG Compressor and Storage

Pathway for CNG Production in India: In India, the domestic share of Compressed natural gas (CNG) is 52%. The remaining (48%) is imported from several countries as liquefied natural gas (LNG), which is regasified, compressed and distributed all over the country to meet the demand [14].

Figure 14: Domestic CNG Production Pathway

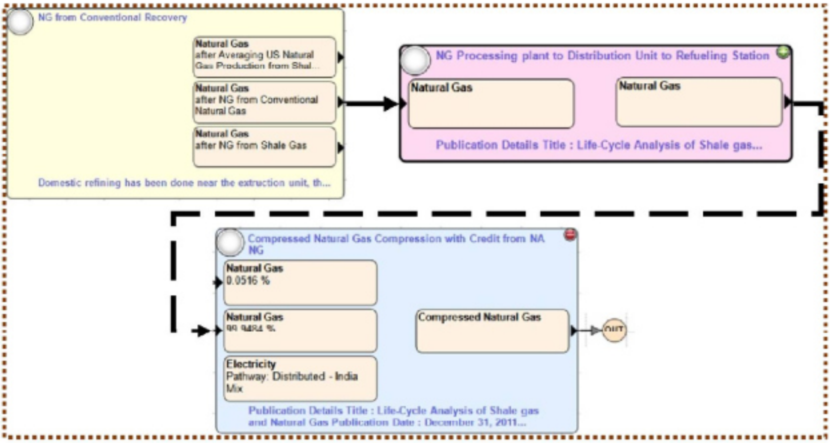


Figure 15: Domestic CNG Production Pathway Created in GREET.

India's domestic CNG production pathway is demonstrated in Figure 14. Figure 15 shows the GREET model for the domestic CNG production pathway. After extraction and processing (Figure 16) of the natural gas from the extraction site, the NG is transported (Figure 17) via different routes. The natural gas is compressed (200-250 bar) at refuelling station.

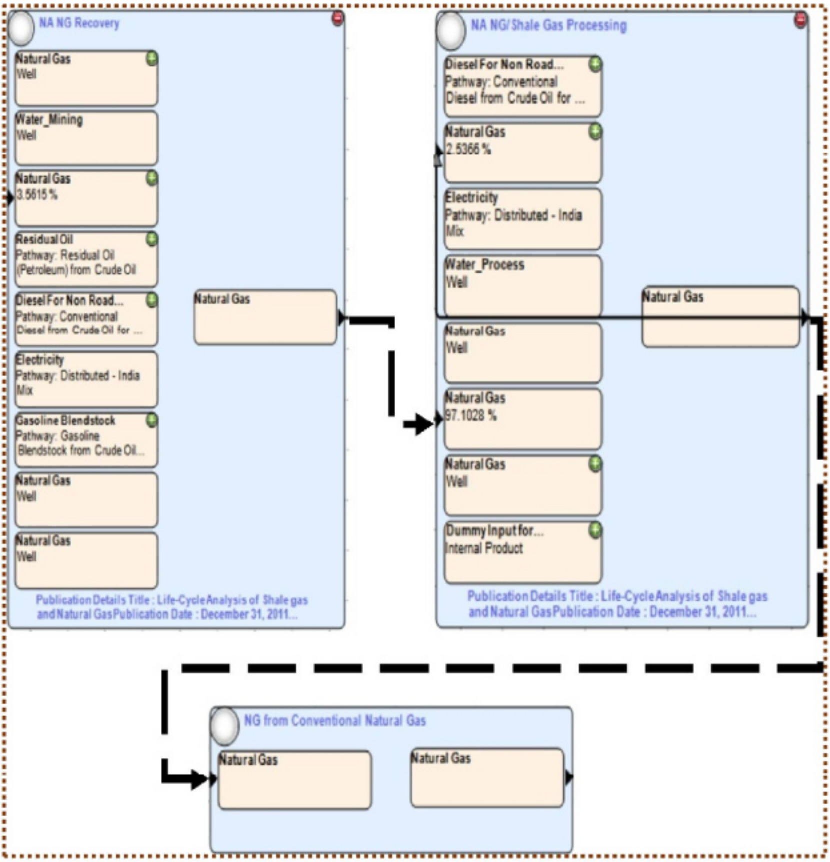


Figure 16: NG by Conventional Recovery Pathway Created in GREET

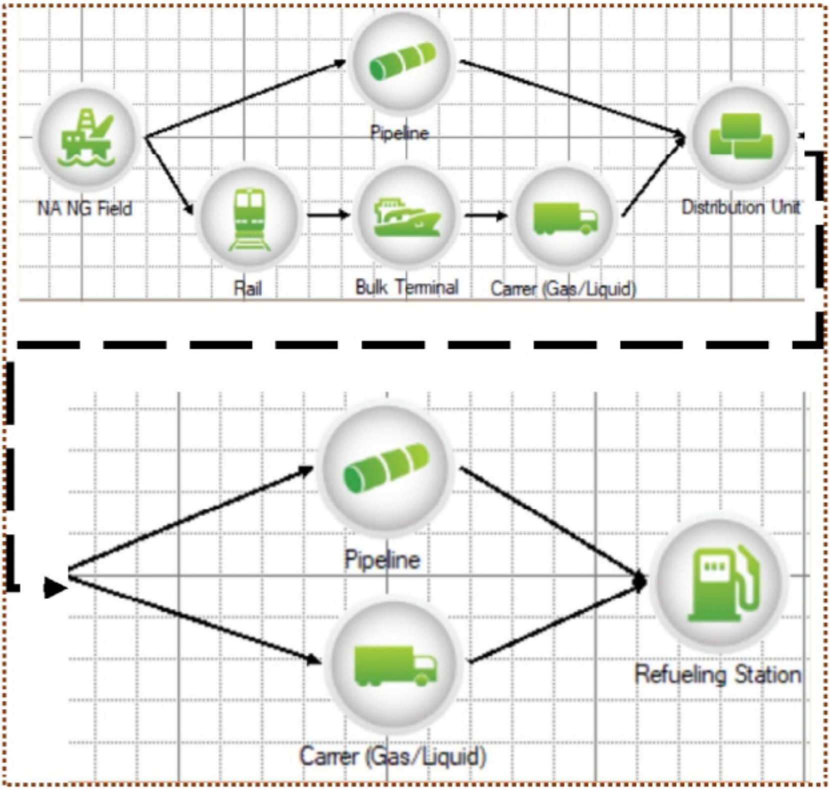


Figure 17: Transportation Model of Domestic CNG Created in GREET

The pathway of imported CNG production (Figure 18) differed from that of the domestic CNG production pathway. The pathway for imported CNG production created in GREET, is shown in Figure 19.

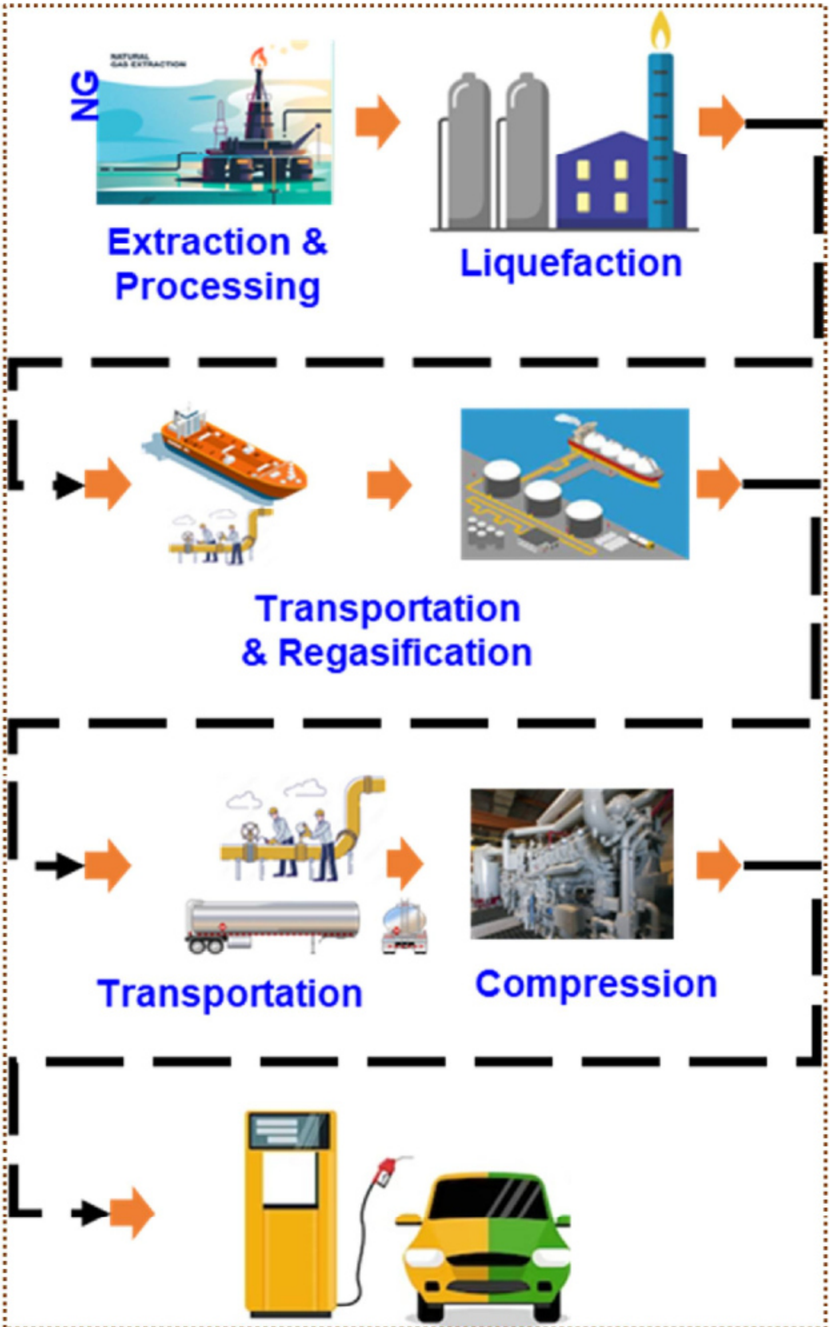


Figure 18: Imported CNG Production Pathway

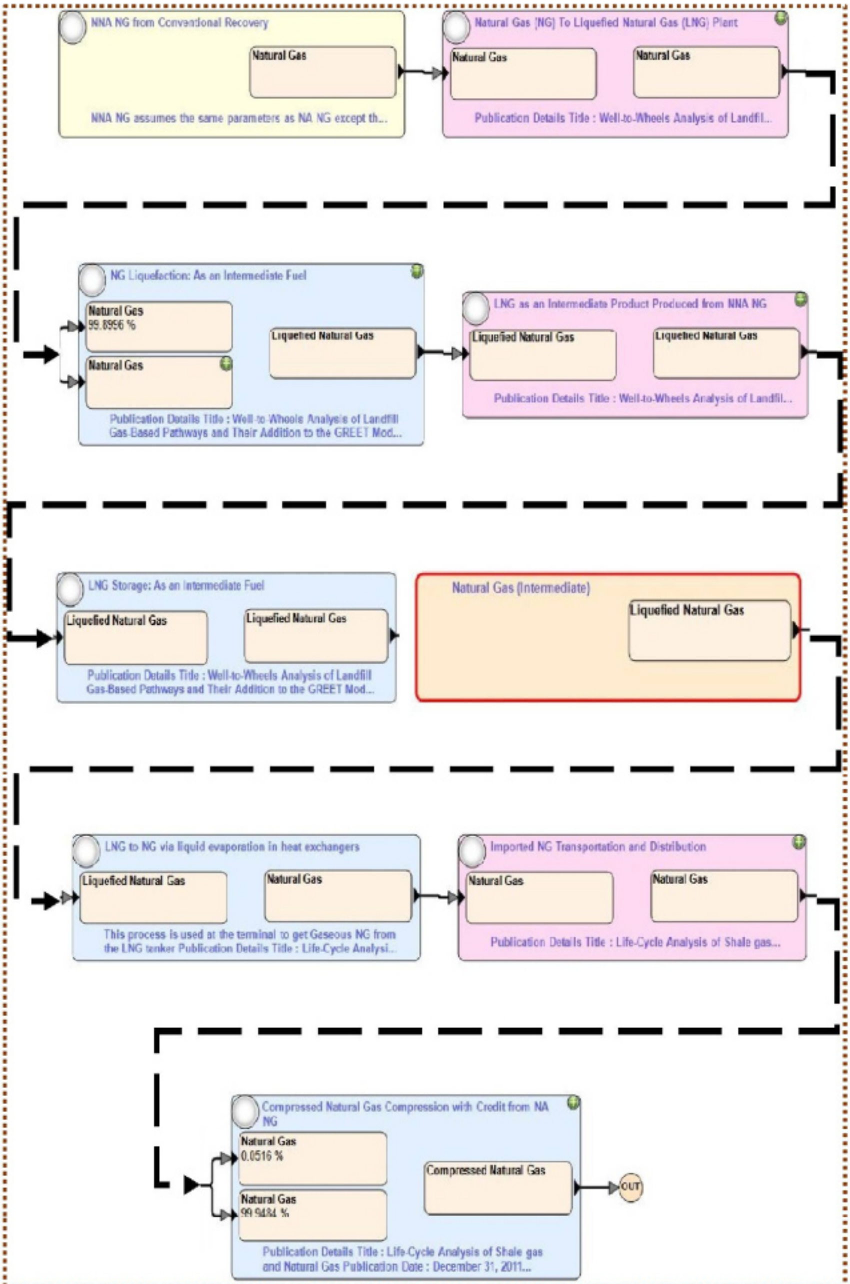


Figure 19: Imported CNG Production Pathway Created in GREET

This pathway had three additional steps compared to the domestic CNG pathway. These additional steps were the liquefication of NG, transportation to India, and regasification. The CNG is imported in LNG. After extraction from the well at the origin and simple processing, NG is transported for liquefication via pipeline (Figure 20). Ocean tankers transport LNG to India via sea (Figure 21). The details of the share (as per the data of 2021) of LNG imports to India from different parts of the world are shown in Table 8. When LNG reaches the Indian terminals, it undergoes a regasification step. It is then transported to the distribution units and eventually to refuelling stations.

Table 8: India's Imported LNG share [15]

Countries	**Share (2021)**	**Approx distance travelled (NM)**
Qatar	42%	1522
USA	16%	15756
UAE	13%	1416
Nigeria	6%	8460
Oman	5%	979
Angola	5%	7175
Others	13%	5885

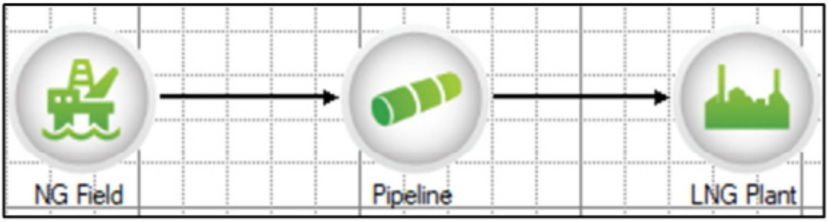


Figure 20: NG Transportation Model to the LNG Plant

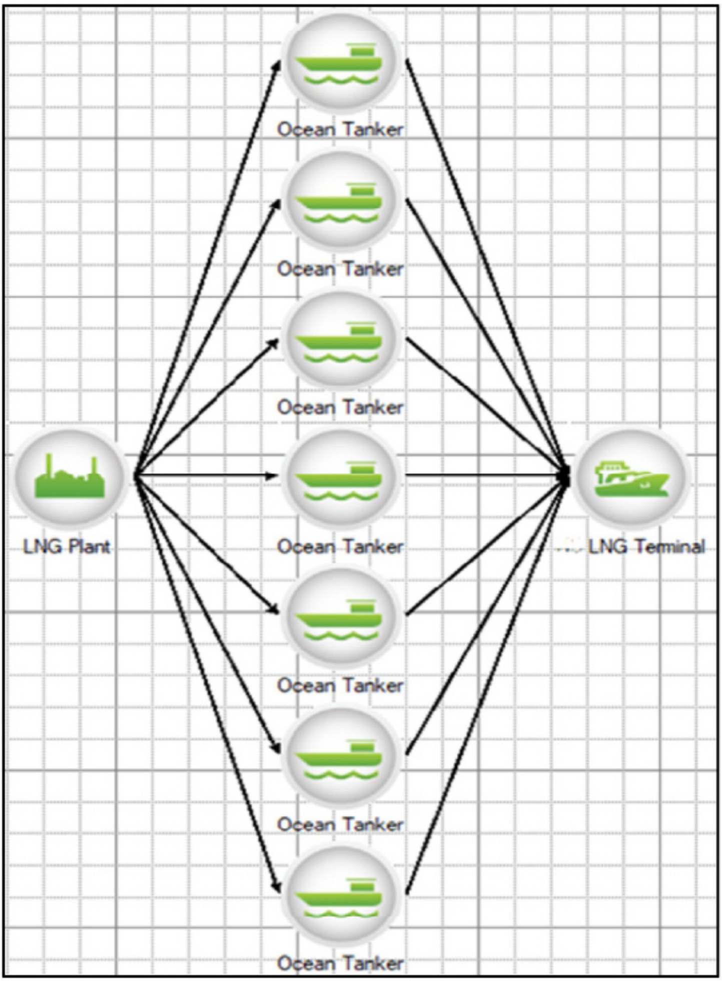


Figure 21: LNG Transportation Model from Various Counties to the Indian LNG Terminals

Pathway for EBP Production in India:

The ethanol-blended Gasoline (EBP) is used all over India. India is a major importer of crude oil. However, ethanol is produced in India domestically, mainly from sugarcane. The LCIA of EBP distributed in the gas station includes emission assessment during various processes, including crude oil extraction, transportation to India, refining, blending with ethanol and transporting to the refuelling stations. For ethanol production, background emissions are from its feedstock production, transportation of sugarcane to the ethanol plants, and blending of the gasoline with ethanol . The EBP is then transported to refuelling stations. The WTP EBP production pathway is shown in Figure 22, and the pathway created in GREET is shown in Figure 23.

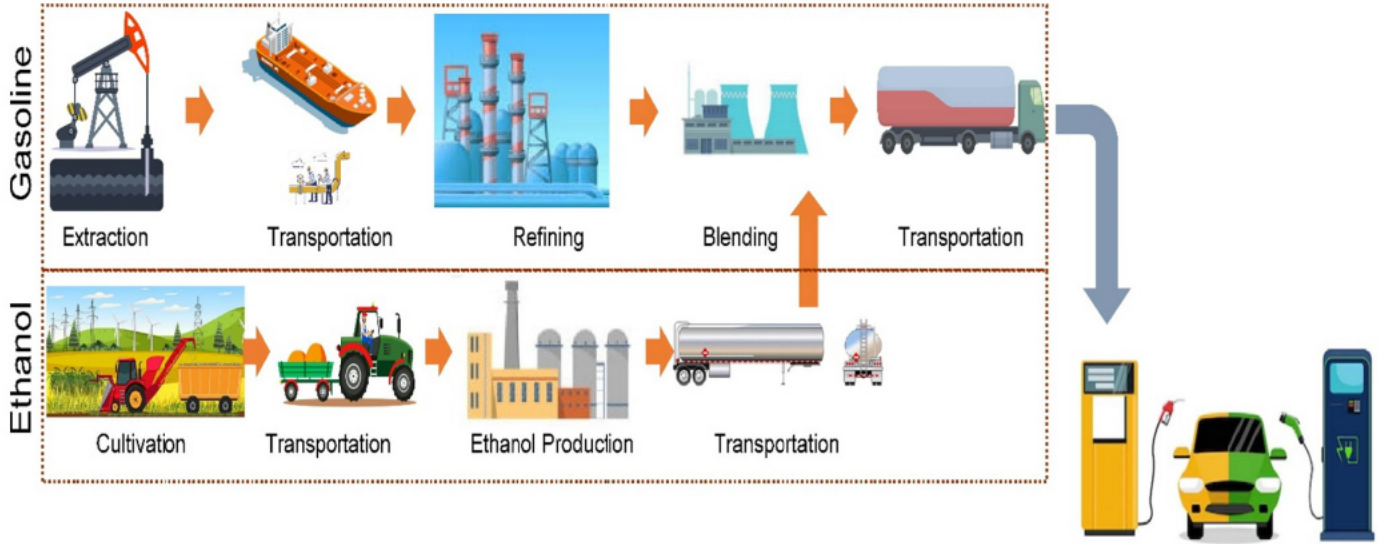


Figure 22: EBP Production Pathway in India

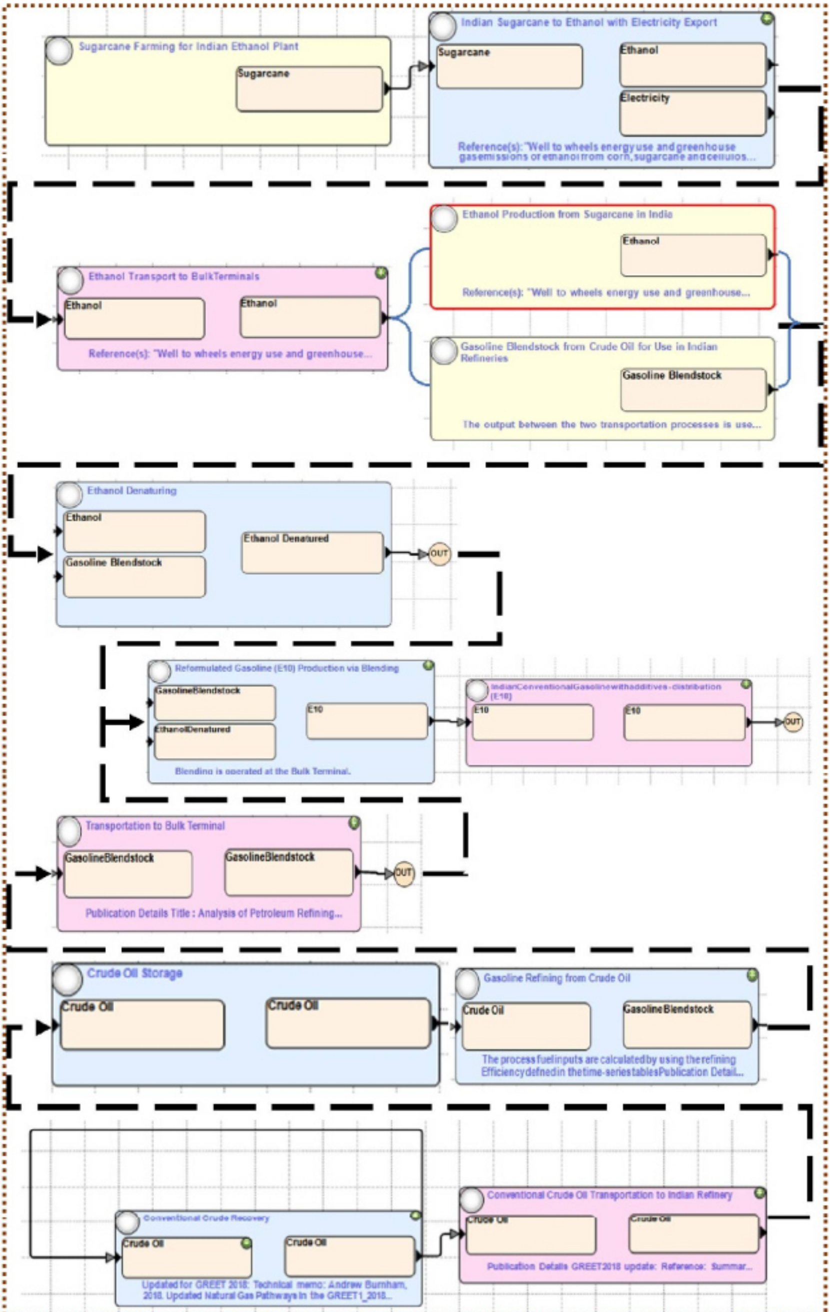


Figure 23: EBP Production Pathway Created in GREET

The background emission data for LCIA of crude oil extraction in a conventional way was taken from the GREET database. The transportation model is complicated, though. A vast amount of crude oil is imported from different countries. The share of imported crude oil from various countries is given in Table 9. India's ethanol production pathway is very similar to Brazil's. Brazil produces ethanol in vast quantities from sugarcane for transportation [16]. The LCIA and corresponding emission data of the feedstock of ethanol were considered as per the GREET model, developed for Brazil. However, this study considered transportation and the following steps for the India.

Table 9: Share of Imported Crude Oil from Various Countries [17]

Crude Oil Exporter to India	Share (%)	Distance from India (NM)
Asia		
Iraq	23.6	1847
Saudi Arabia	16.9	1636
UAE	10	1416
Kuwait	6.47	1802
Oman	2.69	982
Others	4.257	1536.6
Africa		

Nigeria	8.68	8460
Angola	1.94	7194
Egypt	1.43	3276
Others	2.969	6310
South America		
Brazil	2.39	9564
Colombia	2.09	10579
Others	0.76	10071.5
North America		
USA	10.3	15756
Mexico	3.07	12946
Canada	0.25	12251
Europe		
Norway	1.05	7817
Russia	1	6393
Others	0.154	7105

Pathway for Electricity Production in India:

LCIA of electricity production in India needs a comprehensive evaluation of the environmental impacts associated with the entire lifecycle of electricity generation. This assessment for WTP is considered in all stages, from resource material extraction, fuel production, power generation in a power plant, and electricity transmission.

LCIA examined the environmental impacts of resource extraction and associated energy consumption. The operational phase of power plants' emissions of pollutants and greenhouse gases was considered. The considered air pollutants from fossil fuel-based power plants were sulfur dioxide (SO_2), nitrogen oxides (NOx), and carbon dioxide (CO_2). LCA model of electricity generation from various sources was based on the GREET database. However, the share of electricity generation from various sources was based on the data taken from the annual reports of the Central Electricity Authority (CEA) [18]. The transmission and distribution of electricity across the grid involve a variety of energy losses, which were also considered in the LCIA. In other words, the efficiency of the transmission system and the associated environmental consequences were also considered in LCIA. LCIA of electricity production in India accounted for regional variations, such as the energy mix, technological advancements, and specific environmental concerns prevalent in the country. India's diverse energy portfolio, including a significant reliance on coal, posed unique challenges that LCIA addressed here. The electricity generation pathways for India are shown in Figure 24. The electricity-mix model created in GREET for the Indian scenario is shown in Figure 25.

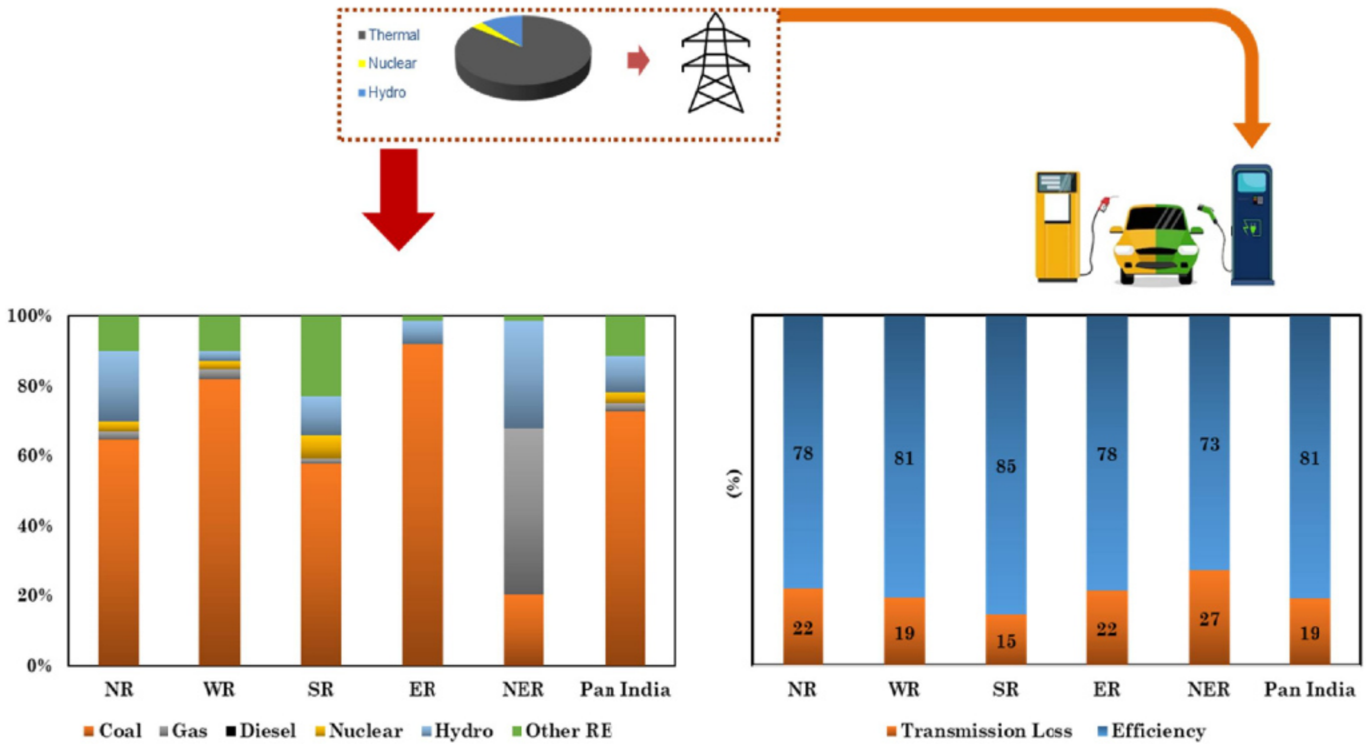


Figure 24: Electricity Generation Pathway of India

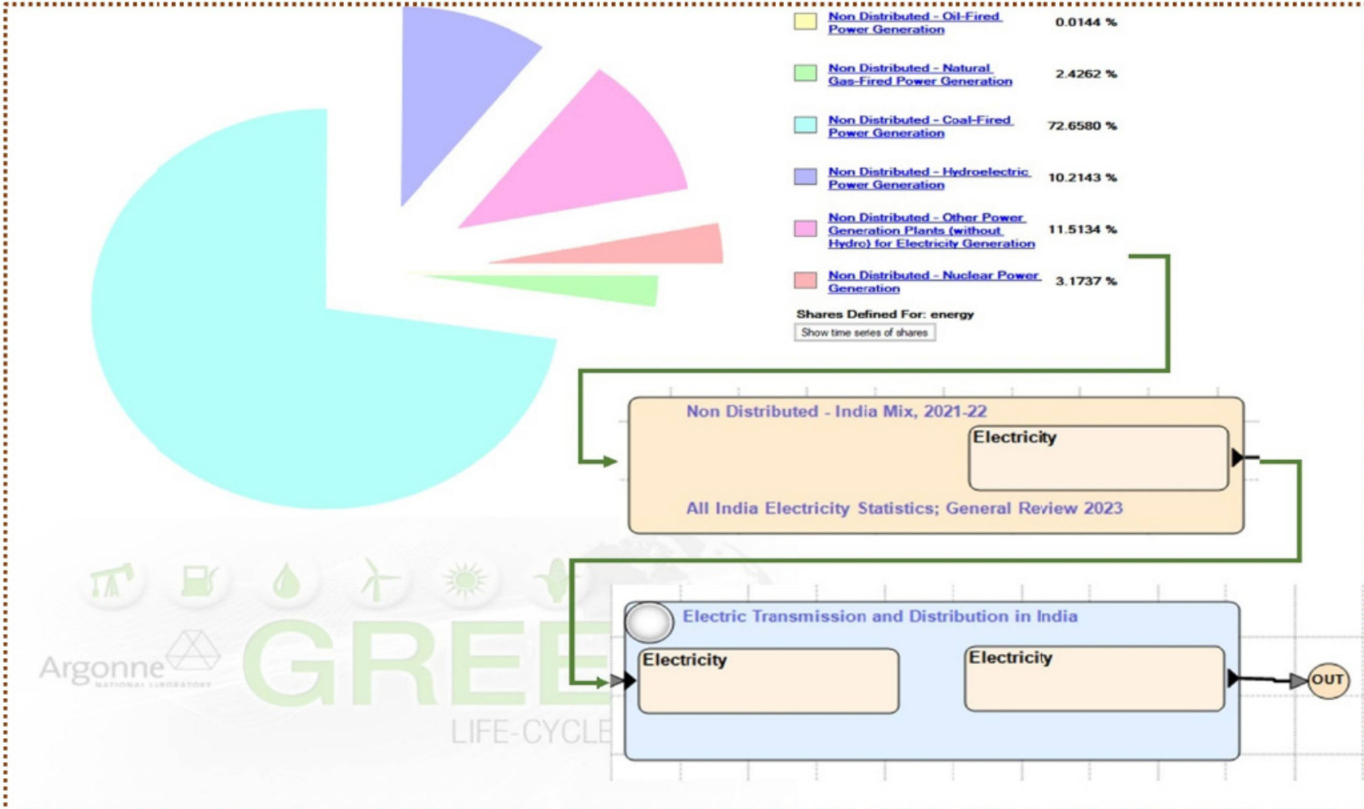


Figure 25: Electricity Generation Pathway Created in GREET

III. <u>Well-to-Wheel (WTW) inventory analysis</u>

WTW is a comprehensive concept that assesses the entire lifecycle environmental impact of transport fuel, considering both upstream and downstream stages. It combines two distinct phases: 'Well-to-Pump' and 'Cradle-to-Grave'. WTW inventory analysis accounts for a transport fuel's production and usage phases, offering a complete understanding of its environmental impact. This integrated approach is crucial for promoting sustainable practices guiding developing and adopting cleaner and more efficient transport solutions.

2.1.3. Lifecycle Impact Assessment:

Before directly jumping to the impact of GHGs on the environment, it is essential to understand the human and natural activities related to various GHGs, as shown in Figure 26. With the rapid growth of the Indian economy, human activities have increased significantly. Its increased industrial growth is directly proportional to transportation growth. These human activities created a higher demand for natural resources, feedstock, and livestock. All these activities directly or indirectly emit GHGs into the atmosphere and harm the environment.

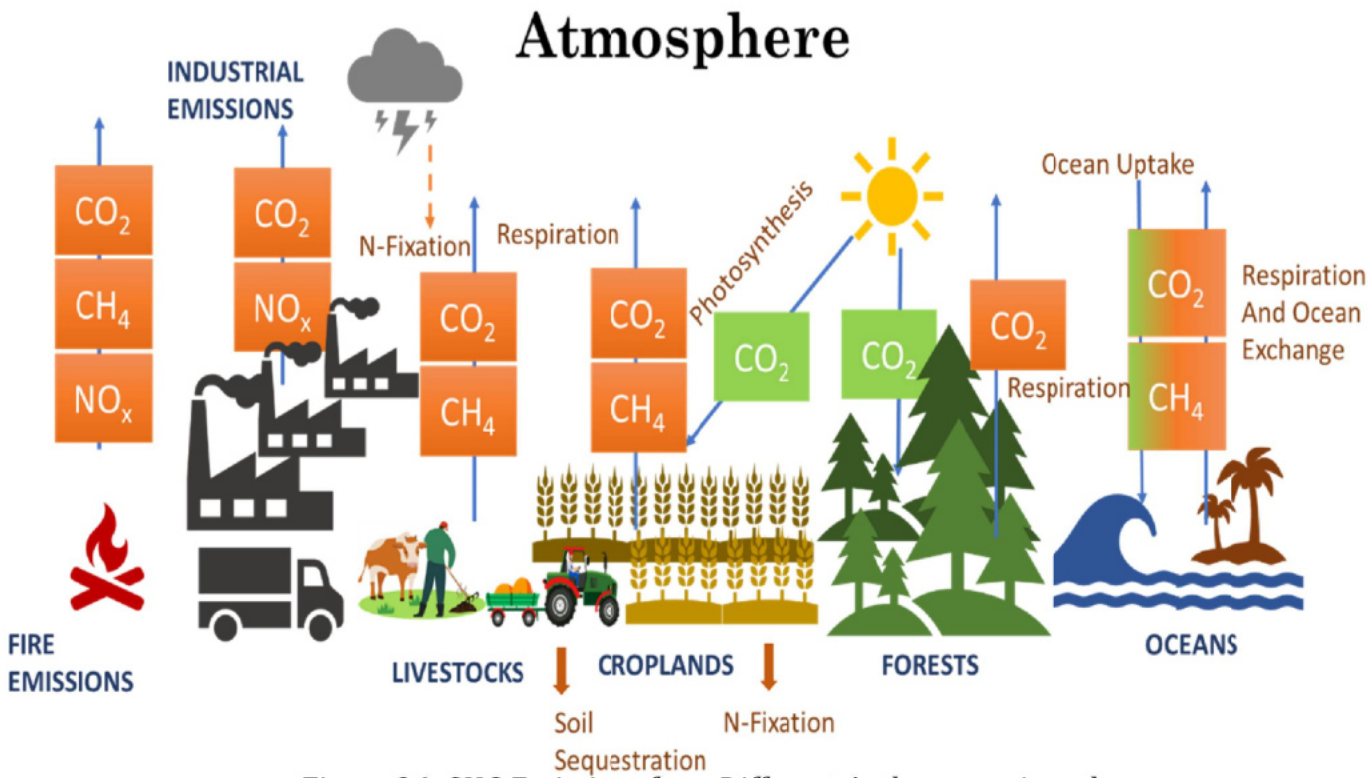


Figure 26: GHG Emissions from Different Anthropogenic and Natural Activities

However, natural activities include some uptake of emissions from the environment to the croplands, forests and oceans. The "net zero" target can only be achieved with the individual efforts of the organisations, and Lifecycle impact assessment is crucial for identifying their net emissions. This comprehensive methodology focuses explicitly on assessing and quantifying a product's or process's potential environmental impacts across various categories. Here, we identified and categorised the potential environmental impacts into distinct categories. Common impact categories include global warming potential, acidification, eutrophication, ozone depletion, and resource depletion. Each category represents a specific aspect of environmental concern. Characterisation factors are used to quantify each category. These factors express the relationship between the emissions or resource consumption and the potential environmental damage. For example, a characterisation factor for global warming potential would express the amount of greenhouse gas emissions in terms of equivalent CO_2 emissions. This study focuses on the GWP of various GHGs. Hence, it is crucial to understand the environmental damage potential of various gases. The GWP is a function of the lifespan of the GHGs in the environment and the energy absorption ability of these GHGs. Figure 27 shows the lifespan of some of the important GHGs in the atmosphere.

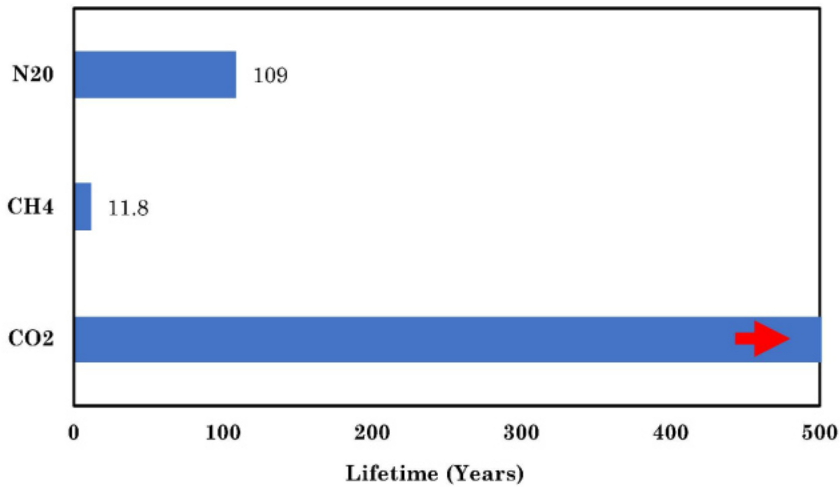


Figure 27: Lifespan of Main GHGs in the Environment [19]

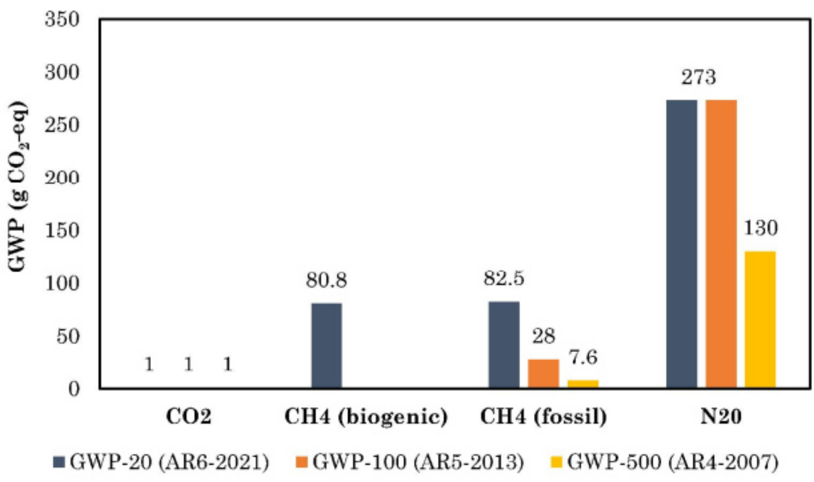


Figure 28: GWP of Various GHGs [20]

As per various reports of the Intergovernmental Panel on Climate Change (IPCC), The GWP is defined for various GHGs in terms of CO_2 equivalent. Figure 28 shows that GWP for

500 years, 100 years and 20 years are significantly different. Assessment Report 4 discussed the GWP for 500 years [19]. CO_2 is a primary GHG responsible for ~75% of GWP impact. It stays in the atmosphere for over a thousand years. CH_4 accounts for ~16% of GWP of all GHG emissions. The lifetime of this gas is about a decade, but it can absorb much more energy and act as a strong GHG. N_2O accounts for only 6% GWP of all GHG emissions. The lifespan of N_2O is more than 100 years, and it can absorb solar energy significantly. Similarly, in assessment Reports 5 and 6 of IPCC, the GWP for 100 years and 20 years are discussed elaborately. As per the assessments, the GWP of CH_4 is much higher in GWP-20, which is ~80 times higher than CO_2. The fossil CH_4 has a bit higher GWP than biogenic CH_4. However, N_2O has a lesser GWP if the assessment is done for 500 years. This study considered GWP for 100 years, as per equation 1, given below.

$$\boldsymbol{GHG_{100}(g\ CO_2\text{-}eq) = \sum_{i=CO_2;CH_4;N_2O\ (g);} GHG_i \times GWP_i} \qquad \textbf{(1)}$$

Lifecycle impact assessment is a very critical tool for decision-makers. It allows them to identify hotspots in the lifecycle of a product or process. This information guides the development of strategies to minimise environmental impact and improve overall sustainability. Policymakers can make informed decisions to optimise materials, manufacturing processes, and end-of-life considerations by identifying areas with significant environmental impact. Governments and regulatory bodies can use impact results to establish standards, regulations, and incentives that encourage industries to adopt more sustainable practices, even in shaping environmental policies. It also provides transparency of environmental performance. Stakeholders can communicate the sustainability of products or processes to consumers, investors, and other interested parties.

Software Used for LCA

Greenhouse Gases, Regulated Emissions and Energy in Transportation (GREET), developed by Argonne National Laboratory (ANL), US Department of Energy (USDoE) in 1995 and updated frequently, was used for this study. GREET_2022 is a tool that falls under the broader category of LCA tools used to assess the environmental impact of various transportation fuels/ energy and technologies. GREET software could analyse energy consumption, GHGs, and regulated emissions associated with different fuels and vehicle technologies. Users of GREET can input various parameters, such as the type of fossil fuels, biofuels, bioproducts, and biopower. GREET provides pinpoint opportunities to mitigate barriers to the sustainable deployment of technology, fuel and vehicle production methods. MS Excel spreadsheet was used for the postprocessing of the output data. The Processes, pathways and scenarios of this study are defined in **Figure 29.**

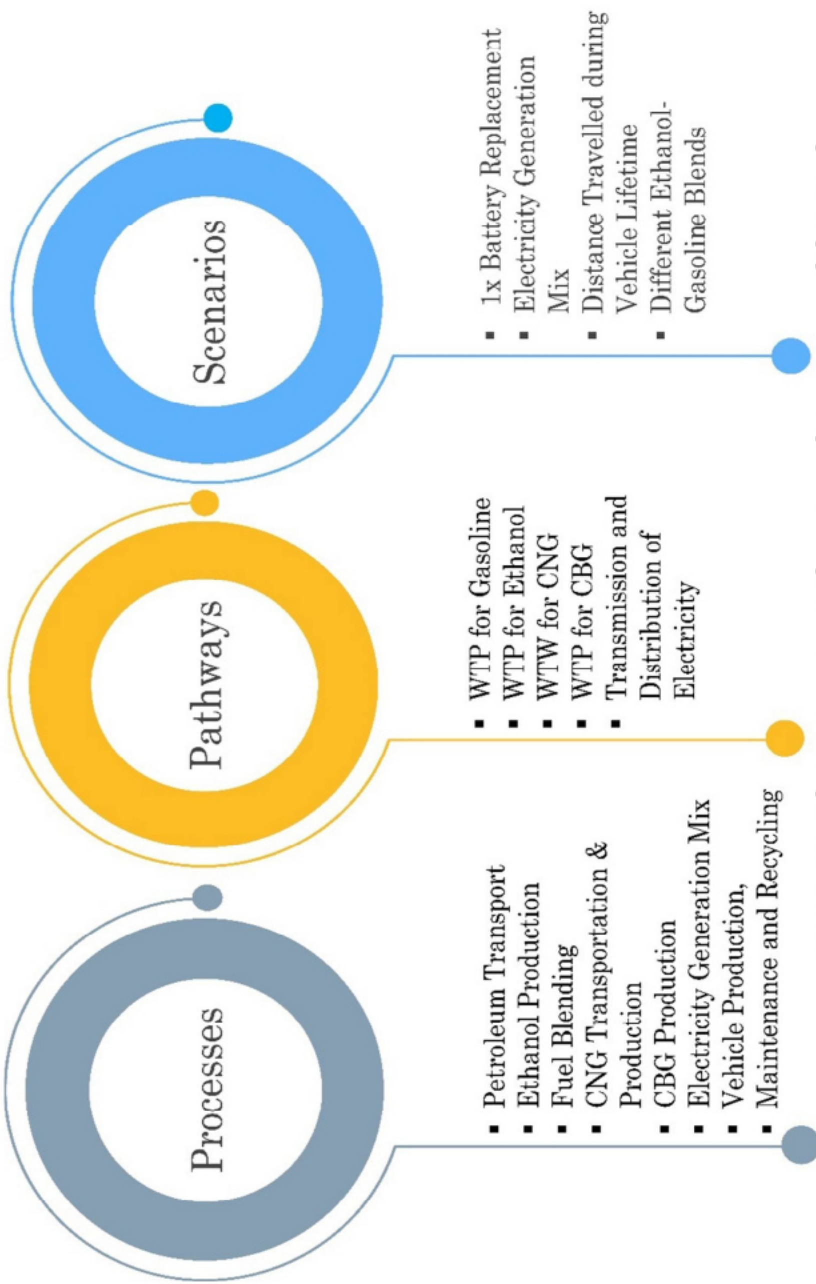


Figure 29: The Processes, Pathways and Scenarios of this Study

GREET Lifecycle Model

The mathematical model used in GREET calculates CO_2, CH_4, N_2O emissions and other criteria pollutants emanating from transportation system lifecycles [21]. The GREET model represents each stage as a stationary or transportation process. At each process step, emissions could be emitted in several ways: (i) combustion of processed fuels that provide heat and energy for the processes, (ii) leakages, usually associated with the storage and transportation of volatile fuels.

The significant model equations are as follows:

The energy associated with producing an input $'i'$ is calculated as

$$\boldsymbol{E(i) = a(i)E_{up}(i)} \qquad \textbf{(2)}$$

E = Energy vector; a = Amount of a resource;

E_{up}= Energy vector associated with upstream energy to produce input;

Emissions are calculated as follows:

$$\boldsymbol{Em(i) = a(i)Em_{up}(i) + a(i)\sum_{t\in T} s(i,t)E(i,t) + Em_{other}} \qquad \textbf{(3)}$$

Em = Emissions vector; t = Technology; s = Share (%)

Em_{up}= Energy vector associated with emissions to produce;

Thus, the emission results are a sum of the upstream, technology, and non-technology-related emissions, i.e., emissions associated with input leakages.

2.2. TCO Methodology

Total Cost of Ownership (TCO) assesses the cost of owning and operating a vehicle throughout its lifecycle. TCO goes beyond the initial purchase price and includes fuel costs, maintenance expenses, insurance, depreciation, and other ownership-related costs, including all upfront and hidden costs. In the context of Indian vehicles, TCO analysis has gained significance as consumers and businesses aim to make informed decisions based on the long-term financial implications of vehicle ownership. It has variable and fixed components: (i) Fixed Price: The initial cost of acquiring the vehicle. It is a significant component of TCO. This includes the vehicle's ex-showroom price and additional expenses such as taxes and registration fees. (ii) Fuel Costs: Considering the fuel price and the vehicle's fuel efficiency is crucial in estimating the overall cost of ownership. Fuel expenses can constitute a substantial portion of the TCO, especially over an extended period. (iii) Maintenance and Repairs: Regular maintenance and servicing contribute to the TCO. Evaluating a vehicle model's reliability and durability is essential in accurately estimating these costs.

(iv) Insurance: The insurance cost, including premiums and coverage, is a significant component of TCO. Insurance expenses vary based on the type of vehicle and coverage chosen. (v) Depreciation and financing cost: Depreciation reflects a vehicle's value reduction over time. While it doesn't involve direct out-of-pocket expenses, understanding depreciation is vital for estimating the vehicle's resale value. For those who finance their vehicle purchase, interest on loans or lease payments contributes to the overall cost of ownership. Our study did not cover this financial component as it may require a lot of sensitivity analysis. (vi) Resale Value: Considering the expected resale value at the end of the ownership period is crucial for obtaining a more accurate TCO. (vii) Government Incentives and Subsidies: Incentives or subsidies the government provides for certain types of vehicles (e.g., electric vehicles) impact the TCO.

TCO assessment allows consumers to make informed decisions by considering the holistic financial implications of owning a vehicle. It encourages a shift from focusing solely on the upfront cost to considering the long-term economic factors associated with different vehicle powertrain options. An overview of the TCO analysis done in this study, is shown in Figure 30.

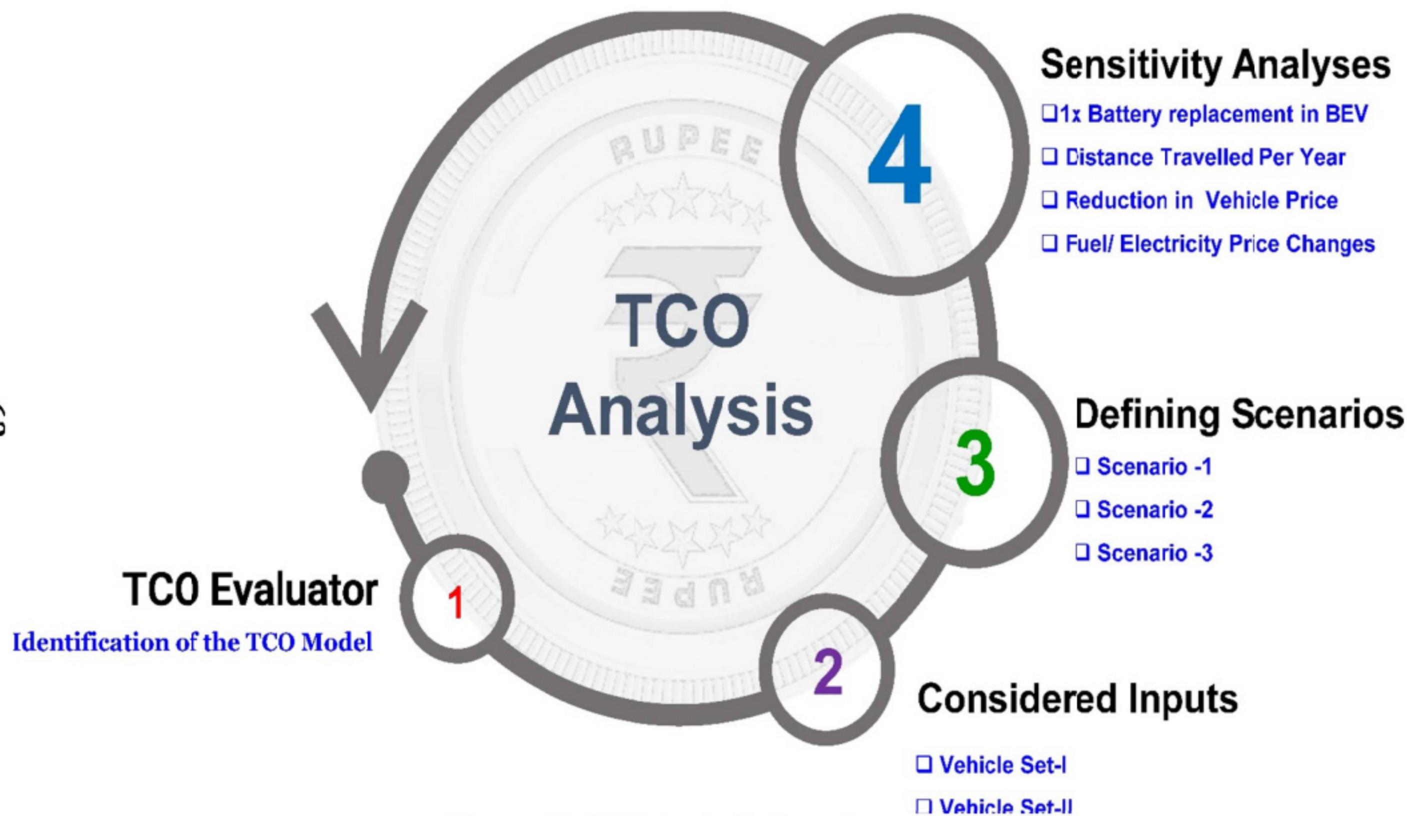


Figure 30: TCO Analysis Overview

2.2.1. TCO Evaluator

The TCO evaluators, such as the WRI TCO evaluator, are available in the open domain. In our study, we did not consider the cost of financing. Hence, the related cost burden on the owner was not considered. The cost of the BEV charging infrastructure is also not considered. The following equations describe the evaluator custom-developed and used in the analysis of this study.

$$\mathbf{TCO} = \left[\frac{\boldsymbol{NFC}+\boldsymbol{BCC}+(\boldsymbol{TVC}\times\boldsymbol{Y_n})}{(\boldsymbol{Y_n}\times\boldsymbol{D})}\right] \quad \mathbf{(4)}$$

NFC (Net Fixed Cost) = *Capital Cost + Tax − *Resale Value − Subsidy (if any);

BCC (Battery Change Cost) = Battery Capacity × ***Battery Cost × No of Replacement;

TVC/year (Total Variable Cost) = (Fuel Consumption × Fuel Price + Insurance Cost + Average Maintenance Cost

Y_n= No of Years; D = Distance travelled per year;

*Capital Cost including GST (after discount);

**Resale Value (As per market survey);

***Battery Cost (per kWh)

Energy Price: As of 01/11/2023 in Delhi.

2.2.2. Considered Inputs

The detailed inputs for this TCO analysis of Indian small cars and Foreign MUVs are provided in Tables 10 and 11, respectively.

Table 10: Required Inputs for Indian Small Cars [1,3,22–26]

	Baleno-E10	Baleno-CNG	Baleno-CBG	Tiago-BEV
Vehicle Holding Period (Year)	10			
Annual Distance Travelled (km)	20000*			
Capital Costs - Currency Cell	INR			
Actual Price of Vehicle	838000	928000		1203999
Discount (%)	*			
Road Tax (Lifetime)	58660	64960		120400
Others	5013	5013		5013
Total Tax	63673	69973		125413
Financial Subsidy	NA	NA		*
Total Fixed Cost	9,01,673	9,97,973		13,29,412
Resale Rate	20	20		10
Resale value	1,67,600	1,85,600		1,20,400
Net Fixed Cost	7,34,073	8,12,373		12,09,012
Total Annual Insurance Cost	10,513	12,935		10,217
Lithium-Ion Battery Cost ($/kWh)	NA	NA		152*
Change in Fuel Cost (%)	*			

Energy Cost	₹ 96.76/ l	₹ 74.59/ kg	₹ 70/ kg	₹ 8/ kWh
Capacity of Battery	NA	NA		24
Number of Battery Replacements				1*
Mileage (km/unit)	19.01	30.6		13.125
Annual Maintenance Cost	5258	5258		3040

*Sensitivity was conducted based on the changes in these parameters. Changes in these parameters may change many other values.

Table 11: Required Inputs for Foreign MUVs [4,6,22–24,27]

	Hyryder -E10	Hyryder -CNG	Hyryder-CBG	MG ZS-BEV
Vehicle Holding Period (Year)	10			
Annual Distance Travelled (km)	20000*			
Capital Costs - Currency Cell	INR			
Actual Price of Vehicle	14,49,000	15,44,000		25,89,800
Discount (%)	*			
Road Tax (Lifetime)	1,44,900	1,54,400		2,58,980
Others	5,013	5,013		5,013
Total Tax	1,49,913	1,59,413		2,63,993
Financial Subsidy	NA	NA		*
Total Fixed Cost	15,98,913	17,03,413		28,53,793*
Resale Rate	20	20		10

Resale value	2,89,800	3,08,800		2,58,980
Net Fixed Cost	13,09,113	13,94,613		20,91,813
Total Annual Insurance Cost	23,984	26,639		36,462
Lithium-Ion Battery Cost ($/kWh)	NA	NA		**152***
Change in Fuel Cost (%)	*			
Energy Cost	₹ 96.76/ l	₹ 74.59/ kg	₹ 70/ kg	₹ 8/ kWh
Capacity of Battery	NA	NA		50.3
Number of Battery Replacements				**1***
Mileage (km/unit)	21.1	26.6		9.2
Annual Maintenance Cost	4992	4992		9100

*Sensitivity was conducted based on the changes in these parameters. Changes in these parameters may change many other values.

2.2.3. Defining Scenarios

The Total Cost of Ownership (TCO) analysis involved delineating scenarios corresponding to the maturity stage of different powertrain technologies. Three distinct scenarios were formulated for the base case and sensitivity analysis.

Scenario 1: Promotional Technology Phase (S1)

Scenario 2: Intermediate Technology Phase (S2)

Scenario 3: Matured Technology Phase (S3)

In Scenario 1, representing the promotional phase, the Indian government, under the 'FAME-II' scheme, provides subsidies to incentivise the acquisition of the promoted powertrain, BEV in this case. During the S1 phase, taxes are completely waived, fostering a conducive environment for their faster adoption.

In Scenario 2, denoting the intermediate phase, the government's support is reduced as the technology matures and its adoption in the economy increases. While the technology is partially promoted, the tax exemption previously granted is discontinued. The S2 phase aims to strike a balance between government intervention and market forces.

Scenario 3 represented the matured phase with no subsidies and tax exemptions offered to any powertrain technologies. All powertrain technologies were treated equally on a level playing field, reflecting a self-sustaining market environment. All powertrain options have to compete in the marketplace on their merit in the S3 phase.

The subsidy under the FAME-II scheme for BEVs was contingent upon the battery capacity. The crucial condition is that the vehicle must be manufactured in India. Notably, the foreign vehicle set, including the MG ZS BEV, an imported car, does not qualify for the FAME-II subsidy due to its origin. To maintain parity in specific sensitivity analyses, it was assumed that the subsidy was provided at the rate of ₹10,000 per kilowatt-hour (kWh), which was capped at 20% of the vehicle purchase price. This assumption aligned with the provisions of the FAME-II scheme. Tables 12 and 13 provide details of the scenarios incorporated in the TCO analysis, highlighting the variations in values corresponding to different sensitivities. It is crucial to acknowledge that the values in these tables were subject to changes in response to various sensitivity parameters, emphasising the dynamic nature of TCO assessment.

Table 12: Defining Various Scenarios for Indian Small Cars

	Baleno-E10		**Baleno-CNG**		**Baleno-CBG**		**Tiago-BEV**	
Scenarios	Subsidy (₹)	Tax (₹)	Subsidy (₹)	Tax (₹)	Subsidy (₹)	Tax (₹)	Subsidy (₹)	Tax (₹)
S1 (Subsidy + no Tax)	0	58,660	0	64,960	0	64,960	2,35,800	0
S2 (Subsidy + Tax)	0	58,660	0	64,960	0	64,960	2,35,800	1,25,413
S3 (no Subsidy + Tax)	0	58,660	0	64,960	0	64,960	0	1,25,413

Table 13: Defining Various Scenarios for Foreign MUVs

	Hyryder-E10		Hyryder-CNG		Hyryder-CBG		MG ZS-BEV	
Scenarios	Subsidy ** (₹)	Tax (₹)	Subsidy (₹)	Tax (₹)	Subsidy (₹)	Tax (₹)	Subsidy (₹)	Tax (₹)
S1 (Subsidy + No Tax)	0	1,49,913	0	1,59,413	0	1,59,413	5,03,000	0
S2 (Subsidy + tax)	0	1,49,913	0	1,59,413	0	1,59,413	5,03,000	2,63,993
S3 (No Subsidy + Tax)	0	1,49,913	0	1,59,413	0	1,59,413	0	2,63,993

Chapter 3
Results

3.1. LCA Analysis

Before discussing the overall LCA results, it was essential to understand emissions in each step. For example, if we consider the WTP results of CBG, the GHG emissions in every step to produce the CBG are shown in Figure 31. The results of the WTP analysis are in gCO_2-eq/MJ. In this study, we analysed various fuels and energy production scenarios. Hence, the functional unit was chosen to better compare and understand the emissions during the production of various fuels. This figure has three parts:

Part A shows each process's mass input and output.

Part B describes the emissions in each process.

Part C describes the avoidances.

It was identified in part A that to produce 1 MJ of energy in the form of CBG, 1060 g of cow dung was required. It was mixed with 1060 g of water in the next process. 2120 g of slurry was prepared and sent to the digester. In the digester, 62 g of biogas was produced, with 2054 g of digestate and 4 g of biogas leakages. In the next step, this 62 g of biogas was purified to produce 21.2 g of biomethane and 40.8 g of gas was filtered out, which contained primarily CO_2, some CH_4, and other trace gases. The 93% (v/v) purity biomethane was then compressed in the next step to produce vehicle-grade CBG.

Part B showed that for transporting 1060 g of cow dung by tractor trolly, 2 g CO_2-eq GHG was emitted because of diesel combustion in the tractor trolley. In the following step, i.e., for preparing the slurry weighing 2120 g, 9 gCO_2-eq GHGs were emitted into the atmosphere because of electricity used for stirring. The anaerobic digestion process produces 62 g of biogas while emitting 28 gCO_2-eq GHG emissions. The next step is the purification of biogas to biomethane. The significant GHG emission of this WTP analysis came from the purification stage. The CO_2 and other trace gasses captured in the biogas were released into the atmosphere in this stage. The loss of traces of CH_4 is also considered here. 176 g CO_2-eq GHGs were emitted here, where 142 g CO_2-eq was the direct emission. The remaining 34 gCO_2-eq emissions were associated with the National grid's electrical energy used by the pressure swing adsorption technology. As the compression stage was also assumed to be driven by electricity, the associated emission in this stage was 34 gCO_2-eq. Hence, the overall emission to produce 1 MJ equivalent CBG was 249 gCO_2-eq.

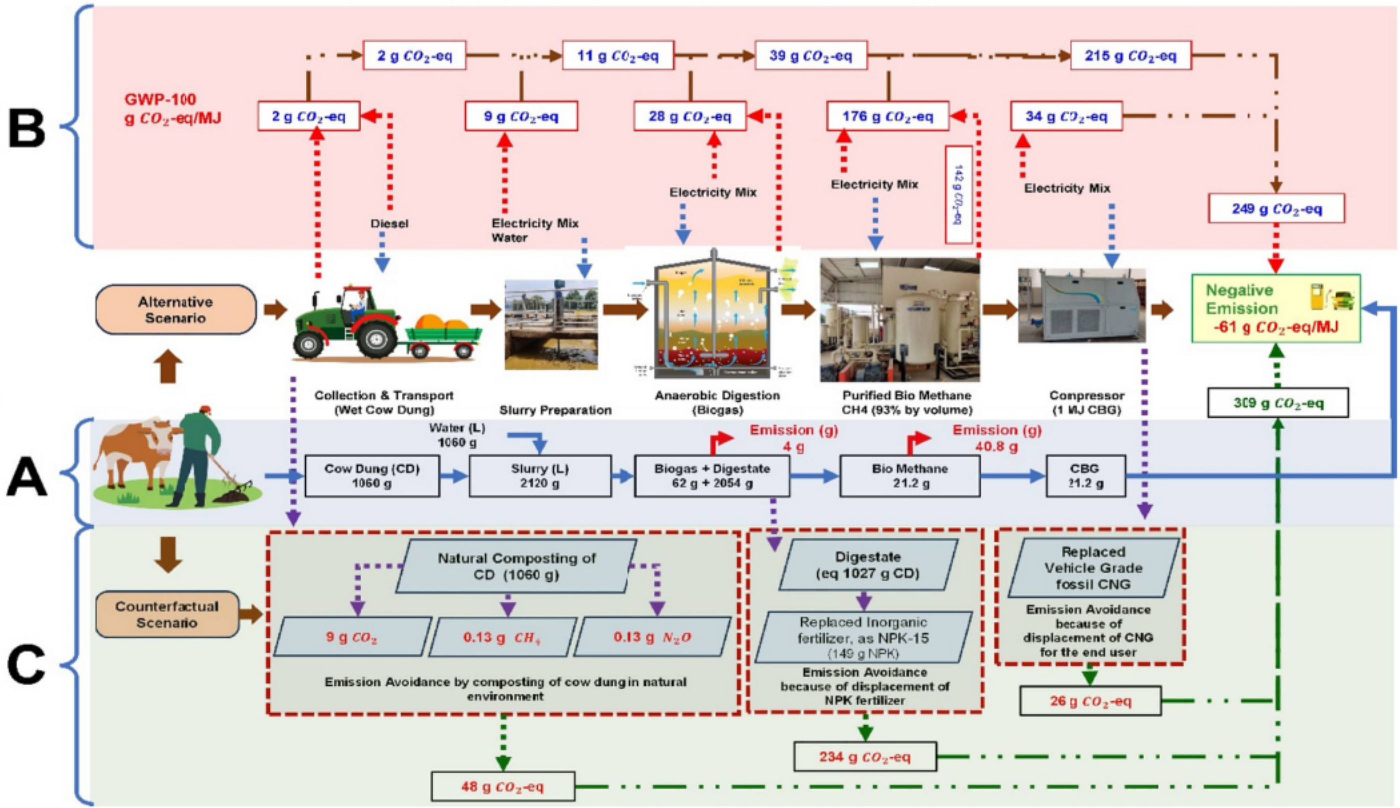


Figure 31: WTP Results of CBG Production

Part C of this figure is crucial for any LCA analysis, which is not discussed extensively in the literature, and is vital for achiving 'Net zero'. In this study, we considered avoiding emissions from the counterfactual scenarios, such as the natural composting of cow dung. These emissions were avoided after implementing alternative scenarios, such as CBG production from the cow dung. If the cow dung were left in the open environment, it would decompose in the environment and produce GHGs. These emissions were effectively avoided by taking the cow dung to the biogas plant for CBG production. Here, approximately 48 gCO_2-eq direct GHG emissions were avoided [28]. The subsequent avoidances were calculated because of the displacement of inorganic fertiliser with organic digestate generated in the anaerobic digestion step during CBG production. It was assessed that the inorganic fertiliser production involves very high GHG emissions, which is effectively avoided by CBG production. The analysis in this study is conducted by considering the NPK (15-15-15) fertiliser. The inorganic fertiliser is specified here for specific emission results since the results could differ if a different inorganic fertiliser is specified for the analysis. It was assumed that 2054 g of organic fertiliser digestate (equivalent to 1027 g of cow dung) produced from the anaerobic digester could displace the use of 149 g of NPK fertiliser. Here, the GHG emission avoidance was 234 gCO_2-eq.

The CBG produced in this process is vehicle grade, displacing an equivalent amount of fossil CNG. Hence, the GHG emission corresponding to the one emitted while producing an equivalent amount of CNG (in the Indian context) was avoided. The GHG emission avoidance here was 26 gCO_2-eq. Hence, a gross avoidance of 309 gCO_2-eq was calculated for 1 MJ energy containing CBG. Therefore, the WTP analysis of CBG concluded that the net emission, in this case, was (-) **61 gCO_2-eq/MJ**. If the results were converted to a per kg CBG basis, the net emissions would be 2.9 kgCO_2-eq/kg CBG in negative. This result differs from animal manure-based CBG production in the US, which was (-) 4.3 kgCO_2-eq/kg CBG (default GREET result). This was mainly because of different technologies used for CBG production, locally produced electricity, and large-scale production. In the Indian context, if bio-CNG was produced from sugarcane bagasse, the net emission reduction reported in the literature is (-) 3.9 kg CO_2-eq./kg bio-CNG [29].

3.1.1. WTP Results

The WTP results for various fuels are analysed and shown in Figure 32. It was assessed from the WTP LCA analysis that the GHG emissions in producing ethanol were 29.9 gCO_2-eq/MJ, which were higher than gasoline production by 51%.

Hence, the Lifecycle GHG emissions of ethanol blends increased with increasing ethanol fraction in the blend. The GHG emissions for E10, E20 and E30 are 20.4, 21.2 and 21.9, respectively.

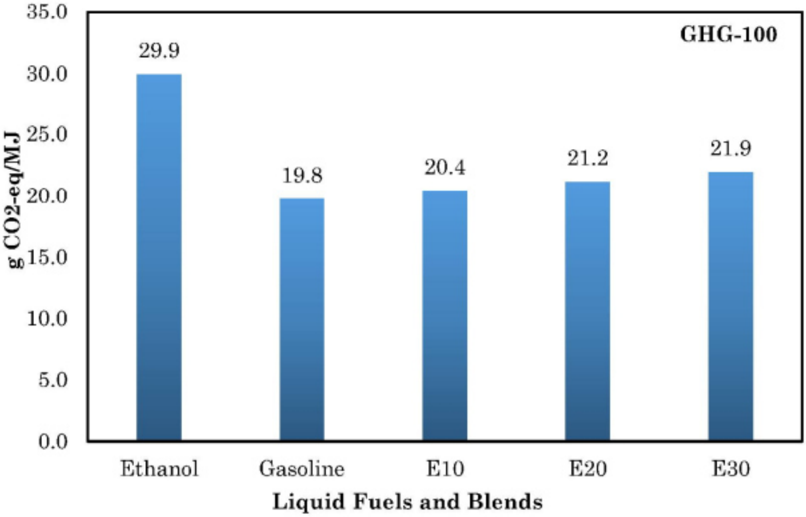


Figure 32: WTP Results for Various Conventional Fuels

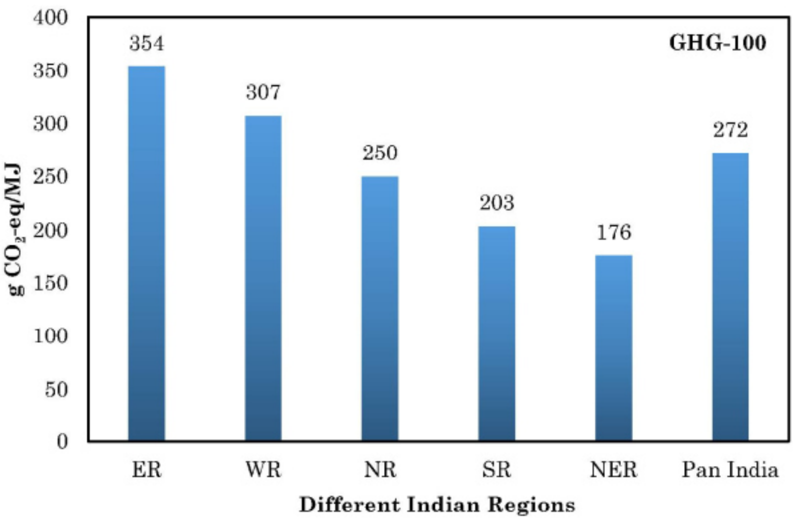


Figure 33: Electricity Generation in Different Indian Regions

The WTP results for electricity generation in different Indian regions are shown in Figure 33. This WTP analysis of electricity generation showed different emissions for different regions due to differences in primary energy sources. Emissions are reduced with renewable energy sources being used for power generation. The lowest emission was 176 gCO_2-eq/MJ in the Northeastern region, and the highest was 354 gCO_2-eq/MJ in the Eastern region. Emissions from electricity generated in the northeast were lower due to the dominant use of hydropower in the electricity mix. In contrast, coal was dominantly used in the eastern region for electricity generation, leading to higher emissions. The emission Pan-India was assessed to be 272 gCO_2-eq/MJ. The electrical transmission losses in Pan India contributed ~60 gCO_2-eq/MJ to GHG emissions.

The WTP GHG emissions for E10, CNG, CBG and electricity are compared in Figure 34. WTP GHG emissions for CNG was ~26 g CO_2-eq/MJ, in which ~9 gCO_2-eq/MJ was contributed by domestic CNG (52% of the total CNG consumed), and the remaining 17 gCO_2-eq/MJ was contributed by imported CNG (48% of the total CNG consumed). The higher emissions in imported CNG were mainly due to additional liquefication and shipping stages. The Net WTP GHG emissions for CBG was

(-)61 g CO_2-eq/MJ. The GHG emissions in the production of CBG in India was 249 gCO_2-eq/MJ, but CBG production avoided emissions of 26 g CO_2-eq by displacing the fossil CNG, 48 gCO_2-eq by avoiding natural composting of Cow dung in the open environment, and 234 g CO_2-eq by avoiding the use of inorganic NPK (15-15-15) fertiliser, which organic fertilisers displaced.

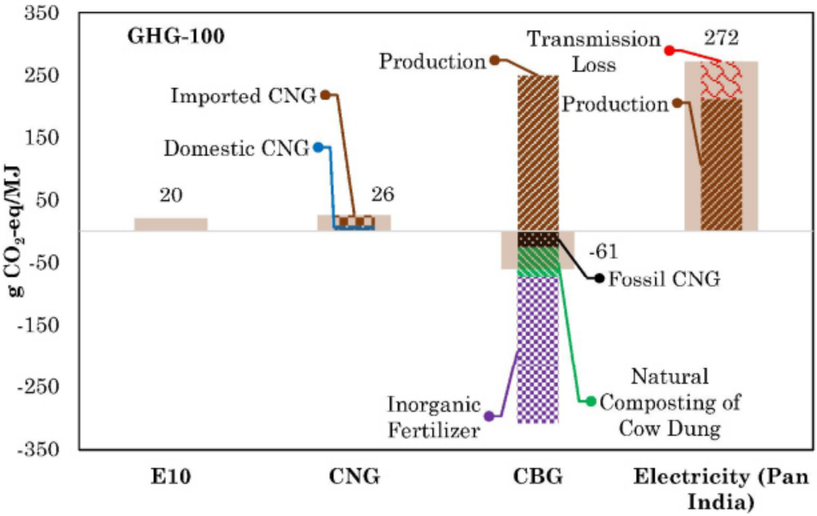


Figure 34: WTP GHG Emissions of Transport Energy

3.1.2. Base Case Analysis (Well-to-Wheel and Cradle-to-Grave)

Indian Small Cars:

It was assumed that the vehicles travelled 200000 km in a 10-year lifespan and were recycled. The results are per km basis. A cradle-to-gate analysis was done and the results are shown in Figure 35. In this analysis, the emissions during vehicle and their components manufacturing are incorporated. Usage phase emissions consider all the consumables and non-consumable vehicle components replaced during maintenance over the vehicle's lifetime.

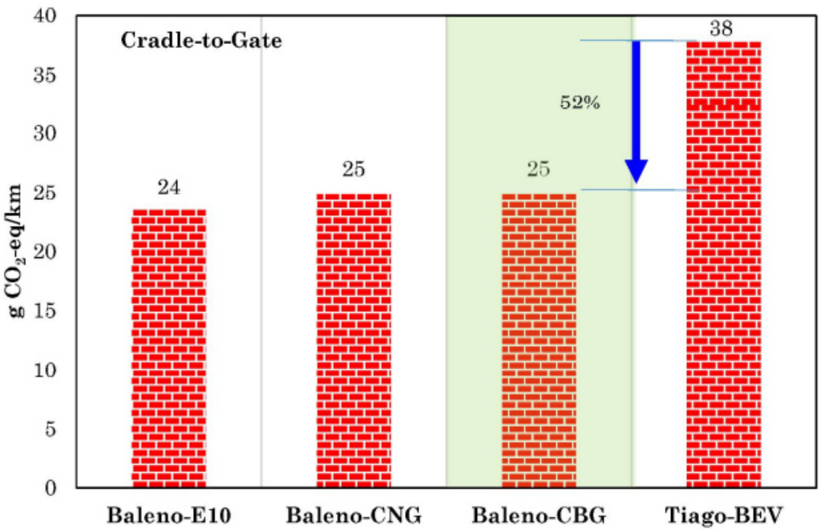


Figure 35: Emissions from Vehicle Manufacturing and Maintenance

It is shown in Figure 35 that the Cradle-to-Gate (CTG) GHG emissions from the Tiago-BEVs were ~52% higher than the CBG/CNG-powered Baleno-ICEV powertrain. The GHG emissions in producing the BEVs were the highest due to GHG-intensive battery manufacturing practices. GHG emissions in producing the Baleno Gasoline ICEV variant were the lowest. There was a very nominal difference between the Gasoline and CNG/CBG ICEV variants' emission footprint during manufacturing and maintenance over the vehicle lifetime.

Figure 36 shows the WTP emissions corresponding to the various powertrain options sold in Indian small cars.

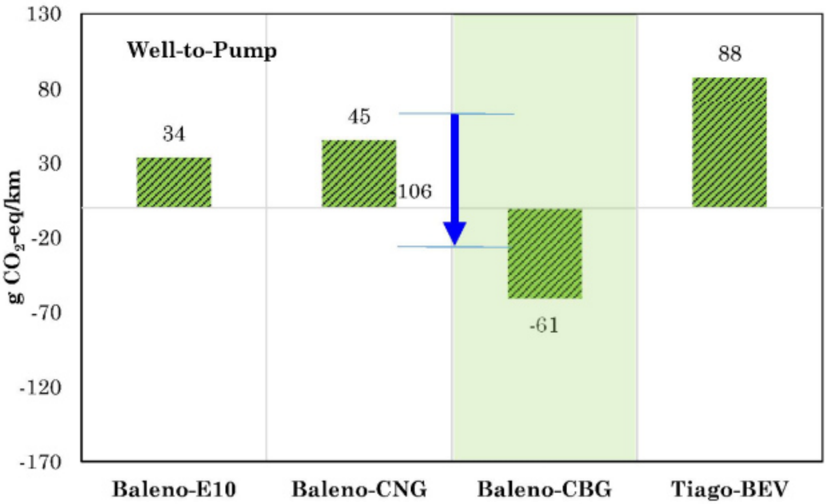


Figure 36: WTP Emissions for Indian Small Cars

In the WTP analysis, CBG-fueled Baleno-ICEV cars showed negative emissions due to the avoidances counted in the fuel production stage. This was calculated as per the rate of fuel consumption by different vehicles.

Figure 37 shows the Pump-to-Wheel (PTW) tailpipe emission results for Indian small cars. In the operational stage, the tailpipe emission of gaseous-fuelled (CNG/CBG) ICEV powertrains emitted lesser emissions than the Gasoline ICEV. The fuel efficiency of the CNG powertrain was higher than that of the Gasoline variant, leading to lower GHG emissions of CNG than the Gasoline ICEV. BEVs had no tailpipe emissions since their PTW tailpipe emissions were from the power plant chimney.

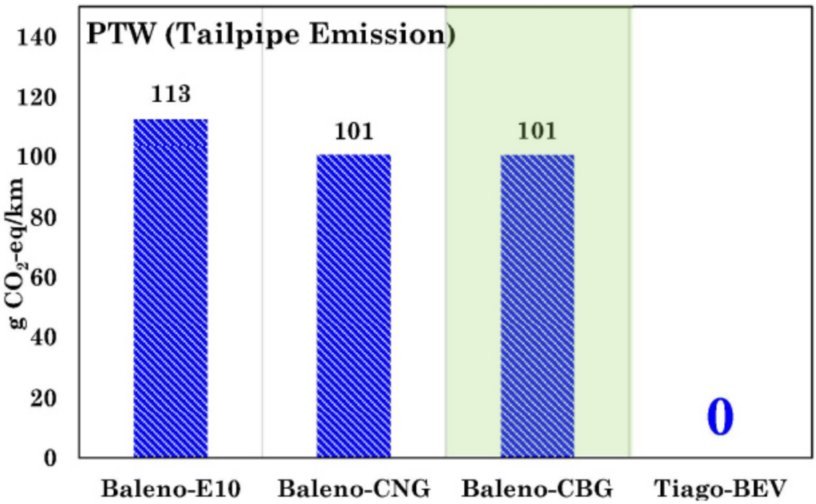


Figure 37: Tailpipe Emissions of Various Powertrains

Figure 38 shows various Cradle-to-Gate (CTG), WTP, PTW and net GHG emissions of different Indian small-car powertrain options considered in this study. The net GHG of the Baleno-CBG car was 20 gCO_2-eq/km, the lowest among all powertrains. Tiago-BEV claimed much lower energy consumption per km, ranking after CBG-powered ICEV at 125 gCO_2-eq/km GHG emissions. It can be noted from Figure 38 that the WTP of CNG was higher than E10. Hence, Baleno-CNG emitted higher GHGs than Baleno-E10 in the ranking of lower GHG emitters among these powertrains.

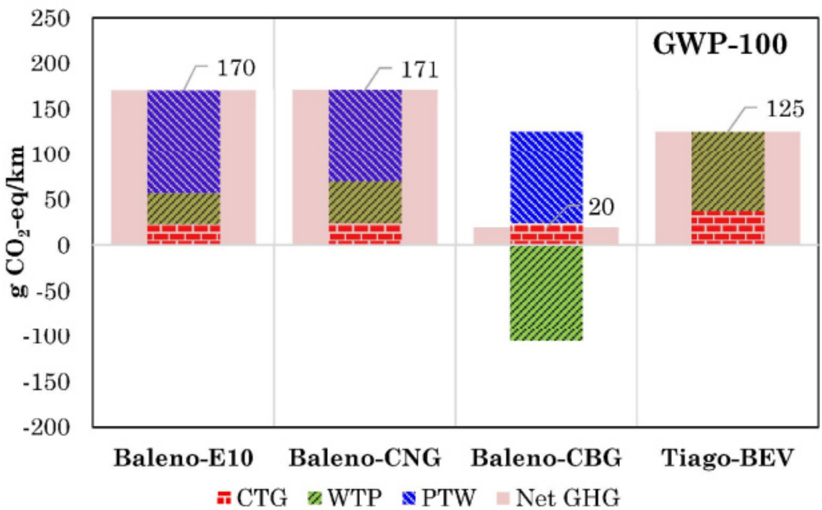


Figure 38: GHG Emissions of Various Powertrains for Indian Small Cars

Some other lifecycle emissions associated with these vehicles include volatile organic compounds (VOC), Carbon monoxide (CO), Particulate matter of 10 micrometres or less in diameter (PM_{10}), Particulate matter of 2.5 micrometres or less in diameter ($PM_{2.5}$), Oxides of Nitrogen (NO_x), Oxides of Sulfur (SO_x) etc. Figure 39 shows that the VOCs from the Baleno-CBG car were (-)264 mg/km. This was mainly because of the avoidance of inorganic fertiliser production. Tiago-BEV's ranking was just after the CBG-powered ICEV, at 37 mg/km VOCs emitted during the production of vehicles and electricity only. It was also noted that the WTP VOC emissions of CNG were lower than E10. Hence, Baleno-E10 emitted higher VOCs than Baleno-CNG.

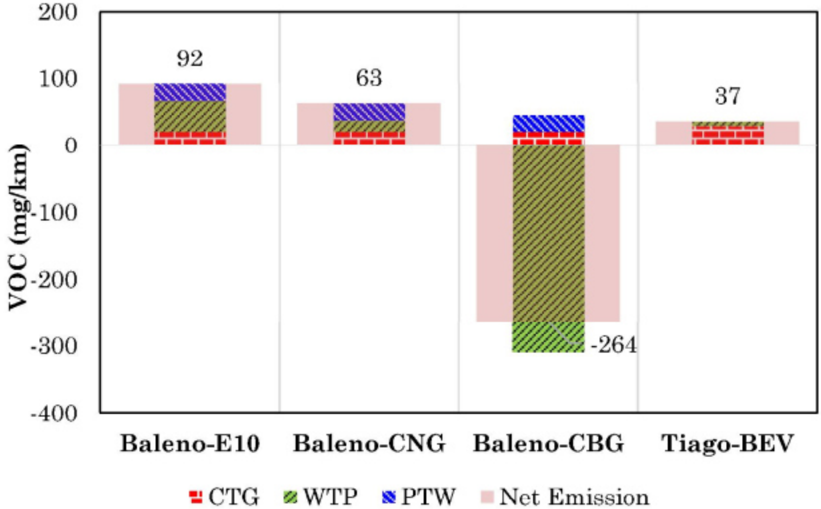


Figure 39: VOC Emissions of Various Powertrains for Indian Small Cars

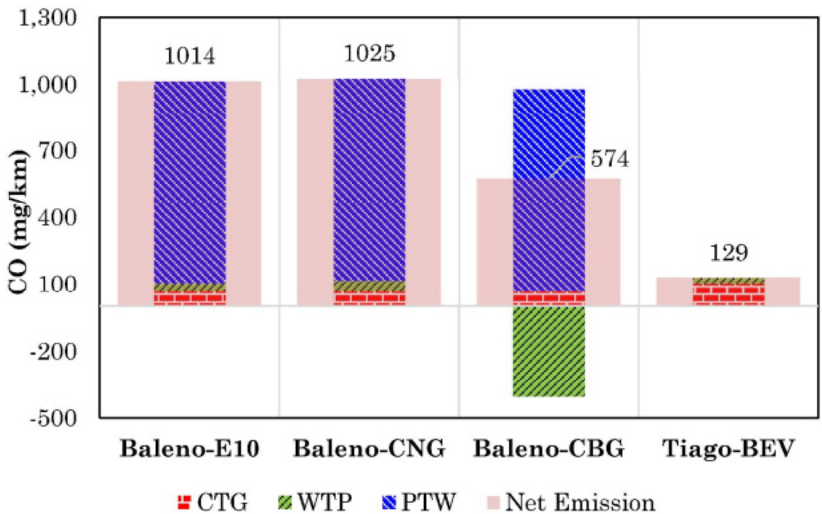


Figure 40: CO Emissions of Various Powertrains for Indian Small Cars

Figure 40 shows that net CO emission from Tiago-BEV was 129 mg/km, which was the lowest among all the powertrains considered. It is clear from Figure 40 that a significant portion of the CO emission was from the PTW stage (internal combustion). The higher CO emission from CNG-powered ICEV than E10 ICEV was primarily due to emissions in the WTP stage. This was primarily due to the more complicated LNG transportation processes involved.

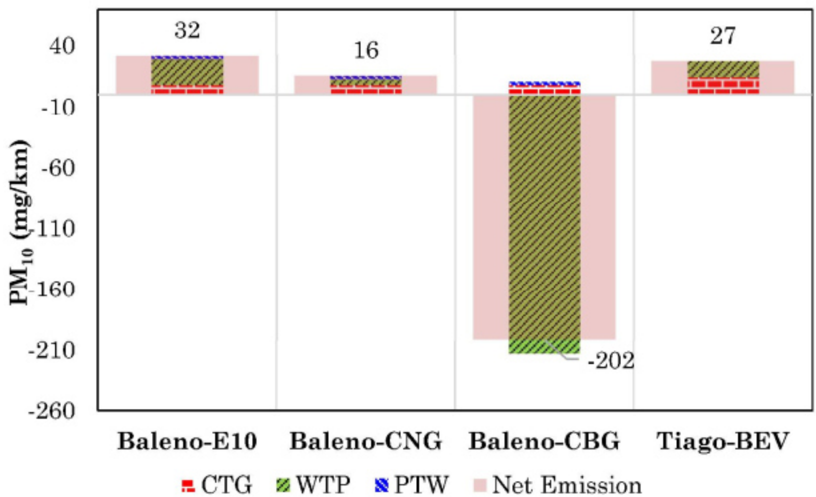


Figure 41: PM_{10} Emissions of Various Powertrains for Indian Small Cars

Figure 41 shows that the PM_{10} from the Baleno-CBG car was -202 mg/km. This was mainly because of the avoidance of PM during inorganic fertiliser production. Baleno-CNG emitted 16 mg/km of PM_{10} emissions. It is also noted that the

WTP and CTG PM_{10} emission of Tiago-BEV was lower than Baleno-E10.

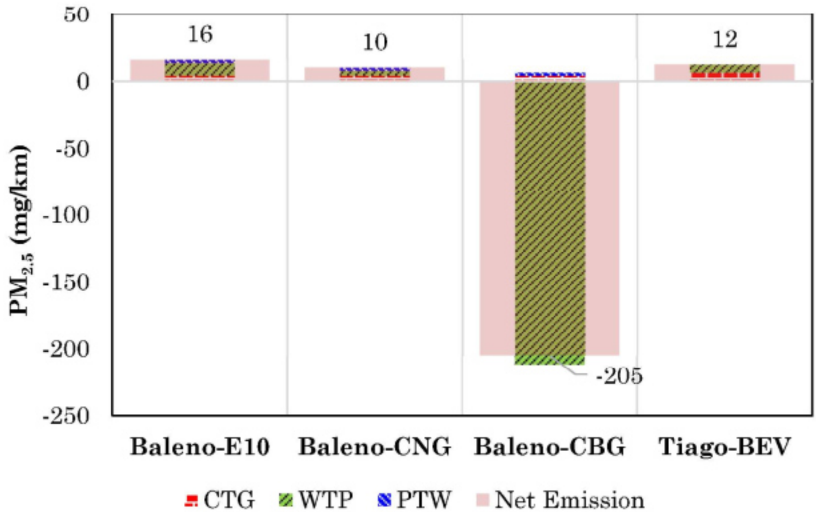


Figure 42: $PM_{2.5}$ Emissions of Various Powertrains for Indian Small Cars

Figure 42 shows that $PM_{2.5}$ from Baleno-CBG car ICEV was -205 mg/km. Baleno-CNG ICEV emitted 10 mg/km $PM_{2.5}$ emissions, most of which were from the WTP and CTG stages. It was also noted that WTP $PM_{2.5}$ emissions of Tiago-BEV were lower than Baleno-E10. However, the CTG $PM_{2.5}$ emission of Tiago-BEV was higher than Baleno-E10.

Figure 43 shows that the NOx emission from the Baleno-CBG car was -676 mg/km. Tiago-BEV ranked just after Baleno-CBG ICEV, with 100 mg/km of NOx emissions, mainly from the WTP and CTG stages. It was also noted that the WTP NOx emission of CNG was higher than Baleno-E10.

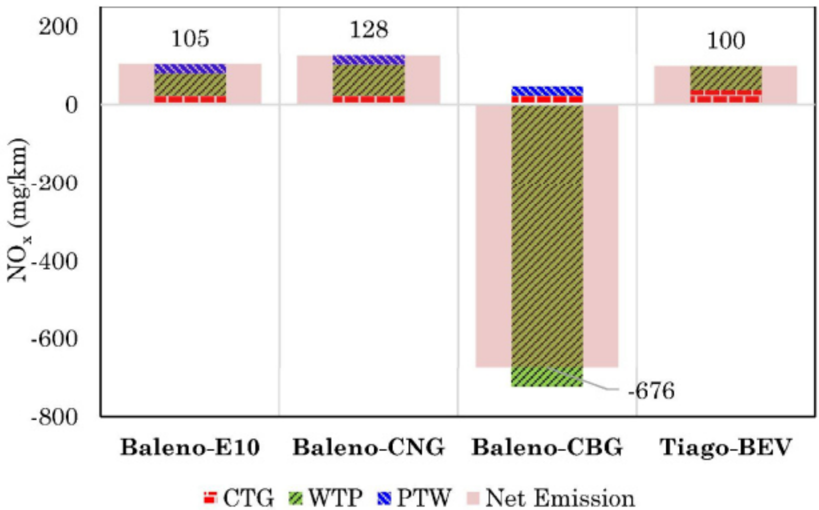


Figure 43: NO_x Emissions of Various Powertrains for Indian Small Cars

Figure 44 shows that the SOx emissions from the Baleno-CBG car were -1012 mg/km. Baleno-E10 ICEV emitted 84 mg/km of SOx, most of which were from the WTP and CTG stages. It was also noted that the WTP SOx emission of CNG was higher than Baleno-E10. Tiago-BEV was the highest LCA SOx emitter among all these powertrains because of higher SOx emissions during the WTP and CTG stages.

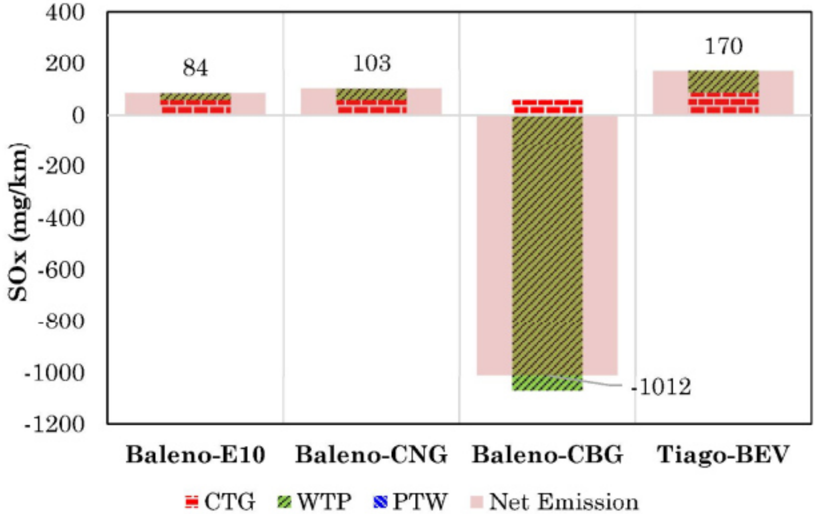


Figure 44: SOx Emissions of Various Powertrains for Indian Small Cars

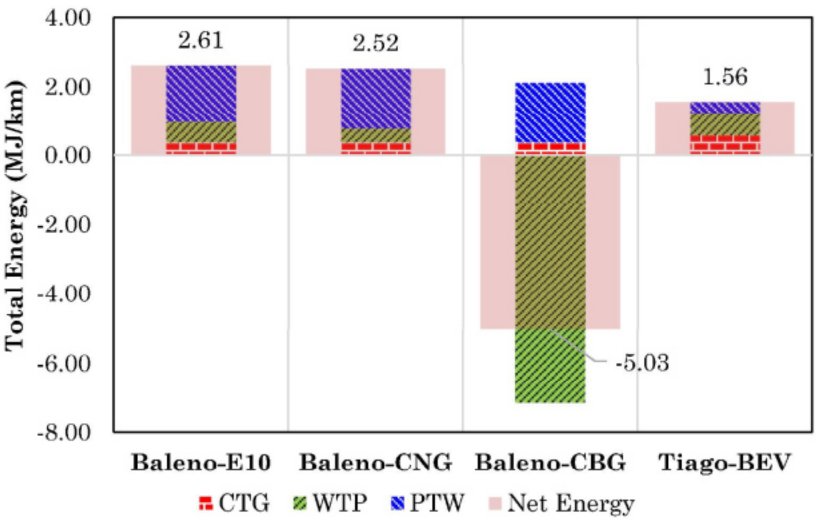


Figure 45: Total Energy Consumption of Various Powertrains for Indian Small Cars

Figure 45 shows that the total energy saved using the Baleno-CBG car was 5.03 MJ/km. The BEV's PTW energy consumption was the lowest, compensating for the higher CTG and WTP energy consumption compared to the fossil fuel-powered ICEVs. Tiago-BEV consumed 1.56 MJ/km. Among CNG and E10-powered ICEVs, Baleno-CNG consumed less energy than Baleno-E10. Baleno-CNG and Baleno-E10 consume 2.52 and 2.61 MJ/km, respectively. However, the results of fossil and non-fossil lifecycle energy consumption of various powertrains are shown in Figures 46 and 47, respectively. This energy consumption can not be directly compared since ICEVs use low-grade energy, whereas BEVs use high-grade energy.

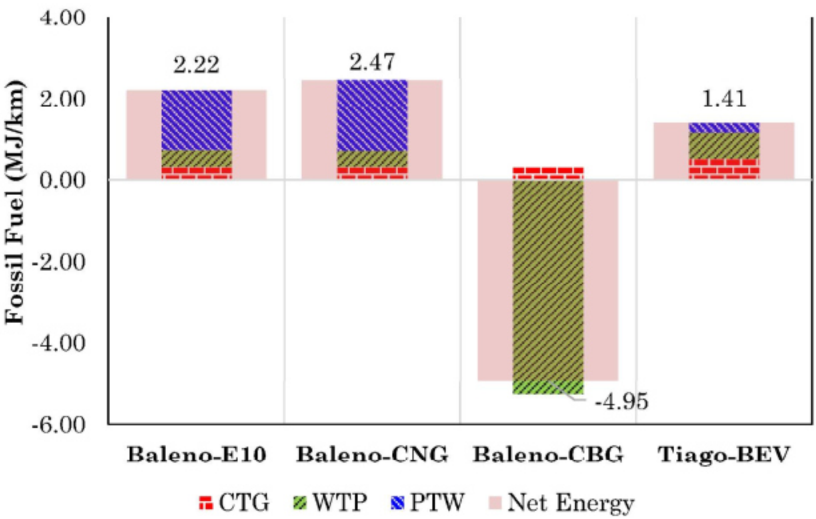


Figure 46: Fossil Fuel Consumption of Various Powertrains for Indian Small Cars

Figure 46 shows that the fossil fuel saved using the Baleno-CBG car was 4.95 MJ/km. There was no PTW fossil fuel consumption in CBG-powered ICEV. Tiago-BEV's direct and indirect fossil fuel consumption was 1.41 MJ/km. Among CNG and E10-powered ICEVs, Baleno-CNG consumed more energy than Baleno-E10. Baleno-CNG and Baleno-E10 consumed 2.47 and 2.22 MJ/km of fossil energy, respectively.

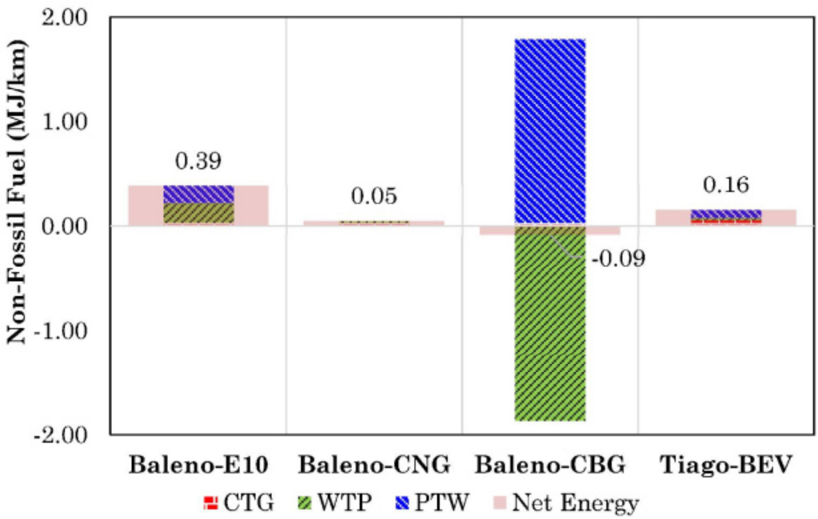


Figure 47: Non-Fossil Fuel Consumption of Various Powertrains for Indian Small Cars

Figure 47 shows that the non-fossil fuel saved using a Baleno-CBG car was (-)0.09 MJ/km. A few non-fossil fuel consumptions in CNG-powered ICEV powertrains are from CTG and WTP. Tiago-BEV's direct and indirect non-fossil fuel consumption was 0.16 MJ/km. Among CNG and E10-powered ICEVs, Baleno-CNG consumed much less non-fossil energy than Baleno-E10. Baleno-CNG and Baleno-E10 consumed 0.05 and 0.39 MJ/km of non-fossil energy, respectively.

Foreign MUVs:

Figure 48 shows the CTG emissions of the Foreign MUV set.

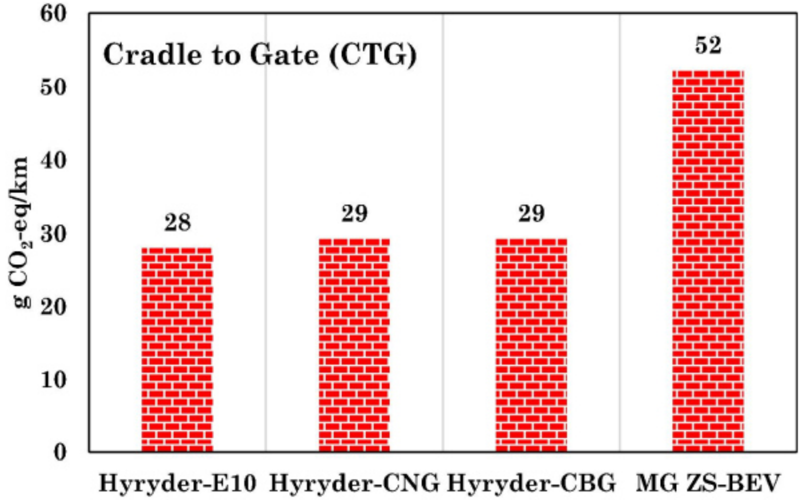


Figure 48: CTG Emissions of the Foreign MUVs

The CTG GHG emissions from the MG ZS-BEV were ~79% higher than the Hyryder-CBG powertrain. MG ZS-BEV emitted the highest GHGs among all the powertrains, 52 gCO_2-eq/km. Hyryder-E10 emitted the lowest GHGs, 28 gCO_2-eq/km. The emissions from the manufacturing of CNG-ICEV and Gasoline ICEV were almost similar.

Figure 49 shows the WTP emissions from the Foreign MUVs considered in this study. In the WTP analysis, CBG-fueled ICEV showed negative emissions due to avoidances in fuel production. This was calculated as per the rate of fuel consumption by different vehicles. A significantly higher emission was observed for MG ZS-BEV. The main reason was the higher specific energy consumption of this vehicle. However, the Hyryder-E10 was more efficient than the other fossil fuel powertrains since the fuel efficiency of this powertrain was superior. The WTP GHG emissions of Hyryder-E10, Hyryder-CNG, Hyryder-CBG and MG ZS-BEVs were 30, 52, -70 and 126 gCO_2-eq/km, respectively.

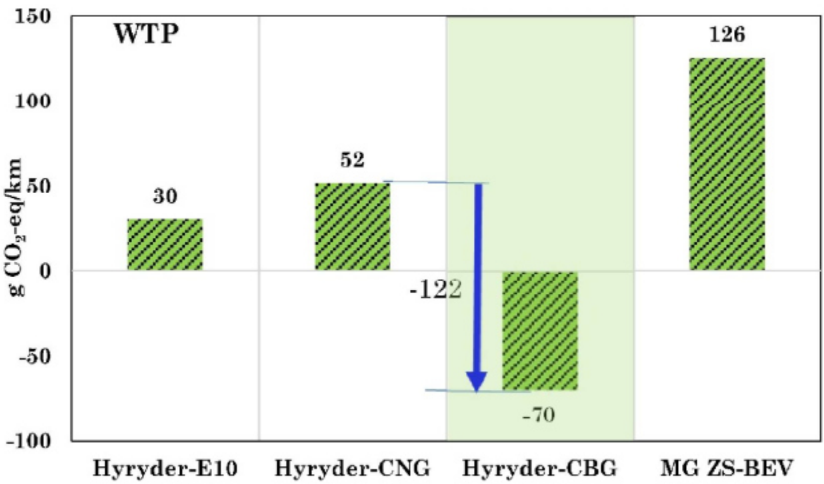


Figure 49: WTP Emissions Analysis of Foreign MUVs

Figure 50 shows the PTW emissions analysis of the Foreign MUVs. In the operational stage, the tailpipe emissions of the CNG/CBG-fuelled Hyryder powertrain emitted higher emissions than the Gasoline version. The tailpipe emissions of Hyryder-E10 and Hyryder-CNG were 102 and 115 gCO_2-eq/km, respectively.

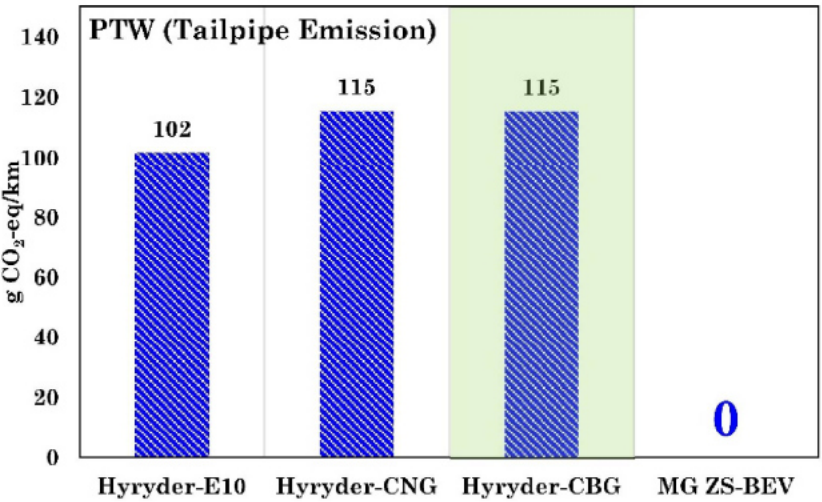


Figure 50: PTW Emissions Analysis of Foreign MUVs

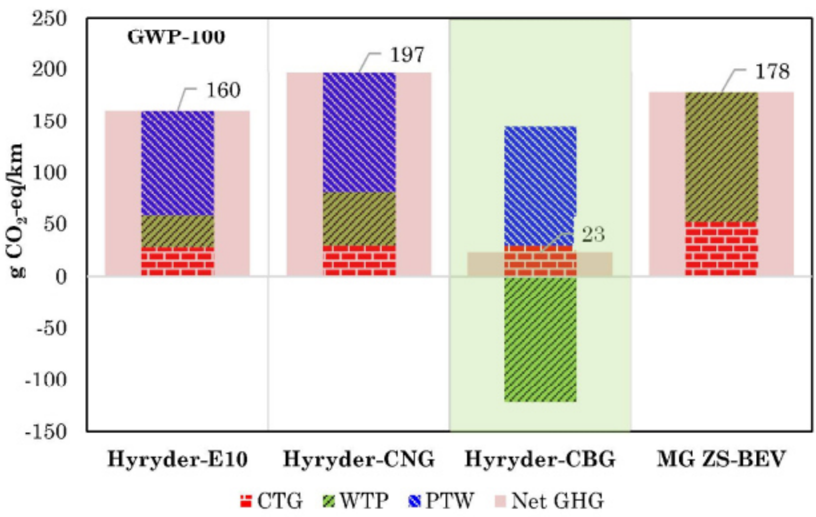


Figure 51: Net GHG Emission of Foreign Powertrains

Figure 51 shows the net GHG emissions of the Foreign MUVs. The net GHG of Hyryder-CBG was 23 g CO_2-eq/km, the lowest among all the powertrains. BEV had no tailpipe emission, but its net emission was higher than the Hyryder-E10. Figure 51 shows that the WTP of Hyryder-CNG was higher than that of Hyryder-E10 and MG ZS-BEV. Hyryder-CBG emerged as the most environmentally sustainable powertrain, significantly better than the BEV, Gasoline-ICEV and CNG-ICEV versions, and their promotion would be a step in the right direction for achieving NET Zero.

Figure 52 shows that the net VOC emissions from the Hyryder-CBG car were (-)309 mg/km. This was mainly because of the avoidance of inorganic fertiliser production. MG ZS-BEV emitted 42 mg/km VOC emissions, mainly during the production of vehicles and electricity. It is also noted that the WTP VOC emission of CNG was lower than E10. Hence, Hyryder-E10 emitted higher VOCs than Hyryder-CNG, positioning it as the least ranked in the lower VOC emitters among these powertrains.

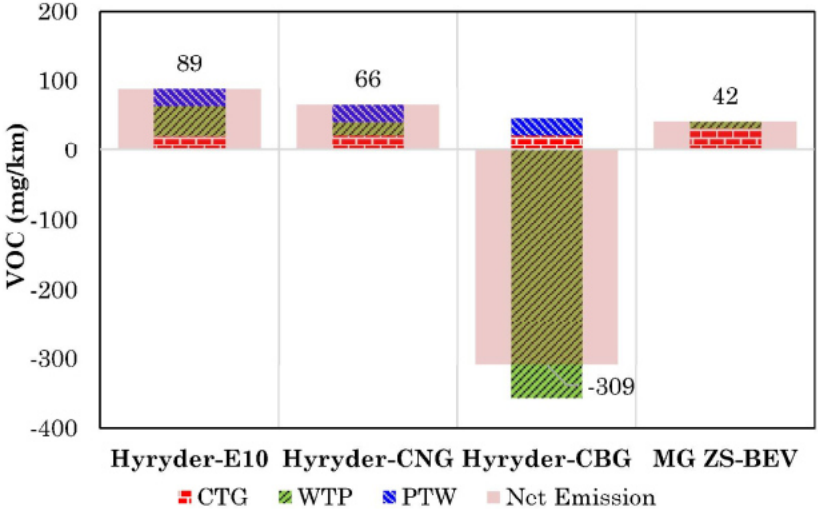


Figure 52: VOC Emissions of Various Powertrains for Foreign MUVs

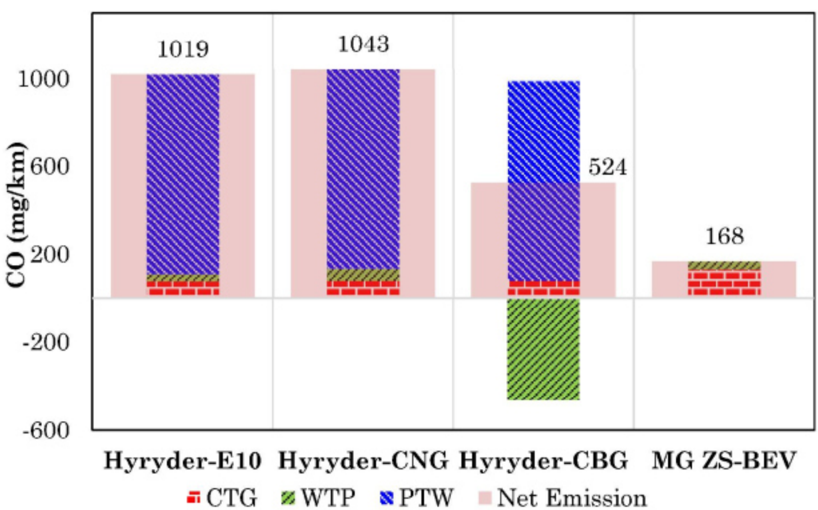


Figure 53: CO Emissions of Various Powertrains for Foreign MUVs

Figure 53 shows that the net CO emission from MG ZS-BEV was 168 mg/km, which was the lowest among all powertrains. It is clear from Figure 53 that a significant portion of the CO emission is from the PTW stage (internal combustion). The higher CO emission from CNG-powered ICEV than the E10 was primarily due to emissions in the WTP stage. This was due to more complicated LNG transportation processes.

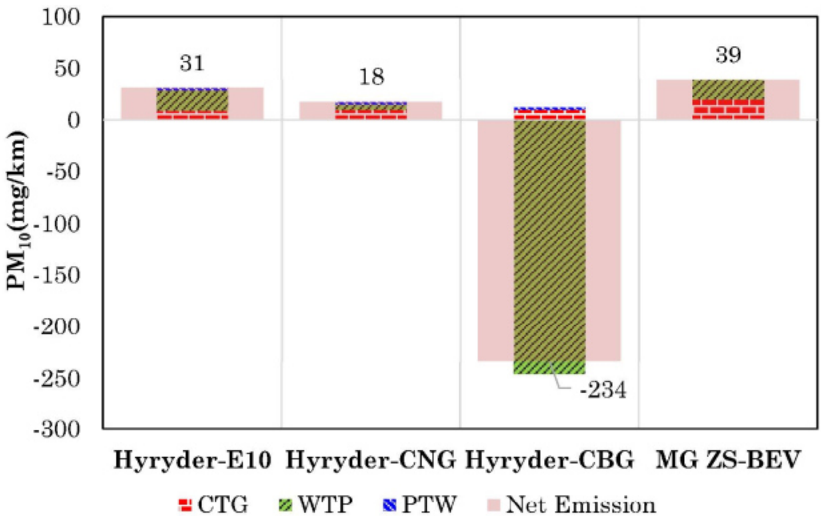


Figure 54: PM_{10} Emissions of Various Powertrains for Foreign MUVs

Figure 54 shows that the PM_{10} emissions from the Hyryder-CBG car were (-)234 mg/km. This was mainly because of the emission avoidance during inorganic fertiliser production. Hyryder-CNG ICEV emitted 18 mg/km of PM_{10} emissions. It is noted that the WTP and CTG PM_{10} emissions from MG ZS-BEV were higher than Hyryder-E10. Hence, MG ZS was the highest PM_{10} emitter among these powertrains.

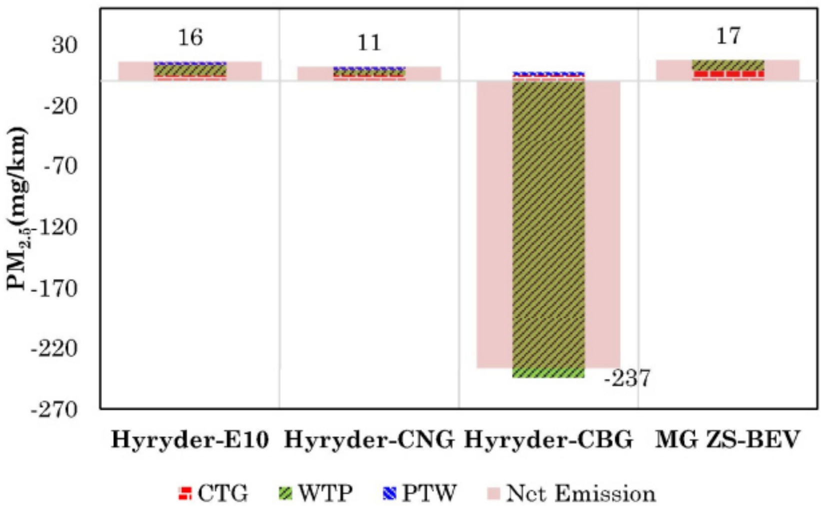


Figure 55: $PM_{2.5}$ Emissions of Various Powertrains for Foreign MUVs

Figure 55 shows that the emission of $PM_{2.5}$ of the Hyryder-CBG car was (-)237 mg/km. Hyryder-CNG ICEV emitted 11 mg/km of $PM_{2.5}$ emissions, primarily from the WTP and CTG stages. It is also noted that the net $PM_{2.5}$ emissions of MG ZS-BEV were higher than that of Hyryder-E10. Overall, MG ZS-BEV was the highest $PM_{2.5}$ emitter among these powertrains.

Figure 56 shows that the NOx emissions from the Hyryder-CBG car were (-)784 mg/km. Hyryder-E10 ICEV emitted 99 mg/km of NOx emissions. It is also noted that the WTP NOx emission of Hyryder-CNG was higher than Hyryder-E10 due to higher NOx emissions from the WTP stage.

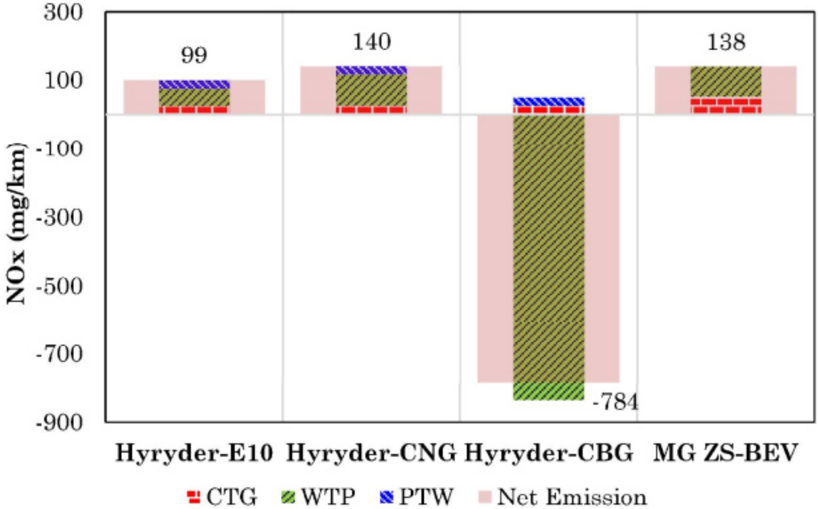


Figure 56: NOx Emissions of Various Powertrains for Foreign MUVs

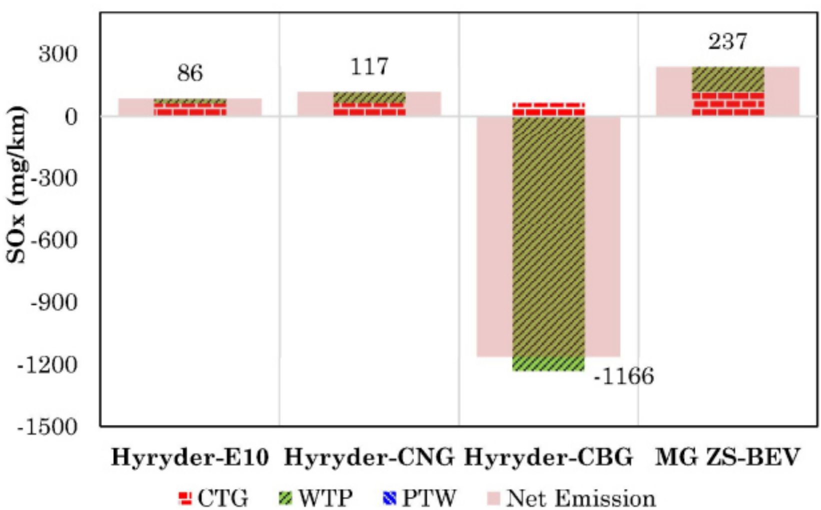


Figure 57: SOx Emissions of Various Powertrains for Foreign MUVs

Figure 57 shows that the SOx emissions from the Hyryder-CBG car were (-)1166 mg/km. Hyryder-E10 ICEV emitted 86 mg/km of SOx emissions, primarily from the WTP and CTG stages. It is also noted that the WTP SOx emissions of CNG were higher than Hyryder-E10. MG ZS-BEV was the highest SOx emitter among these powertrains because of higher SOx emissions during the WTP and CTG stages.

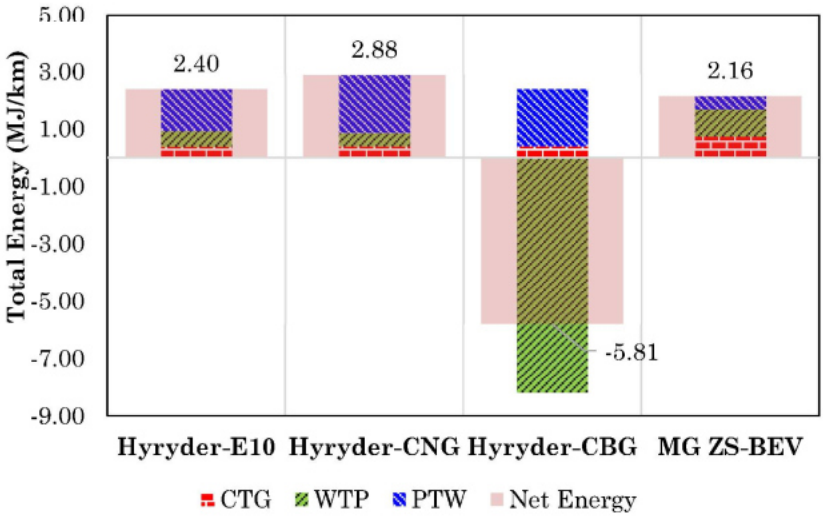


Figure 58: Total Energy Consumption of Various Powertrains for Foreign MUVs

Figure 58 shows that the total energy saved using the Hyryder-CBG car was 5.81 MJ/km. The BEV's PTW energy consumption was the lowest, compensating for the higher CTG and WTP energy consumption compared to the fossil fuel-powered ICEV. MG ZS-BEV consumed 2.16 MJ/km. Among CNG and E10-powered ICEVs, Hyryder-E10 consumed less energy than Hyryder-CNG. Hyryder-CNG and Hyryder-E10 consumed 2.88 and 2.40 MJ/km, respectively.

This energy consumption can not be directly compared since ICEVs use low-grade energy, whereas BEVs use high-grade energy.

Results of fossil and non-fossil lifecycle energy consumption of various powertrains are shown in Figures 59 and 60, respectively.

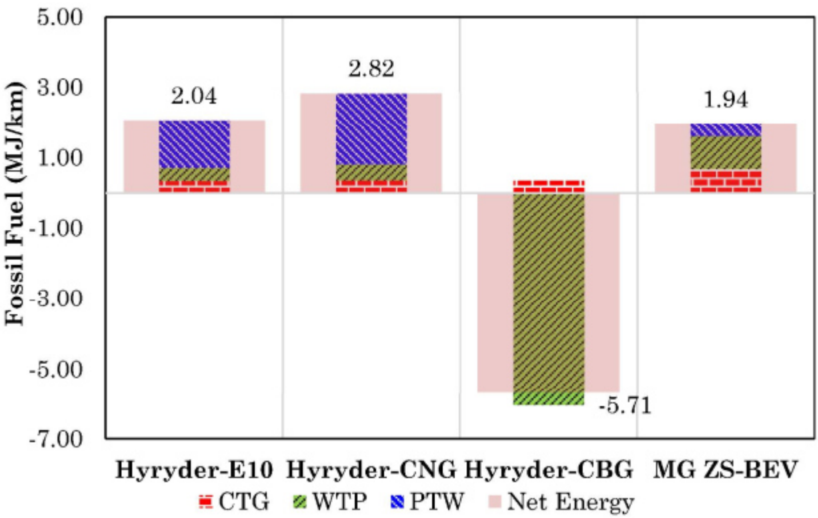


Figure 59: Fossil Fuel Consumption of Various Powertrains for Foreign MUVs

Figure 59 shows that the fossil fuel saved by the Hyryder-CBG car was 5.71 MJ/km. There was no PTW fossil fuel consumption in CBG-powered ICEV. MG ZS-BEV's direct and indirect fossil fuel consumption was 1.94 MJ/km. Among CNG and E10-powered ICEVs, Hyryder-CNG consumed more energy than Hyryder-E10. Hyryder-CNG and Hyryder-E10 consumed 2.82 and 2.04 MJ/km, respectively.

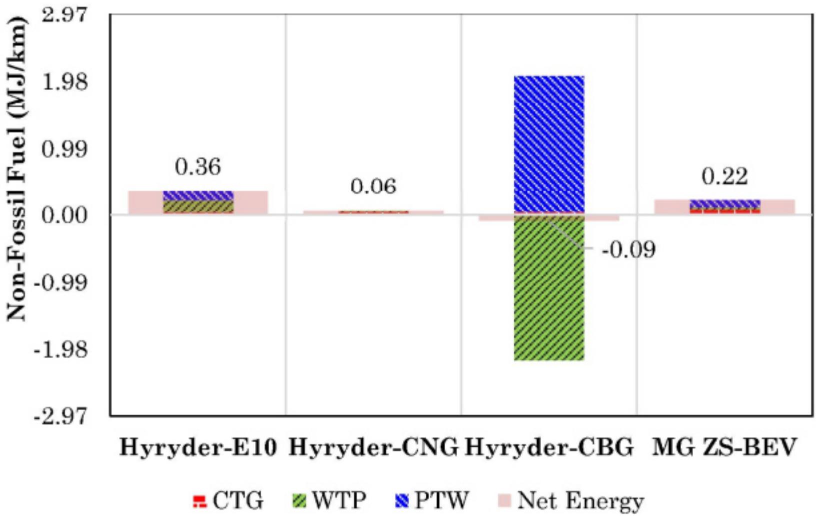


Figure 60: Non-Fossil Fuel Consumption of Various Powertrains for Foreign MUVs

Figure 60 shows the non-fossil fuel saved by the Hyryder-CBG car was (-)0.09 MJ/km. A few non-fossil fuel consumptions in CNG-powered ICEV powertrains were from CTG and WTP. MG ZS-BEV's direct and indirect non-fossil fuel consumption was 0.22 MJ/km. Among CNG and E10-powered ICEVs, Hyryder-CNG consumed much less non-fossil energy than Hyryder-E10. Hyryder-CNG and Hyryder-E10 consumed 0.06 and 0.36 MJ/km of non-fossil energy, respectively.

3.1.3. Sensitivity Analysis for Distance Travelled

Indian Small Cars

Figure 62 shows the sensitivity analysis results of Indian small cars for annual distance travelled in 10 years. GHG emissions from all powertrains decreased with increasing distance travelled over vehicle lifetime. GHG emissions from CBG-powered ICEVs were far lower than those from BEVs, CNG, and Gasoline-powered ICEVs for all distances travelled over the lifetime. If the travelled distance was less than 5000 km/year, the emissions from all vehicles were much higher than CBG. BEVs didn't show significant differences vis-à-vis CNG and Gasoline-fuelled ICEVs. The trendline has been drawn for all powertrain options considered in Figure 61.

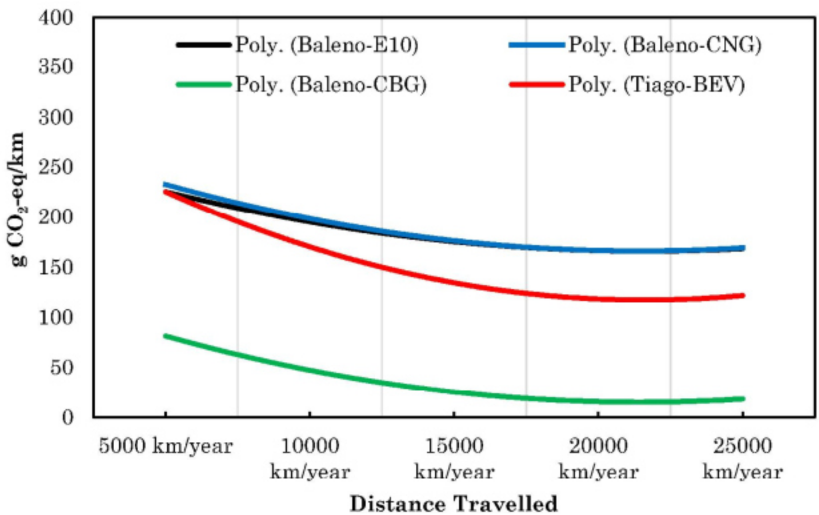


Figure 61: Trend of the Net Emissions for Various Annual Distances Travelled by Indian Small Cars

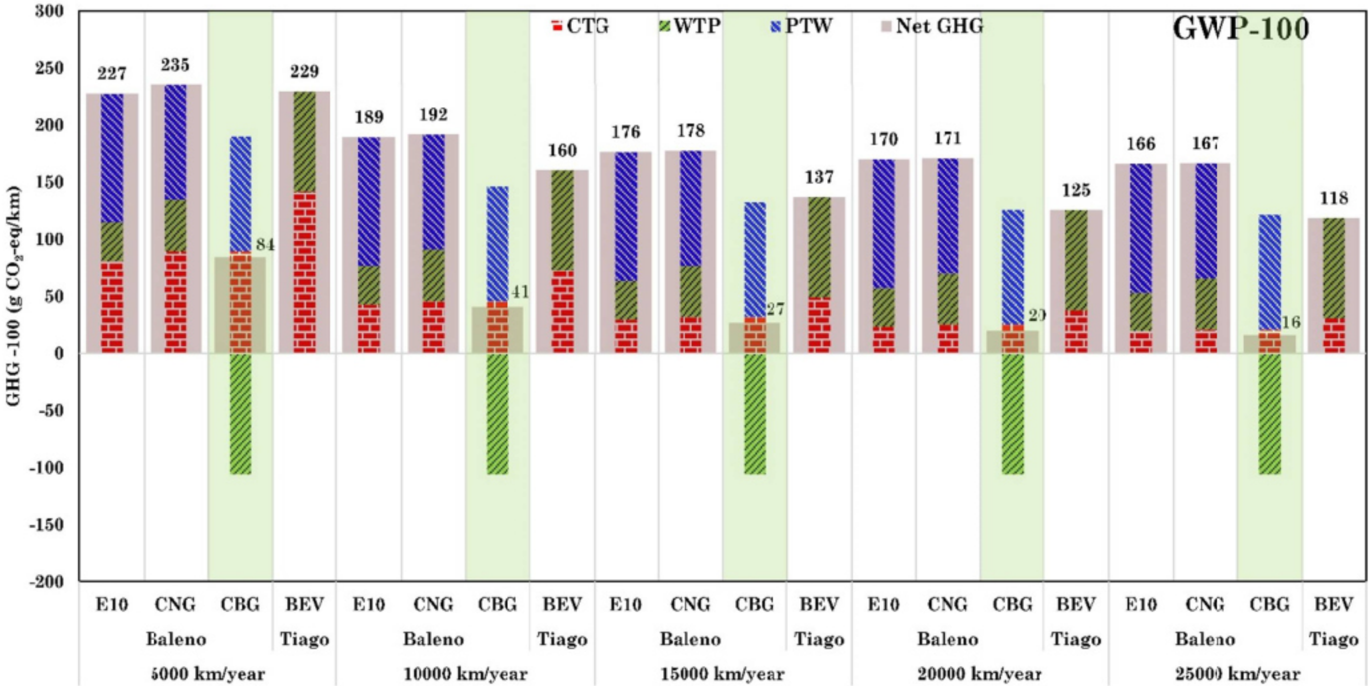


Figure 62: Sensitivity Results of Indian Small Cars for Annual Distance Travelled in 10 Years

Foreign MUVs

Figure 64 shows the sensitivity results of foreign MUVs for annual distance travelled in 10-year lifetimes. GHG emissions from all powertrains decreased with increasing annual distance travelled over the vehicle lifetime. GHG emissions from CBG-powered ICEVs were far lower than those from BEVs, CNG, and Gasoline-powered ICEVs for all distances travelled over the lifetime. If the average annual travelled distance was more than 10000 km/year, the emissions from BEVs were lower than CNG ICEVs. However, they come closer to Hyryder Gasoline ICEV after 20000 km/year. Still, it was significantly higher than CBG-fuelled Hyryder. The trendline is drawn for all powertrain options in Figure 63.

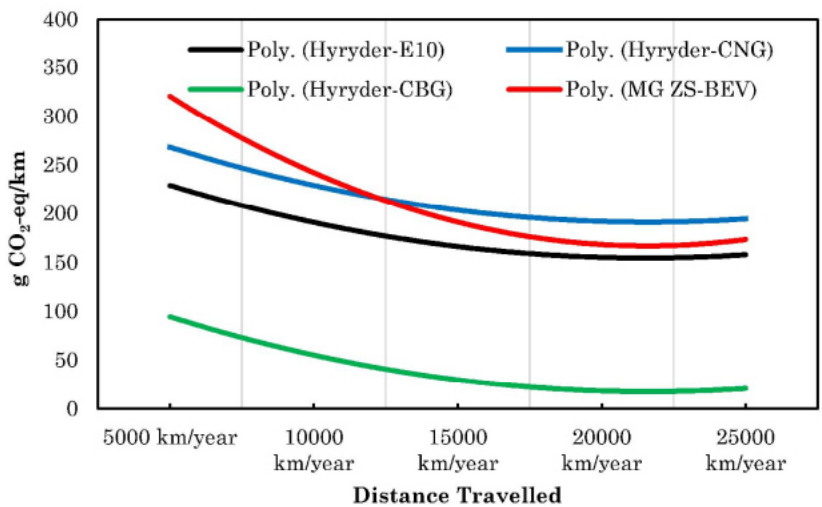


Figure 63: Trend of the Net Emissions for Various Annual Distances Travelled by Foreign MUVs

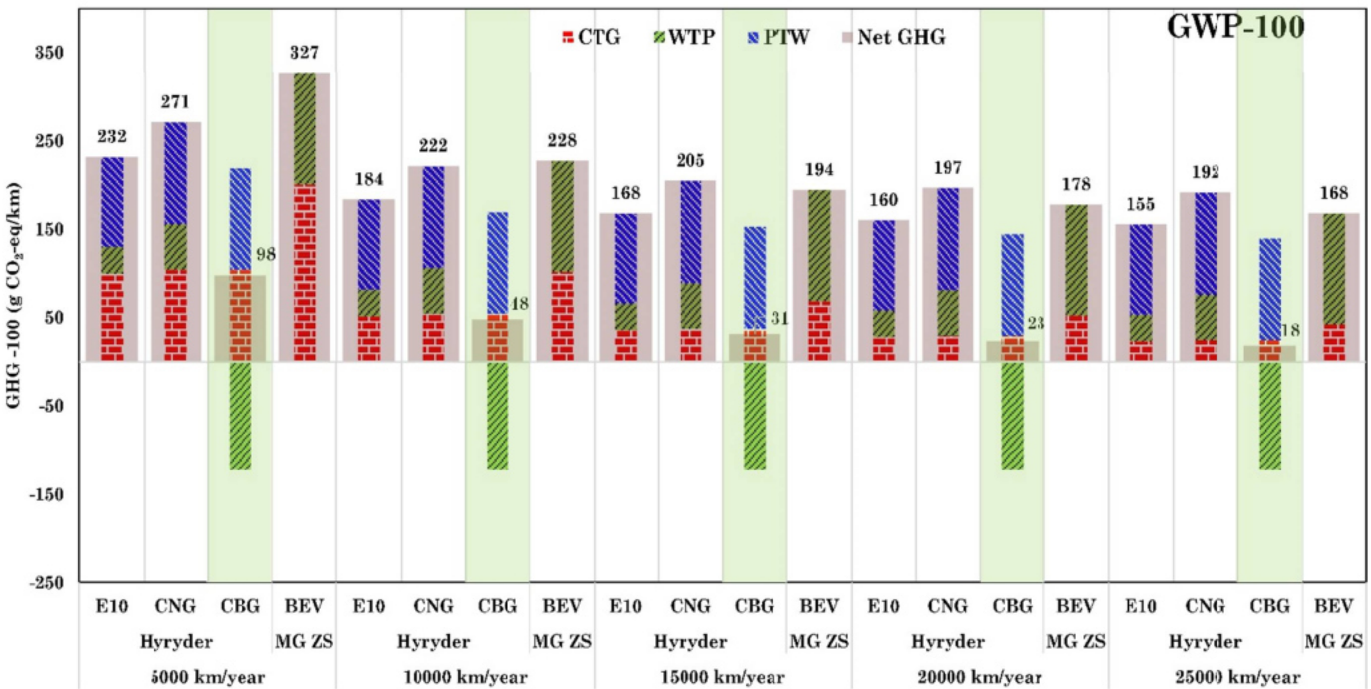


Figure 64: Sensitivity Results of Foreign MUVs for Annual Distance Travelled in 10 Years

3.1.4. Sensitivity Analysis for Different Energy Sources

Indian Small Cars

Figure 65 shows the sensitivity analysis results for Indian small cars for different energy sources. Vehicles powered by different fuels were considered, and CBG emerged as the cleanest fuel option. With the cleanest electricity generation in the Northeastern region, BEVs emitted 95 g CO_2-eq/km. In contrast, CBG-fuelled ICEV emitted only 20 g CO_2-eq/km, 79% lower than BEVs and 87% lower than E30-powered ICEVs after 200,000 km distance travelled in 10 years. CNG-fuelled ICEVs showed higher net emissions due to large imported share (48%), twice as GHG-intensive as domestically produced CNG.

Foreign MUVs

Figure 66 shows the sensitivity analysis results of foreign MUVs for different energy sources. Here, vehicles powered by different fuels were also considered, and CBG emerged as the lowest net GHG-emitting fuel option. With the cleanest electricity generation in the Northeastern region, BEVs emitted 134 g CO_2-eq/km. In contrast, CBG-fueled ICEVs emitted 23 g CO_2-eq/km, 82% lower than BEVs and 85% lower than E30-fuelled ICEVs after 200,000 km of distance travelled in 10 years. CNG-fueled ICEVs showed higher GHG emissions due to a higher imported share (48%) of CNG and a higher energy consumption rate by CNG powertrains.

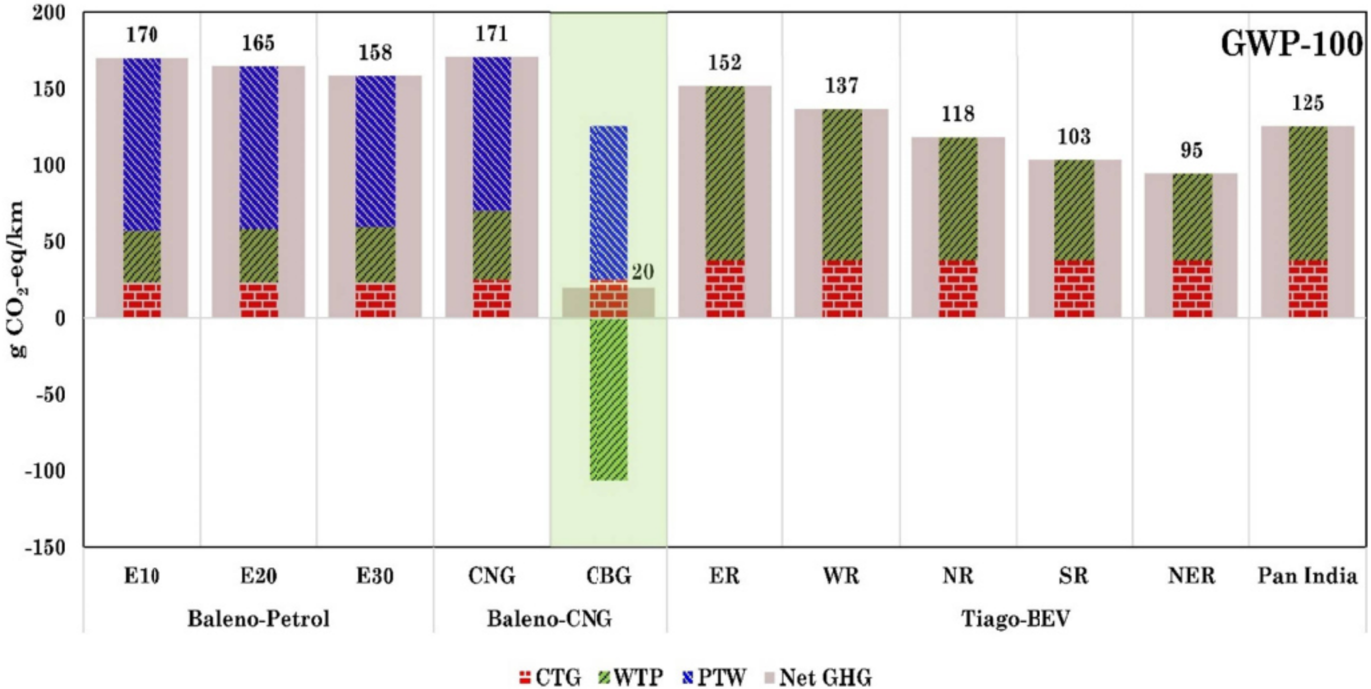


Figure 65: Sensitivity Results of Indian Small Cars for Different Energy Sources

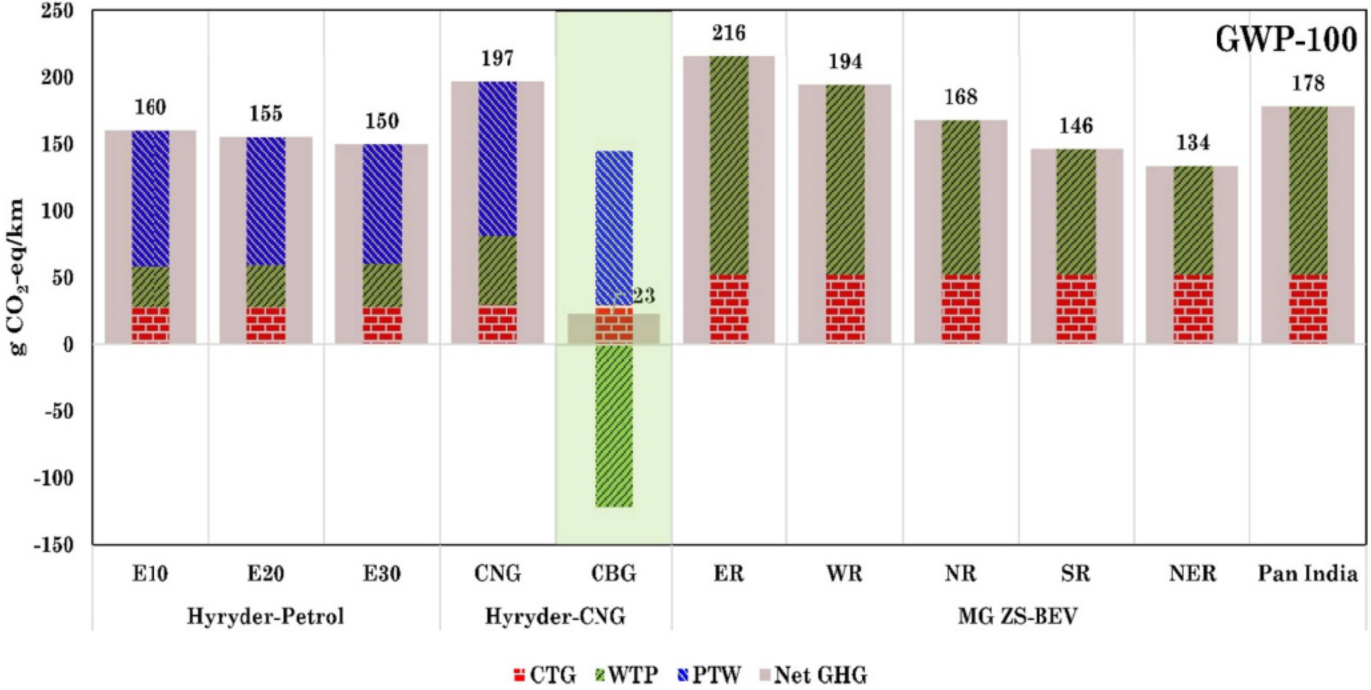


Figure 66: Sensitivity Results of Foreign MUVs for Different Energy Sources

3.1.5. Sensitivity Analysis for One-Time Li-Ion Battery Replacement for BEVs

Indian Small Cars

Figure 67 shows the sensitivity analysis results of Indian small cars for one-time Li-Ion battery replacement for BEVs. The Lifecycle GHG emissions for Baleno-BEV increased by 6.4% in Pan India after 1x battery replacement. Notably, the lifecycle GHG emissions for E30-Powered Baleno-ICEVs were lower by 1.2% vis-à-vis BEVs operated in the eastern region after 1x battery replacement.

Foreign MUVs

Figure 68 shows the sensitivity analysis results of foreign MUVs for one-time Li-Ion battery replacement for BEVs. The lifecycle GHG emissions for MG ZS-BEV increased by ~9% in Pan India after 1x battery replacement. Lower energy consumption by the gasoline-powered Hyryder-ICEVs exhibited that they were more environmentally friendly than MG ZS-BEVs in most Indian grid regions and Pan India. CNG-powered Hyryder-ICEVs showed lower GHG emissions by 8.7% and 15%, respectively, than MG ZS-BEVs in the eastern region before and after 1x Li-ion Battery replacement. Hyryder-CBG was dominating here, also. After 1x battery replacement of MG ZS-BEVs, the lifecycle GHG emissions of BEVs Pan India were 7.4 times higher than CBG-powered ICEVs.

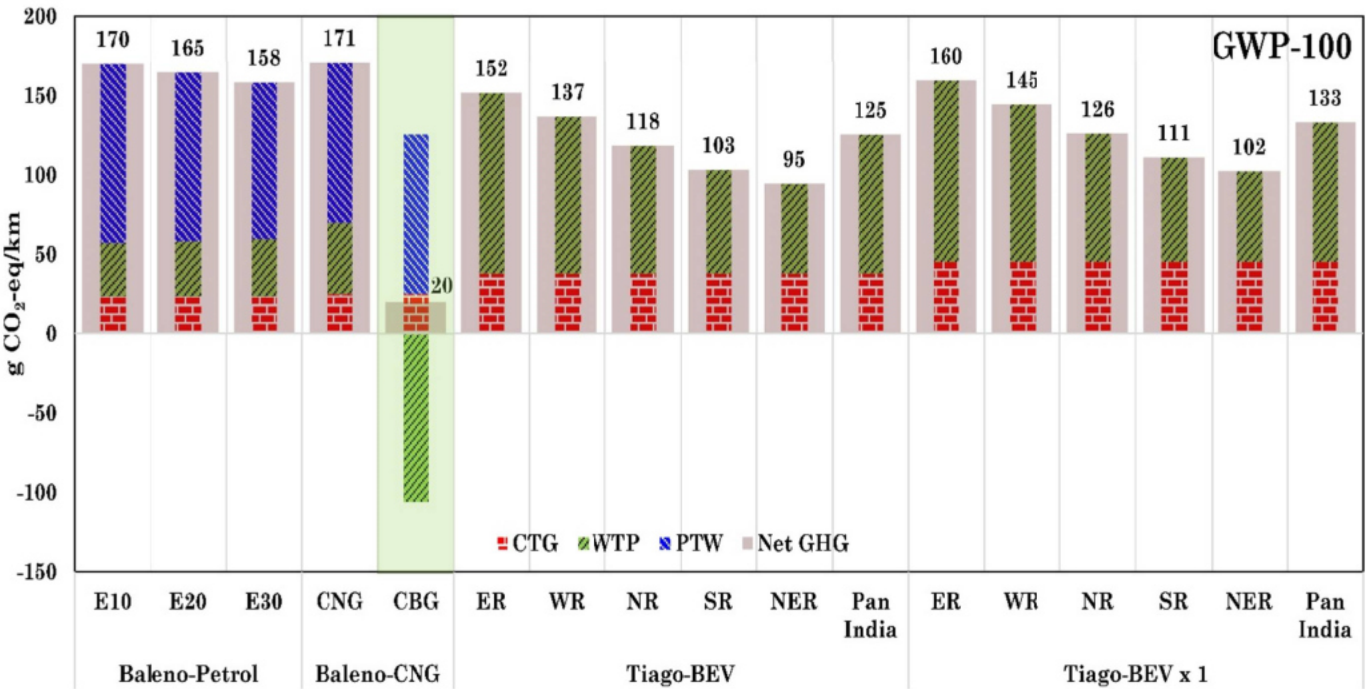


Figure 67: Sensitivity Results of Indian Small Cars for One-Time Li-Ion Battery Replacement for BEVs

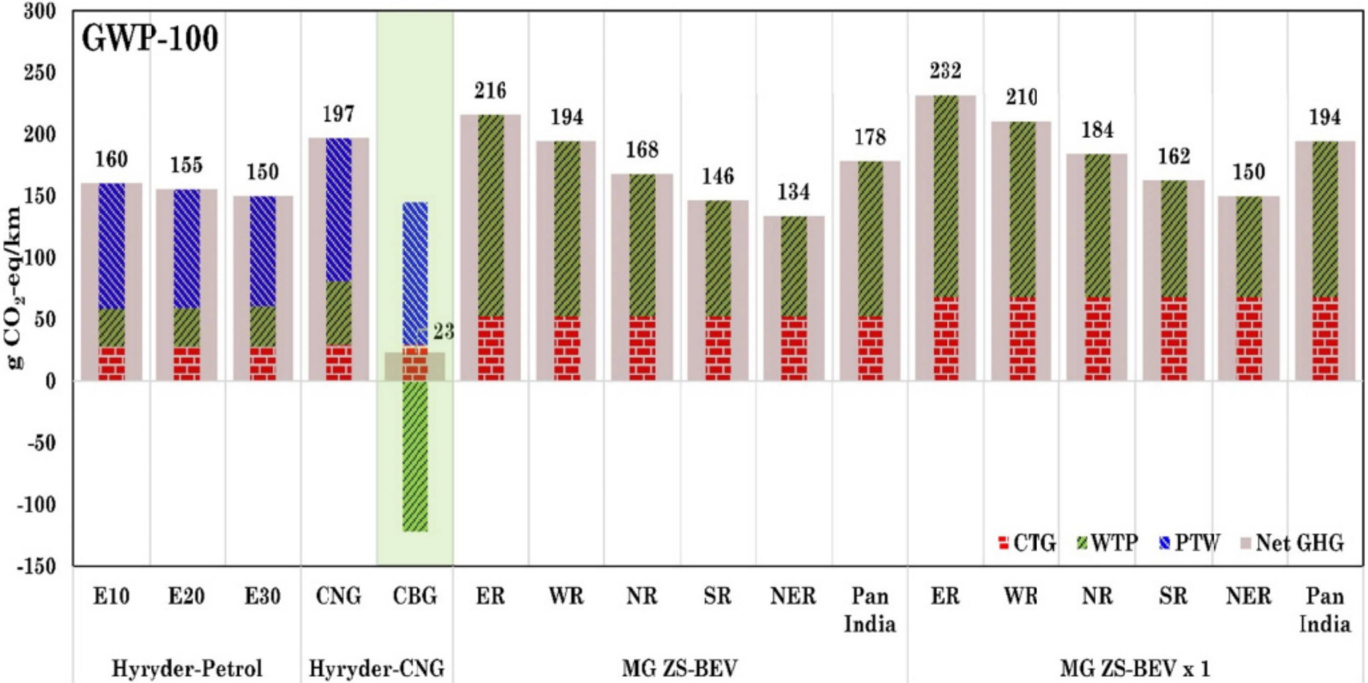


Figure 68: Sensitivity Results of Foreign MUVs for One-Time Li-Ion Battery Replacement for BEVs

3.1.6. Summary of LCA Analysis

Indian Small Cars

- WTP emission of one Baleno-CBG car (-61 gCO_2-eq/km) can negate WTP emission from almost two Baleno-E10 fueled cars (34 gCO_2-eq/km) and this will be an important proposition in the direction of achieving 'net zero'.
- After 200,000 km travel in 10 years, net GHG emission from CBG-powered Baleno-ICEV was 20 gCO_2-eq/km, which was lower than Tiago-BEV, Baleno-E10 and Baleno-CNG by 84%, 88% and 87%, respectively.
- GHG emissions from CBG-powered Baleno-ICEV were far lower than those from Tiago-BEV, CNG, and E10-powered ICEV for all lifetime travel distances.
- If the travelled distance was less than 5000 km/year, the GHG emissions of all powertrains were much higher than the Baleno-CBG powertrain. Meanwhile, Tiago-BEV showed no significant difference in GHG emissions from Baleno-CNG and Baleno-E10 ICEVs.
- Baleno-CBG emitted 79% lower GHG emissions than Tiago-BEV, with the cleanest source of electricity generation in the northeastern region, and 87% lower than E30-powered Baleno-ICEV after 200,000 km.

- The Lifecycle GHG emissions of Tiago-BEV increased by 6.4% after 1x battery replacement in Pan India.
- Even lifecycle GHG emissions for E30-Powered Baleno-ICEVs were lower by 1.2% vis-à-vis BEV operated in the eastern region after 1x battery replacement.
- CBG ICEV was the cleanest powertrain option among all powertrains considered.

Foreign MUVs

- WTP emission of one Hyryder-CBG car (-70 gCO_2-eq/km) can negate WTP emission from more than two Hyryder-E10 fueled cars (30 gCO_2-eq/km) and this will be an important proposition in the direction of achieving 'net zero'.
- After 200,000 km travel in 10 years, the GHG emissions from CBG-powered Hyryder-ICEV were 23 gCO_2-eq/km, which was lower than MG ZS-BEV, Hyryder-E10 and Hyryder-CNG by 87%, 85% and 88%, respectively.
- GHG emissions from CBG-powered ICEV were far lower than those from MG ZS-BEV, CNG, and Gasoline-powered ICEV for all distances travelled over the lifetime.

- If the travelled distance was lower than 10,000 km/year, the MG ZS-BEV emissions were much higher than Hyryder-CNG ICEV. Meanwhile, the MG ZS-BEV exhibited higher GHG than the Hyryder-E10 ICEV.
- Hyryder-CBG ICEV emitted 82% lower GHG emissions than MG ZS-BEV, with the cleanest electricity generation in northeastern India, and 85% lower than E30-powered ICEV after 200,000 km of operation in 10 years.
- The lifecycle GHG emissions for MG ZS-BEV increased by ~9% after 1x battery replacement in Pan India.
- Even the lifecycle GHG emissions for E30-Powered Hyryder-ICEV were similar to MG ZS-BEV, which operated with the cleanest electricity in northeastern India after 1x battery replacement.
- Hyryder-CBG ICEV was the cleanest powertrain option among all powertrains considered.

3.2 TCO Analysis

3.2.1. Base Case Scenario

The base case scenario was evaluated for 200,000 km distance travelled. The incentives to the BEVs and corresponding running costs associated with this travel distance were incorporated in the TCO calculations. The battery replacement cost after 160,000 km was considered. Since the tax exemption for BEV is not entertained in Delhi, the base case calculations are done with applicable taxes.

Indian Small Cars

Figure 69 shows yearwise TCO results for the Indian small cars (Set-1). A subsidy of ₹ 2,35,800 was considered for BEVs per the FAME-II scheme. The results showed that, in the initial days, the TCO of BEV was higher than all other powertrain options considered. After 3rd year, Tiago-BEV showed lower TCO than Baleno-E10. 5th year onwards, Tiago-BEV showed lower TCO than Baleno-CBG ICEV powertrain. In the 8th year, when the battery replacement cost for BEV was considered, a hike in BEV's TCO was noticed. In this stage, BEV's TCO was higher than CNG- and CBG-powered ICEVs. The final results at the end of the 10-year lifetime are shown in Figure 70. It was noted that the Baleno-CBG ICEV was the most pocket-friendly option among the powertrain options considered. The TCO of the CBG-powered Baleno-ICEV powertrain was 23% and 3.8% lower than Baleno-E10 ICEV and Tiago-BEV, respectively.

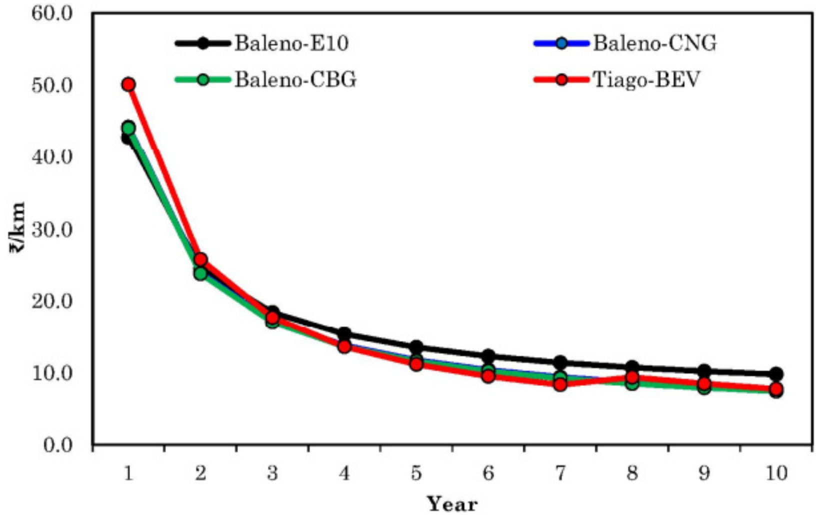


Figure 69: Yearwise TCO Results for Indian Small Cars

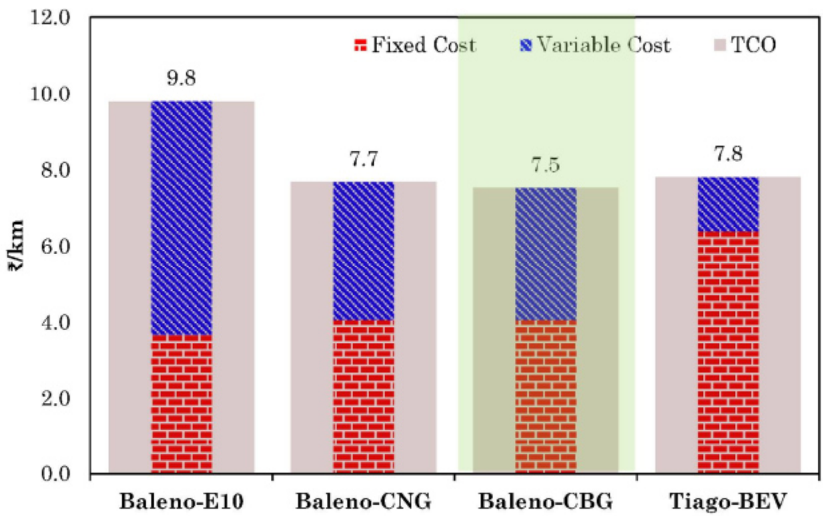


Figure 70: TCO Results of Base Case Scenario for Indian Small Cars

Foreign MUVs

The MG ZS-BEV didn't get any subsidy under the FAME-II scheme because it is not an Indian-manufactured vehicle. However, in the base case scenario, we have considered a subsidy of ₹ 10,000 /kWh up to 20% of vehicle price was assumed for MG ZS-BEV, for parity with Indian manufactured vehicles as per the FAME-II scheme (hypothetical scenario, applicable to BEV promotional policies of the government). Figure 71 shows TCO results for the foreign MUV set. The results showed that the TCO of MG ZS-BEV was always higher than all other powertrain options despite subsidies considered. After 7th year, the TCO of BEV came closer to ICEVs but increased significantly in the 8th year because of the battery replacement cost incorporation.

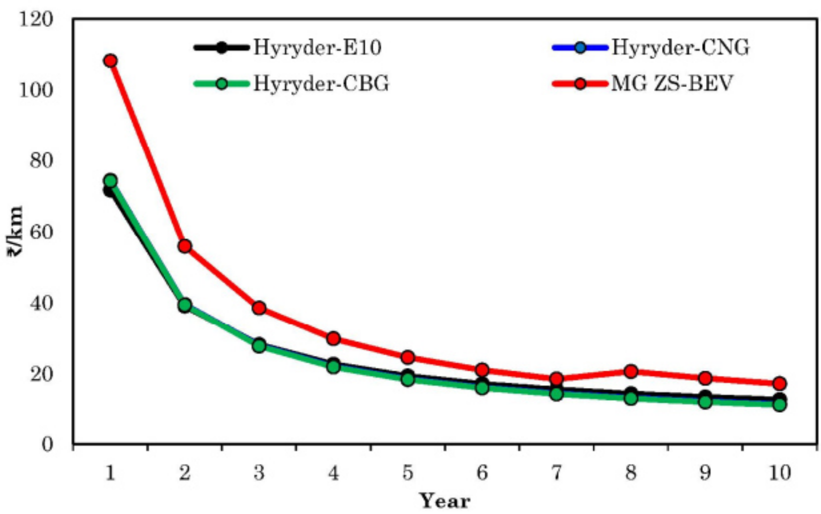


Figure 71: Yearwise TCO Results for Foreign MUVs

The final results at the end of the 10-year lifespan are shown in Figure 72. It was observed that Hyryder-CBG was the most pocket-friendly among all the considered powertrain options. TCO of CBG-powered Hyryder-ICEV was ~11% and ~34% lower than Hyryder-E10 and MG ZS-BEV, respectively.

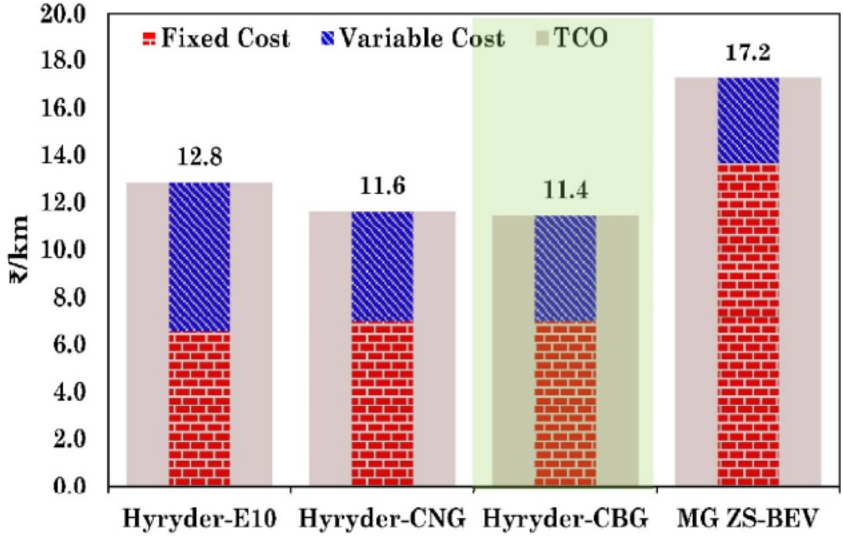


Figure 72: TCO Results of Base Case Scenario for Foreign MUVs

3.2.2. Sensitivity Analyses for Distance Travelled Per Year

Indian Small Cars

Figure 73 shows the TCO results of Indian small cars with sensitivity analyses for yearly distance travelled. With increasing distance travelled per year, the TCO of all vehicles decreased. As the scenario changes from the Promotion

Phase (S1) to the Matured Phase (S3) via the Intermediate Phase (S2), the TCO of Tiago-BEV in ₹/km increased significantly. If the travelled distance was 5,000 km/year or even lower, the TCO of Tiago-BEV was higher than any ICEV powertrain option. After travelling 20,000 km/year for ten years, the TCO of Tiago-BEV in the S1 phase was lower by 4% than the Baleno-CBG powertrain option. CBG-powered Baleno-ICEV emerged as the most economical powertrain option among all the options considered.

Foreign MUVs

Figure 74 shows the TCO results of foreign MUVs with sensitivity analyses for yearly distance travelled. With increasing distance travelled per year, the TCO of all vehicles decreased. As the scenario changed from the Promotion Phase (S1) to the Matured Phase (S3) via the Intermediate Phase (S2), the TCO of MG ZS-BEV in ₹/km increased significantly. The TCO of MG ZS-BEVs was higher in all the scenarios than in all ICEV options. CBG-powered Hyryder-ICEV was the most economical powertrain option among all the options considered.

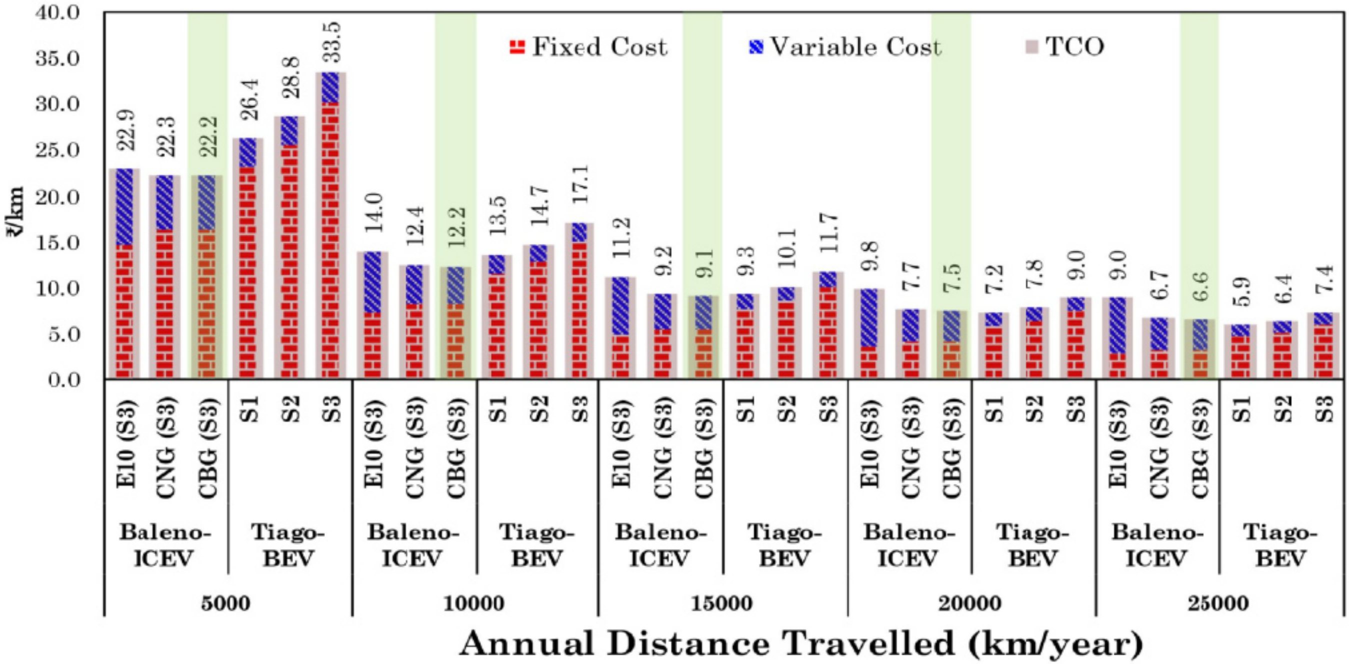


Figure 73: TCO Results of Indian Small Cars with Sensitivity Analyses for Yearly Distance Travelled

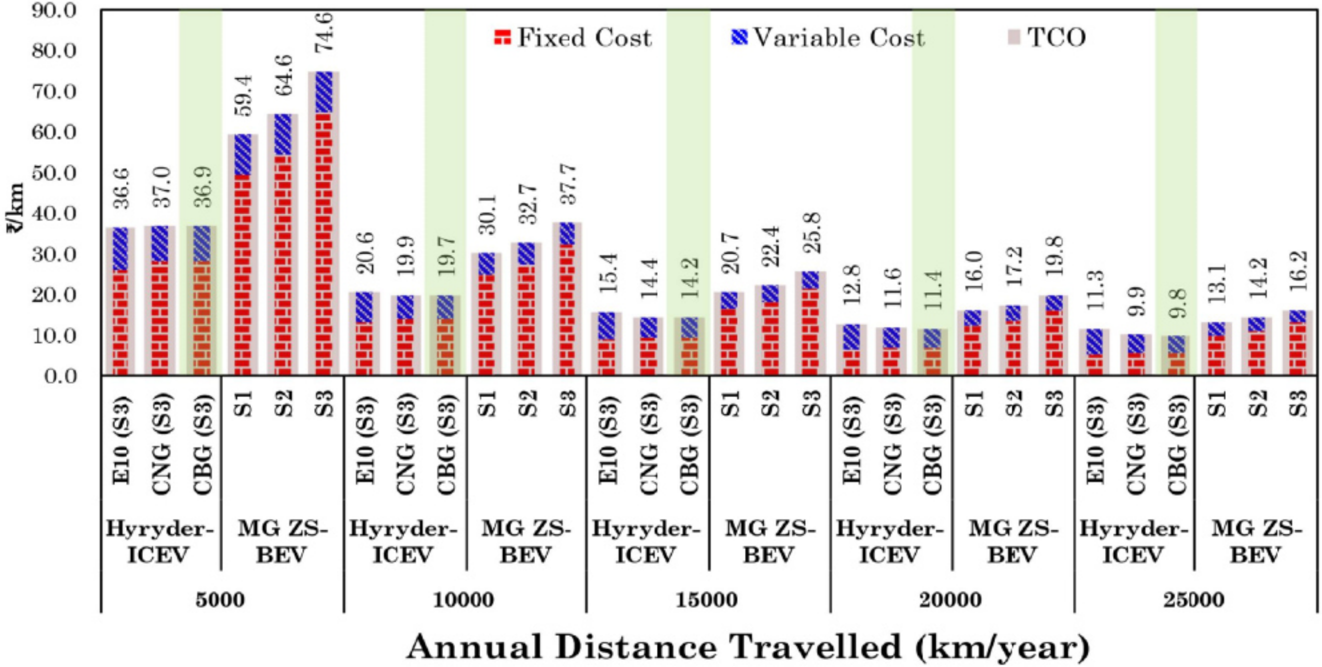


Figure 74: TCO Results of Foreign MUVs with Sensitivity Analyses for Yearly Distance Travelled

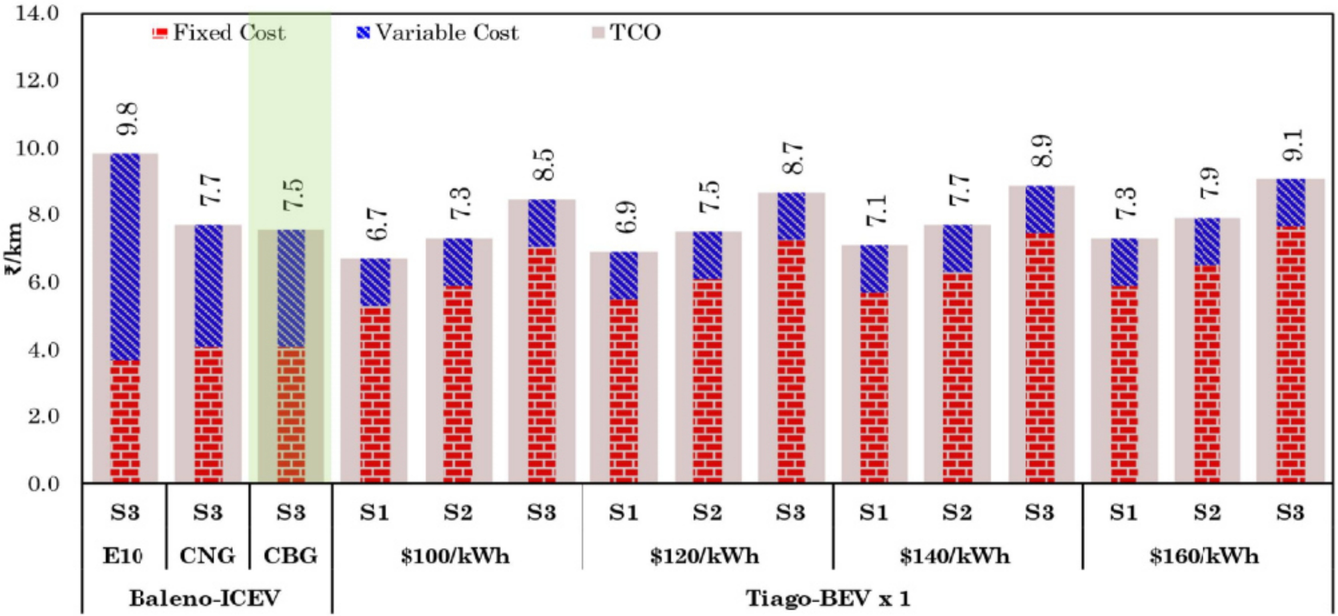
3.2.3. Sensitivity Analyses for Changes in Replacement Battery Cost

Indian Small Cars

Figure 75 shows the TCO results of Indian small cars with sensitivity analysis for Li-ion replacement battery cost changes. With increasing battery price, the TCO of Tiago-BEV increased. In the matured phase (S3), the TCO of Tiago-BEV for all battery price categories was higher than that of Baleno-CBG and CNG. Also, in the Intermediate Phase (S2), with a battery price of more than $120/kWh, the TCO of Tiago-BEV was higher than that of Baleno-CBG. CBG-powered Baleno-ICEV was the most economical powertrain option on a level playing field, even with tax exemption to Tiago-BEV.

Foreign MUVs

Figure 76 shows the TCO results of foreign MUVs with sensistivity analysis for changes in Li-ion battery cost. With increasing replacement battery prices, the TCO of MG ZS-BEV increased. In the matured phase (S3), the TCO of MG ZS-BEV for all the battery price categories was higher than the Hyryder-CBG and CNG ICEV powertrains. As the scenario changed from the Promotion Phase (S1) to the Matured Phase (S3) via the Intermediate Phase (S2), the TCO of MG ZS-BEV in ₹/km was higher than other ICEV options. CBG-powered Hyryder-ICEV was the most economical powertrain option, even with tax exemption and subsidy (if applied) to MG ZS-BEV.



Changes in Battery Cost (200000 km)

Figure 75: TCO Results of Indian Small Cars with Sensitivity Analysis for Changes in Li-Ion Battery Cost

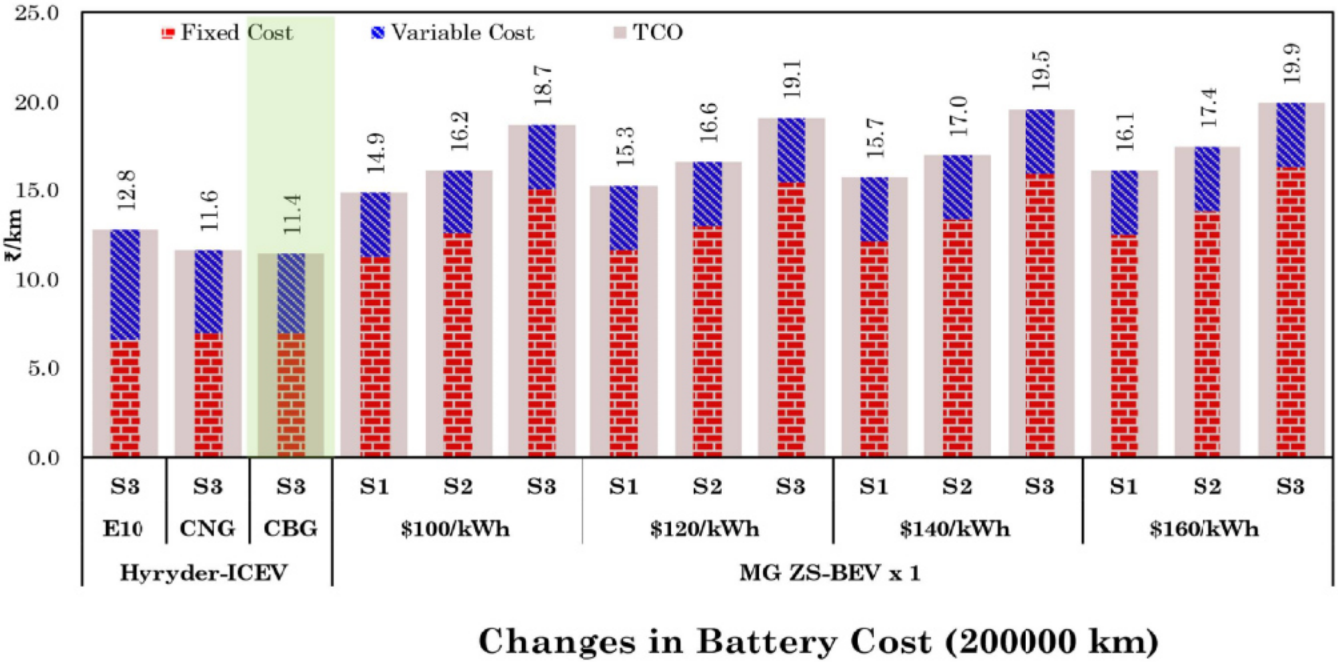


Figure 76: TCO Results of Foreign MUVs with Sensitivity Analysis for Changes in Li-Ion Battery Cost

Sensitivity Analyses for Changes in Initial Vehicle Purchase Price

Indian Small Cars

Figure 77 shows the TCO results of Indian small cars with sensitivity analysis for changes in vehicle purchase price. With increasing vehicle purchase prices, the TCO of Tiago-BEV increased. In the matured phase (S3) and intermediate phase (S2), the TCO of Tiago-BEV for all the vehicle price categories was higher than CNG and CBG-powered Baleno-ICEVs. CBG-powered Baleno-ICEV was the most economical powertrain option on a level playing field, even with tax exemption to the Tiago-BEV.

Foreign MUVs

Figure 78 shows the TCO results of foreign MUVs with sensitivity analysis for changes in vehicle purchase price. With increasing vehicle purchase prices, the TCO of MG ZS-BEV increased. As the scenario changes from the Promotion Phase (S1) to the Matured Phase (S3) via the Intermediate Phase (S2), the TCO of MG ZS-BEV in ₹/km was higher than other ICEV options. CBG-powered Hyryder-ICEV was the most economical powertrain option, even with tax exemption and subsidy (if applied) to MG ZS-BEV.

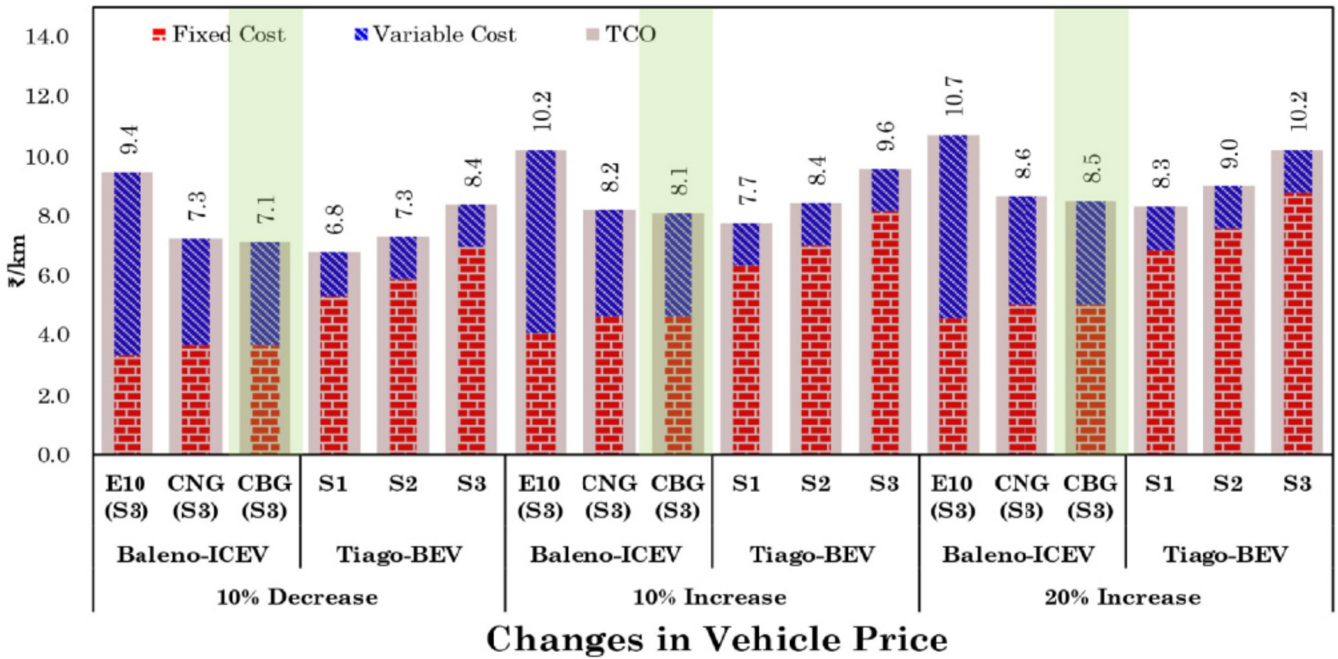


Figure 77: TCO Results of Indian Small Cars with Sensitivity Analysis for Changes in Vehicle Purchase Price

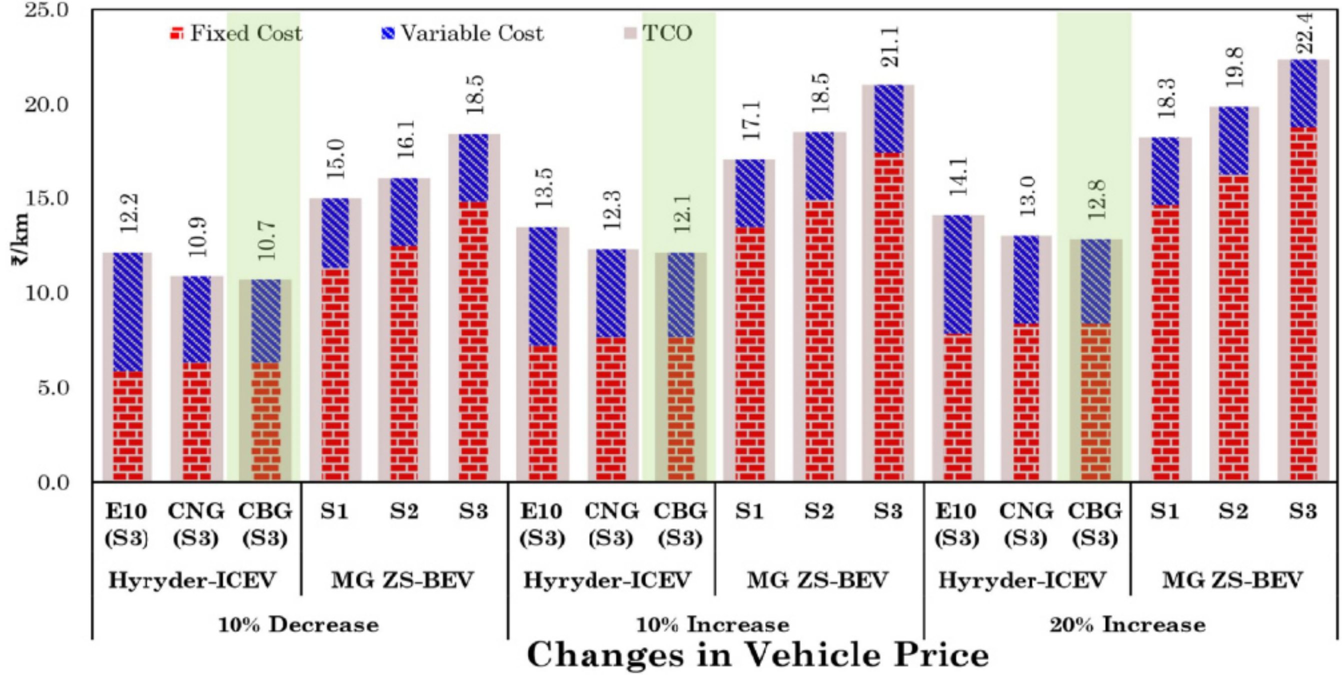


Figure 78: TCO Results of Foreign MUVs with Sensitivity Analysis for Changes in Vehicle Purchase Price

3.2.4. Sensitivity Analyses for Changes in Energy Prices

Indian Small Cars

Figure 79 shows the TCO results of Indian small cars with sensitivity analysis for changes in the energy price. With a 20% increase in energy prices, the TCO of Tiago-BEV was 13.8% higher than Baleno-CBG on a level playing field. With a 20% decrease in energy prices, the TCO of Tiago-BEV was ~25.4%, 23.6% and ~1.1% higher than Baleno-CBG, CNG and E10 ICEVs on a level playing field. CBG-powered Baleno-ICEV was the most economical powertrain option in a reduced energy price scenario.

Foreign MUVs

Figure 80 shows the TCO results of foreign MUVs with sensitivity analysis for changes in energy price. Changes in energy prices do not significantly affect the TCO of BEVs. With a 20% increase in energy prices, the TCO of MG ZS-BEV was ~65%, ~63% and ~45% higher than Hyryder-CBG, CNG, and E10 on a level playing field. With a 20% reduction in energy prices, the TCO of MG ZS-BEV was ~80%, ~78% and ~65% higher than Hyryder-CBG, CNG and E10 on a level playing field. CBG-powered Hyryder-ICEV was the most economical powertrain option on a level playing field in a reduced/ increased energy price scenario.

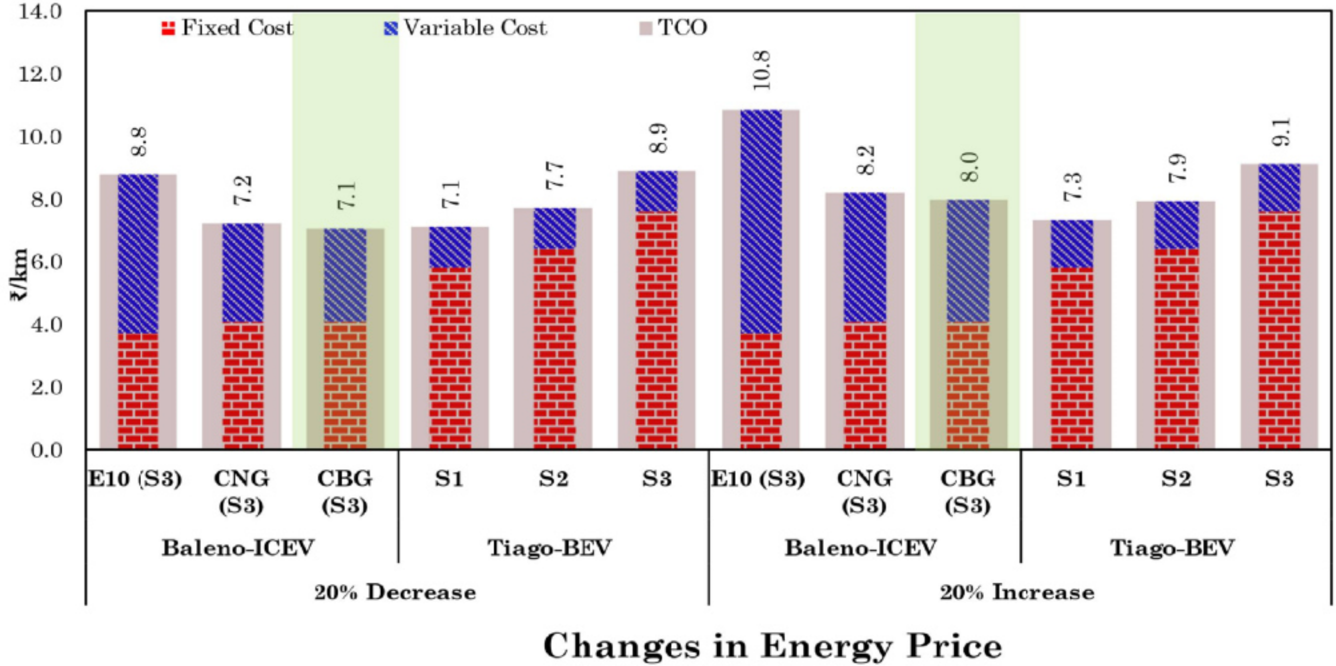


Figure 79: TCO Results of Indian Small Cars with Sensitivity Analysis for Changes in Energy Price

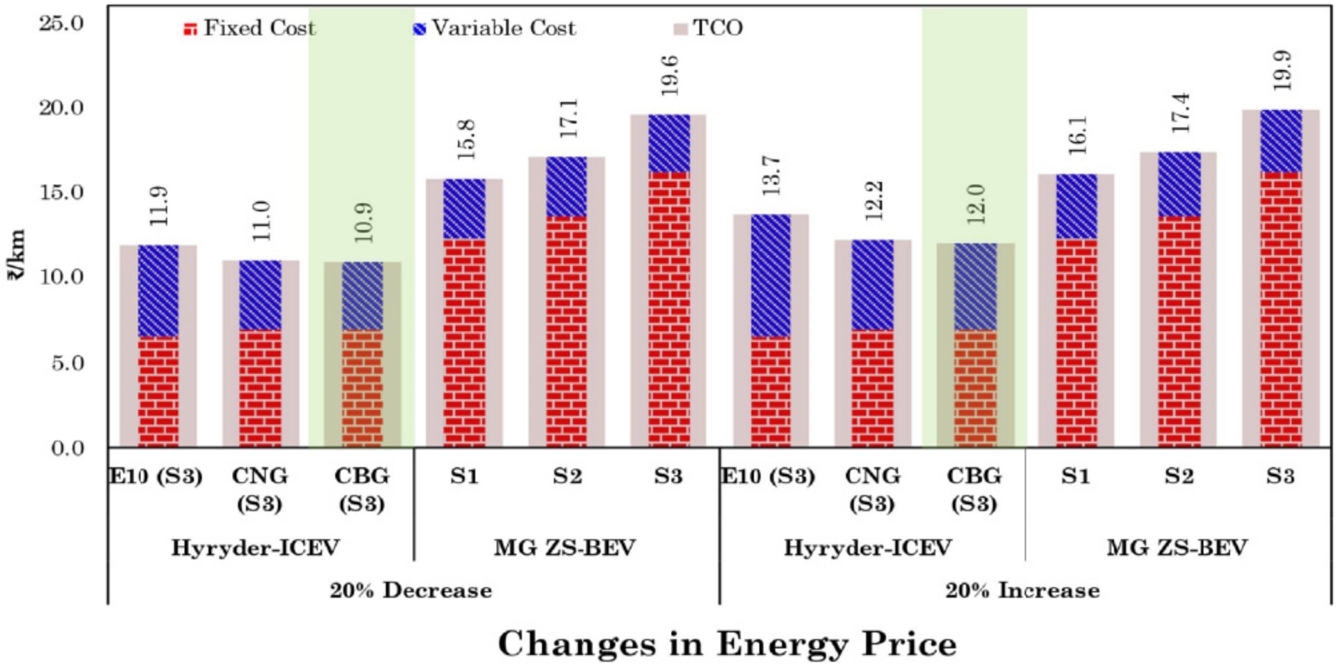


Figure 80: TCO Results of Foreign MUVs with Sensitivity Analysis for Changes in Energy Price

Summary of TCO Analysis

Indian Small Cars

- ❑ Baleno-CBG showed the lowest TCO among all powertrain options.
- ❑ A significant portion of the TCO of Tiago-BEV was contributed by its fixed cost, which included a 1x battery replacement after 160,000 km/8 year.
- ❑ With increasing distance travelled per year, the TCO of all vehicles decreased.
- ❑ As the scenario changes from the Promotion Phase (S1) to the Matured Phase (S3) via the Intermediate Phase (S2), the TCO of Tiago-BEV in ₹/km increased significantly for variable distance travelled.
- ❑ If the distance travelled was 5,000 km/year or lower, the TCO of Tiago-BEV was higher than any ICEVs.
- ❑ After travelling 20,000 km/year for ten years, the TCO of Tiago-BEV for S1 reduced by 4% compared to Baleno-CBG.
- ❑ In the matured phase (S3), the TCO of Tiago-BEV for all battery price categories was higher than Baleno-CBG and CNG.
- ❑ With increasing vehicle purchase prices, the TCO of Tiago-BEV increased significantly.
- ❑ In the Matured Phase (S3) and Intermediate Phase (S2), the TCO of Tiago-BEV for all the vehicle purchase price

categories was higher than CNG and CBG-powered Baleno-ICEVs.

- With a 20% increase in energy prices, the TCO of Tiago-BEV was 13.8% higher than Baleno-CBG ICEV on a level playing field.
- With a 20% reduction in energy prices, the TCO of Tiago-BEV was ~25.4%, 23.6% and ~1.1% higher than Baleno-CBG, CNG and E10 on a level playing field.

Foreign MUVs

- Hyryder-CBG exhibited the lowest TCO among all powertrain options.
- A significant portion of the TCO of MG ZS-BEV was contributed by fixed costs, which included a 1x battery replacement cost after 160,000 km/8 year.
- TCO of CBG-powered Hyryder-ICEV was ~11% and ~34% lower than Hyryder-E10 and MG ZS-BEV, respectively.
- As the scenario changes from the Promotion Phase (S1) to the Matured Phase (S3) via the Intermediate Phase (S2), the TCO of MG ZS-BEV in ₹/km increased significantly for:
    - the variation in annual distance travelled,
    - the changes in battery prices and

- the changes in vehicle purchase price.

- With a 20% increase in energy prices, the TCO of MG ZS-BEV was ~65%, ~63% and ~45% higher than Hyryder-CBG, CNG, and E10 on a level playing field.
- With a 20% decrease in energy prices, the TCO of MG ZS-BEV was ~80%, ~78% and ~65% higher than Hyryder-CBG, CNG and E10 on a level playing field.
- Hyryder-ICEVs powered by CBG, CNG and E10 were more economical than MG ZS-BEV throughout the sensitivity analyses for all scenarios under consideration.

Chapter 4

Overarching Conclusions

- Emissions during electricity production in different regions of India differ mainly because of the primary energy sources used.
- WTP GHG emissions for CNG are ~ **26 gCO_2-eq/MJ**, whereas WTP GHG emissions for CBG were ~ **(-) 61 gCO_2-eq/MJ.**
- WTP emission of one CBG car can negate WTP emission from two E10 fueled cars and this will be an important proposition in the direction of achieving 'net zero'.
- After 200,000 km of vehicle travel in 10 years, the GHG emissions from CBG-powered Baleno-ICEV was merely **20 gCO_2-eq/km**, which was significantly lower than **Tiago-BEV, Baleno-E10 ICEV and Baleno-CNG ICEV by 84%, 88% and 87%, respectively.**
- After 200,000 km travel in 10 years, the GHG emissions from CBG-powered Hyryder-ICEV was **23 gCO_2-eq/km**, which was significantly lower than **MG ZS-BEV, Hyryder-E10 ICEV and Hyryder-CNG ICEV by 87%, 85% and 88% respectively.**
- **CBG-fuelled ICEV powertrains emerged as the most environmentally sustainable powertrains,**

significantly better than the BEVs and Gasoline and CNG-fuelled ICEVs, and their promotion would be a step in the right direction to achieve 'NET Zero'.

- ❐ **Baleno-CBG ICEV powertrain exhibited the lowest TCO among all options considered among Indian Small Cars.**
- ❐ As the scenario changed from the Promotion Phase (S1) to the Matured Phase (S3) via the Intermediate Phase (S2), the TCO of Tiago-BEV in ₹/km increased significantly.
- ❐ **Hyryder-CBG exhibited the lowest TCO among all powertrain options in Foreign MUVs.**
- ❐ Hyryder-ICEV powered by CBG, CNG and E10 were more economical than BEV in all sensitivity analyses for all scenarios in the Foreign MUVs.

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Research Focus at ERL

- ❑ Internal Combustion Engines
- ❑ Regulated/ Unregulated Emissions
- ❑ Particulate Characterisation and Control
- ❑ Exhaust Gas After-Treatment using DOC/ DPF
- ❑ Emission Toxicology
- ❑ Gasoline Direct Injection (GDI) Engines
- ❑ Gasoline Compression Ignition (GCI) Engines
- ❑ Low-Temperature Combustion (HCCI/PCCI/RCCI) Engines
- ❑ CNG/ Hydrogen/ HCNG
- ❑ Biodiesel, Biofuels, Methanol, Ethanol, and Butanol
- ❑ Dimethyl Ether (DME) and Diethyl Ether (DEE)
- ❑ Laser Ignition of Combustible Mixtures
- ❑ Combustion Visualisation Using Schlieren/ Shadowgraphy
- ❑ Optical Diagnostics of Engine Combustion
- ❑ Particle Image Velocimetry (PIV) for In-Cylinder Flow Visualization
- ❑ Phase Doppler Interferometry (PDI) for Dense Spray Characterization
- ❑ Lubricating Oil Characterization and Tribology
- ❑ Engine Simulation (1-D and 3-D)
- ❑ Lifecycle Assessment
- ❑ Techno Economic Assessment


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