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Implication viability assessment of electric vehicles for different regions: An approach of life cycle assessment considering exergy analysis and battery degradation

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ABSTRACT

The rapid urbanization witnessed in the last few decades has contributed to the increasing demand for vehicles worldwide. An overwhelming majority of these vehicles run on fossil fuels, leading to environmental degradation. Emissions from the transport sector are a major contributor to local as well as global air pollution and deterioration in air quality. Countries such as the United States of America, China, India, Indonesia, etc., having the largest number of registered vehicles, are also responsible for a higher proportion of vehicular emissions. As new technologies emerge, electric vehicles (EV) are being envisioned as a replacement to the conventional internal combustion engine (ICEV) vehicle fleet, thus directly reducing tailpipe emissions. However, their indirect emissions are dependent on the energy grid of that particular nation. This study aims to assess the viability of implementing electric vehicles in the nations with high vehicle population. The top ten countries with the highest number of vehicles were identified, along with their power grid characteristics. A detailed review of emission factors of various power generation sources was carried out considering exergy analysis. Furthermore, battery degradation models were used to estimate the lifetime emissions from the battery of electric vehicles. The viability index calculations include well to wheel (WTW) emissions for power generation sources, in case of EVs, and for conventional vehicle fuels. The study concludes that EV implementation has varying effect on nations' air pollution, which depends upon their share of renewable sources in power generation. Implementation of EVs is found to be sustainably viable for France and Brazil, marginally viable for nations including China and India, while it is found to be not viable for Indonesia.

1. Introduction

Transportation is an essential need for humans, whether it is for the movement of goods or passengers. The global scenario indicates that the number of registered vehicles is growing significantly, especially in countries like the United States of America (USA), China, India, etc. [1]. The increasing rate of urbanization is the major factor in generating or increasing the demand for passenger vehicles [2]. Mainly, in developing nations like India, which is witnessing high economic growth, the rate of urbanization is significant, where it is predicted that 50% of its citizens will be living in urban areas by 2050 [3]. With this increasing growth, the demand for mobility has also increased. Today, USA leads the world in terms of the number of vehicles registered in a particular nation. This has resulted in the transportation sector contributing a significant share of pollutants in local as well as global emissions. According to an estimate by the International Energy Agency, transportation sector alone contributes to 20% of primary energy use at global level and 25% of carbon emission associated to energy [4]. Globally, the road transport sector contributes ¾-share in total transport greenhouse gas emissions [5]. The transport sector consumes oil and emits CO_2 in a large amount [6].

Globally, electric vehicle have been implemented in large numbers during the last ten years, resulting in the number of passenger EV cars crossing 5 million in 2018, attributing to 63% increment from last year [1]. In 2019, the EV sales added 2.26 million units and boosted the stock to 7.2 million globally [7]. China has emerged as the largest EV market globally, catering almost half (45%) of global EV stock, having 2.3 million electric vehicles in active use. The United States and Europe have 1.1 and 1.2 million EVs respectively. While in China only 5.2%

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Nomenclature

EI_{ICEV}	Emission index of Internal combustion engine vehicle (ICEV)
$\widehat{E}_{wtt}$	Well to tank (WTT) per unit emissions of vehicle fuel
$\widehat{E}_{ICEV}$	Total emissions -Well to wheel (WTW) per unit fuel
η_{comb}	ICEV Combustion efficiency
$\eta_{\pi ICEV}$	ICEV Exergy efficiency
$\widehat{E}_{t}$	Per unit emission due to transportation fuel
$\widehat{E}_{ex}$	Per unit emissions due to excavation of fuel
$\widehat{E}_{ref}$	Per unit emissions due to refining of fuel
Ex_{tm}	Thermo-mechanical exergy
Ex_{ch}	Chemical exergy
EI_{EV}	Emission Index of EV
$\widehat{E}_{EV}$	Total emissions generated from electric vehicle
$\widehat{E}_{up}$	Per unit emissions generated from upstream activities
$\widehat{E}_{down}$	Per unit emissions generated from downstream activities
$\widehat{E}_{fuel-cycle}$	Per unit emissions generated from fuel-cycle activities
$\widehat{E}_{oper}$	Per unit emissions generated from operational activities
$\widehat{E}_{mat-ext}$	Per unit emissions due raw material extraction
$\widehat{E}_{mfg}$	Per unit emissions due to construction material manufacturing
$\widehat{E}_{const}$	Per unit emissions due to power plant construction
$\widehat{E}_{fuel-ext}$	Per unit emissions in fuel extraction
$\widehat{E}_{fuel-proc}$	Per unit emissions in fuel processing
$\widehat{E}_{trans}$	Per unit emissions in transporting the fuel to power plant
$\widehat{E}_{storage}$	Per unit emission due to power consumption and energy loss in storing the fuel
$\widehat{E}_{decom}$	Per unit emissions in decommissioning of power plant
$\widehat{E}_{disman}$	Per unit emissions in dismantling of the power plant
$\widehat{E}_{recycle}$	Per unit emissions in recycling
$\widehat{E}_{maintenance}$	per unit emissions in maintenance of system
EI_{EVM}	Emission index of the electric vehicle (EV) charged by mix power generation sources
I_{rev}	Thermal losses due to irreversibility
I_{tot}	Total destructive exergy
Ex	Total Exergy
Ex_{aux}	Exergy of the auxiliary components
η_{comb}	Efficiency of coal combustion
$\eta_{turbine}$	Efficiency of steam turbine
η_{Boiler}	Efficiency of Boiler
$\eta_{\pi,EV}$	Exergy efficiency of EV
η_{u}	Exergy efficiency of EV unit
η_{m}	Motor efficiency
η_{t}	Transmission efficiency
$E_{l(o)}$	Other energy losses at coal power plant - flue gasses losses, Condenser losses etc.
$\mu_{o,i}$	Chemical potential- species i
m_{i}	Mass potential - species i
T_{o}	Reference temperature (K) of the environment
P_{o}	Reference pressure (atm) of the environment
E	Total energy
E_{kin}	Kinetic energy
E_{pot}	Potential Energy
V	Volume of system contents
$dV/d\ddot{I}$	Rate of change of cylinder volume with crank angle
S	Entropy of system contents
m	Masses of total cylinder contents
m_{f}	Masses of the fuel contents
$a_{f,ch}$	Fuel chemical exergy
$\dot{s}_{gen}$	Entropy production rate in the cylinder due to irreversibility (J/K)
m_{u}	Unburned masses of cylinder contents
m_{b}	Burned masses of cylinder contents
e_{i}	Total exergy of each chemical species i
$\dot{Q}_{J}$	Heat transfer through boundary at temperature T_j and location j
e^{ph}	Physical exergy
E_{max}	Maximum extractable exergy
$\dot{W}$	Work rate
W_{ind}	Indicated work output
I_{B}	Terminal current of battery
V_{B}	Terminal voltage of battery
$-k_{j}^{eff}$	Effective conductivities in liquid phase
σ_{j}^{eff}	Effective conductivities in solid phase
t^{0}	Transference number of the lithium-ion
F	Faraday's constant
i_{j}^{tot}	Total current transferred between solid electrodes particles and electrolyte solution
$\phi_{1,j}$	Potentials in solid phase of battery
$\phi_{2,j}$	Potentials in liquid phase of battery
c_{J}^{s}	Lithium-ion concentration
D_{j}^{S}	Diffusion coefficient in solid materials
ε_{j}	Electrode porosity
D_{j}^{eff}	Effective diffusion coefficient
c_{p}	Specific heat capacity
λ	Heat conductivity
Q_{i}	Heat source term
Q_{rev}	Total reversible heat production
Q_{rxn}	Total reaction heat generation
Q_{ohm}	Total ohmic heat production
i_{j}^{F}	Faradaic current in battery
i_{j}^{S}	Electrolyte reduction current
U_{j}	Battery open circuit potential
R_{f}	Total SEI film resistance
S_{j}	Active interfacial area
$R_{f}(t)$	Resistance of produced film in cycling
$R_{f,ini}$	Resistance of Initially formed SEI layer
$R_{p,pos}$	Radius of spherical electrode particles
V_{0}	Molar volume of $LiMn_2O_4$
$CL_{calender,n}$	Calendar loss of battery
A	Pre-exponential factor
E_{a}	Activation energy

vehicles are electric, 56% of Norway's vehicles are running on electricity [1].

The global EV sales in 2020 were 3.24 million with an year on year (Y-O-Y) growth of 43% [7]. Overall, the region-wise EV sales and market share can be viewed in Fig. 1.

To carry out the study, specific countries have been selected from different parts of the globe with high vehicular population (Fig. 2) and where the government is focusing on implementing electric vehicles. The government is setting targets of EV adoption in the respective nations and introducing schemes and policies to achieve the targets in a

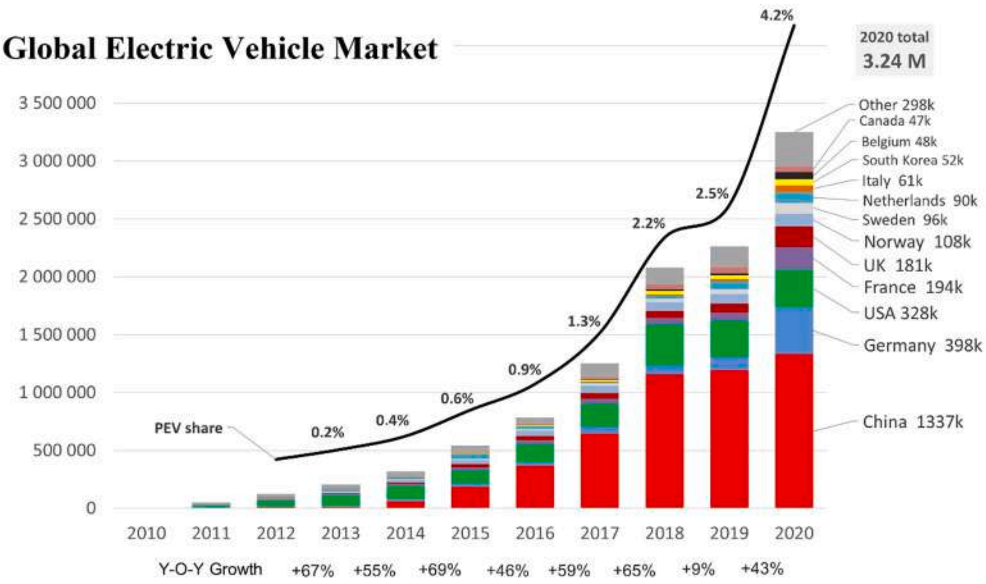

Fig. 1. Global EV market share [7]

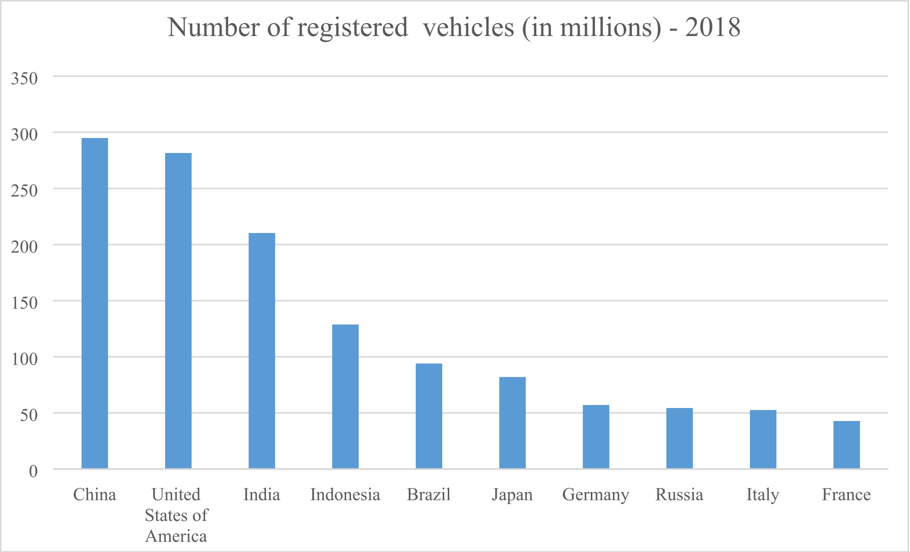

Fig. 2. Countries and their vehicle population – 2018 [8]

proposed time-frame. These countries (USA, France, China, Germany, Brazil, Italy, India, Indonesia, Japan, and Russia) belong to different regions (continents) and power generation grids (ratio of renewable and non-renewable).

The impact of EVs is found to be different for different regions according to their respective power generation mix. According to literature,

- By 2025, EVs are expected to increase global passenger vehicle sales by 10%, bringing it to 28% in 2030 and 58% in 2040 [9].
- An Indonesian company, PLN Technology, has projected over 326,000 on-road EVs between 2020 and 2025, which would reduce Indonesia's dependence on oil [10]. To attract investors and manufacturers, Indonesia has provided tax incentives to EV manufacturers and battery producers. Also, Indonesia is on the way to offer preferential tariff agreements with countries willing to source EVs from Indonesia [10].
- As per the International Energy Agency, China already had 2.58 million electric vehicles in 2019, compared to just 0.88 million in the USA and 0.97 million in Europe [1]. The Ministry of Industry and Information Technology in China is planning to electrify and sell almost 25% of new cars by 2025 [11].
- India's National E-mobility Programme (NEMP) is focusing on accelerating the whole e-mobility system, including charging infrastructure development companies, electric vehicle manufacturers, fleet operators, and service providers, etc.[12]. The government of India also has its eyes on charging infrastructure and policy framework for electrifying 30% of vehicular population [12].
- In Germany, EVs are expected to grow from 72,014 unit sales in 2018 to 880,017 unit sales by 2025, with a CAGR of almost 43% [13].
- Brazil is focusing on procuring zero-emission buses by 2025 and has a target to convert all the major city centers as zero-emission zones [14].
- The government of Japan has set a target of selling 23–33% of all its new vehicles as electric vehicles by 2030 [15].

- The government of France has proposed a law to eliminate all fossil fuel vehicles and replacing them with electric vehicles by 2040 [16].
- The Russian government has a consumer demand increment plan by providing perks like exemption from transportation tax, free charging stations, free tolled highways for EV users, and providing free vehicular parking, even in core urban areas [17].
- Italy has a target of 1 million electric cars on its roads by 2022. The Italian government is providing incentives for using EVs, which includes annual circulation tax (ownership tax) exemption for five years from the date of purchase of the EV [18].

Concern over air pollution has propelled the need for alternative fuel vehicles, and electric vehicles are in the forefront to providing a sustainable solution, as compared to other options. Several studies [19–26] have compared electric vehicles with conventional vehicles. Most of them agree with the positive effect of EVs on reducing local and global emissions of road transport, depending upon the source of energy used in charging the vehicle. The electric vehicles will have a dominant role in transforming transportation into low-carbon transportation [2,27–29]. However, most of the EV and ICEV comparison studies have not considered battery degradation, which has a significant role in EV performance, i.e., efficiency, power consumption, and life cycle greenhouse emission. A study by Yang et al. [30] has assessed the impact of battery degradation on the life cycle emission of an electric vehicle. The findings of the study reveal that battery degradation can reduce the driving intensity and battery efficiency. The results indicate that the life cycle GHG emission from EV might increase up to 29% per mile.

A study by Kittner et al. [31] has estimated the global cumulative sale of EVs to be 42 million by 2025, 134 million by 2030, 562 million by 2040. This increase in the sale of EVs will reduce the dependency on oil but significantly increase the load on power generation sources. Most of the countries, such as India, China, Indonesia, etc., do not have a clean electricity grid. However, these countries have the most number of vehicles and have the potential to adopt EVs in large numbers. Past studies have shown that the emission reduction capability of EVs depends upon the power generation sources of any particular nation [25]. A few such studies are listed in Table 1, which describes the previous work done in the same field.

In this study, ten countries, in terms of the most number of registered vehicles, targets for EV adoption, and policy incentives by their respective government, are selected and considered for further analysis. The selected countries are either developing or developed economies, which are expected to be affected by this large-scale shift of the vehicles from conventional sources to electricity. Therefore, these countries need to examine the viability of this shift and the possible after effects that will take place. It will not only help them in making amends to the policies to ensure a smooth transition but also help them in preparing and mitigating any problems or complications that they may face in the long term.

The study deals with assessing the environmental impacts of implementing electric vehicles. To carry out the research, firstly the sources of power generation of all the selected nations have been identified. After this, the life cycle emission assessment of recognized power sources and conventional fuel is reviewed from various existing studies. The battery degradation model is adopted from the literature to assess the impact of total life cycle emissions from EVs in a more accurate manner. Subsequently, the exergy analysis for each considered power generation source is carried out. After that, this data is used to develop a viability index of implementation of EV over ICEV. The study applies a unique integrated approach considering exergy analysis and battery degradation model for estimating degree of viability for switching to EV over ICEV. This viability index will indicate the benefits of EV over ICEV for the current power generation scenario. Furthermore, these results can be used to develop policies regarding the sustainable implementation of EV in these nations.

1.1. Power generation sources

Electricity is an essential entity for day-to-day life of an individual. It can be generated from various sources like thermal power plants, hydropower, nuclear, solar power and wind power, etc. Power generation for any particular nation depends on the sources available in the country. The global power generation scenario is majorly dependent on coal and natural gas. The share of renewable power generation sources is significantly less when compared to non-renewable fossil fuel sources, as depicted in Fig. 3 [37]. The dependency on non-renewable power generation sources makes electricity generation a significant contributor to air pollution. The emission intensity of the power grid is different in each nation as it depends upon the share of power generation sources. The burning of fossil fuels leads to the emission of various gases like CO_2,

Table 1

Findings from the previous studies.

Author	Focus of the study	Study Findings
(Zuccari et al., 2019) [32]	Well to wheel analysis and comparison between conventional, hybrid and electric power train, in real conditions of use, by considering the consumption of non-renewable primary energy and CO_2 emissions	• Significant reductions in fuel consumption and CO_2 emissions compared to the conventional powertrain (petrol and diesel) in case of hybrid and electric powertrain. • Emissions and consumptions from electric powertrains, potentially for consumption and zero emissions, is linked to the production and distribution of electricity
(Choi, Yoo, Seol, Kim, & Song, 2020)[33]	Well-to-wheel GHG emissions of representative vehicle types–internal combustion engine vehicle (ICEV), hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), battery electric vehicle (BEV), and fuel cell electric vehicle (FCEV)–in the future (2030) and an analysis of various energy policies affecting future emissions by considering: • Life cycle assessment (LCA) of eight base fuels • Analysis of fuel economies for seven types of vehicles.	FCEVs were the lowest-GHG-emitting option because over 97% of hydrogen used in FCEVs was produced by the naphtha cracking process, which emits very low GHG emissions.
(Qiao, Zhao, Liu, He, &Hao, 2019)[34]	Life cycle assessment considering CO_2 emission from the production of electric and conventional vehicles in China	• CO_2 emission from the production of EV is 59–60% higher than ICEV. • LI-on battery and components such as traction motor and electric controller are the main reason. • CO_2 emission can be reduced by the development taking place in the production of battery manufacturing techniques.
(Nimesh & John, 2012)[35]	Total lifecycle economic cost and EIA of Lithium-ion battery electric vehicles (BEVs) versus internal combustion engine vehicles (ICEVs)	• BEV is 44% more expensive than ICEV • BEV has 23% less GWP impact than ICEV • BEV has 3 times greater Human Toxicity Potential
(Hall & Lutsey, 2018)[36]	Impact assessment of battery manufacturing on EV lifecycle GHG emissions	• Electric cars are much cleaner than ICEV throughout their lifetime • Grid decarbonization offers a substantial opportunity to reduce the impact of battery manufacturing

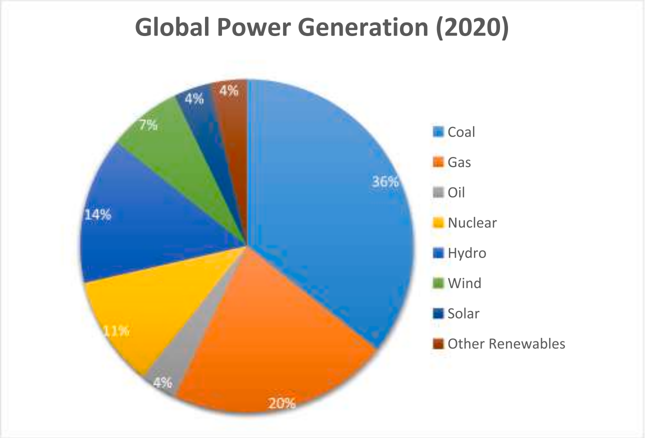

Fig. 3. Global power generation by the year 2020 [37]

SO_x, NO_x, CH_4, etc. [38]. In this study, equivalent CO_2 emission is considered, to consolidate the effect of all greenhouse gases in a single unit.

1.2. CO_2 equivalent (CO_2-eq)

The term CO_2 equivalent (CO_2-eq) is used to describe the effect of different greenhouse gases (GHGs) in a standard unit [39]. Equivalent CO_2 (CO_2-eq) is the concentration of CO_2, in terms of the number of metric tons of CO_2 emissions with the same global warming potential (GWP) as one metric ton of another GHG [40]. The quantity of a greenhouse gas can be expressed as CO_2-eq by multiplying the GHG by its global warming potential (GWP) as described in eq. (1) [41–43]. In this study, the emission factor or emission intensity of a particular source of power generation is indicated in terms of CO_2-eq. The emissions and their CO_2-eq are given in Table 2.

$$GHG_{LC} = CO_{2,LC} + 25CH_{4,LC} + 298N_2O_{LC} \quad (1)$$

where, GHG_{LC} is total greenhouse gas emission life cycle, $CO_{2,LC}$ carbon dioxide emission in the life cycle, $CH_{4,LC}$ methane emission in the life cycle and N_2O_{LC}nitrogen oxide emission in the life cycle.

1.3. Life cycle assessment of power generation sources

Life cycle analysis is a method to evaluate the total environmental impact of a product or a system. In this study, the life cycle assessment of different power generation sources has been reviewed. The life cycle assessment of fuel-based power generation sources is divided into four steps – Upstream, Fuel-Cycle, Operation, and Downstream, as described in Fig. 4. In upstream, the environmental impact of raw material extraction, construction material manufacturing, and power plant construction is considered. Fuel-cycle consists of fuel extraction, fuel processing, transportation, and storage of fuel. In operation, the environmental impact of power plant operation, power supply losses, and maintenance is considered [44]. After that is the ecological impact of the downstream step, which includes plant decommissioning, dismantling, and recycling. As per the life of a power plant, it is considered in estimating total life cycle GHG emissions from power plants. In power generation from renewable sources, all the steps are same, except for the fuel cycle, as there is an absence of fuel in the power generation process [45,46].

Table 2
Emissions and their CO_2 equivalent factors [40].

Emission (Gas)	CO_2 equivalent factor
1 kg CO_2	1 kg CO_2-eq
1 kg CH_4	25 kg CO_2-eq
1 kg N_2O	298 kg CO_2-eq

Table 3 indicates the life cycle emission factor in terms of CO_2-eq. various literature has been reviewed to extract the emission factor data.

Fig. 5 shows the box-whisker plot for emission factors in terms of CO_2-eq for different power generation sources. The plot indicates a significant variation in emission factors for coal power, natural gas, and oil. Coal, natural gas, and oil quality, according to the geographical location. However, emission depends on certain other factors also, i.e., transportation, power plant technology, etc. This variation, in case of renewable sources such as solar, biomass, nuclear, geothermal, wind, and hydroelectric, is less. According to Fig. 5, the median value of emission factors of coal, oil, natural gas, solar, biomass, nuclear, geothermal, wind, and hydroelectric are 975, 596, 519, 47, 37, 24, 50, 13, and 7 gCO_2-eq/kWh respectively.

2. Methodology

The study assesses the viability index of the implementation of EVs in the selected countries. The flowchart of the methodology is described in Fig. 6. Firstly, the highest vehicle populated countries have been identified from sources that include reports from WHO, World Bank, etc. Secondly, the data of power generation sources, and their ratios, are collected from existing literature. Thirdly, the emission factors for each power generation source are assimilated through an exhaustive literature review. In this study, the emission factor is considered in terms of CO_2-equivalent, rather than for individual gas emission. Fourthly, total grid emission intensity is calculated for each selected country. A study by Nimesh et al. [25] has conducted the exergy analysis of ICEV and EV when powered with only coal power plant for India. In this study, this methodology is furthered by carrying out an exergy analysis of all the available power generation sources. Finally, the implication viability index is estimated for all the nations, as per the adopted methodology from the study by Nimesh et al. [25], by including few more parameters for life cycle assessment, i.e. downstream emissions and battery degradation model.

3. Emission index

The emission index for any particular system is described as the emission (m_i) released per unit of the energy value (kWh).

$$EI = \frac{m_i}{kWh} \quad (2)$$

A correlation between the emissions and the accountable factors is identified by life cycle assessment to evaluate the impact. After that, Emission Index (E.I.) is developed for EVs and ICEVs [25].

3.1. Emission index for internal combustion engine vehicle (ICEV)

The emission index of ICEV is defined as a function of engine, combustion and transmission efficiency. Moreover, the emissions resulting from the life cycle assessment of petroleum fuel are accounted for *E.I.* calculations.

Emission Index of ICEVs:

$$EI_{ICEV} = f\left(\sum \widehat{\mathrm{E}}_{ICEV}\right) \quad (3)$$

$$\widehat{\mathrm{E}}_{ICEV} = f\left(\widehat{\mathrm{E}}_{wtt}, \widehat{\mathrm{E}}_{d}, \eta_{comb.}, \eta_{\pi,ICEV}, \eta_{t}\right) \quad (4)$$

$$\widehat{\mathrm{E}}_{wtt} = f\left(\widehat{\mathrm{E}}_{t}, \widehat{\mathrm{E}}_{ex}, \widehat{\mathrm{E}}_{ref}\right) \quad (5)$$

The emission index of the ICEV (EI_{ICEV}) is defined as the total well to wheel (WTW) emissions generated per unit of fuel produced($\widehat{E}_{ICEV}$) [25].

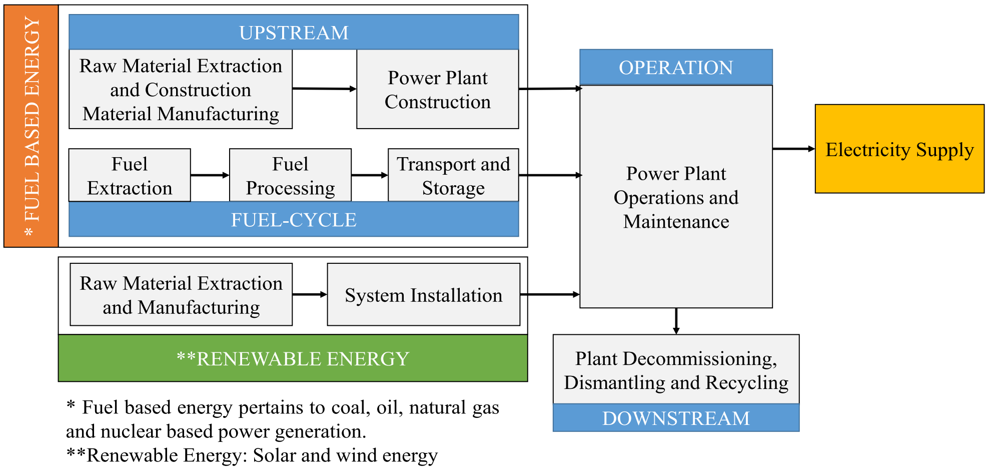

Fig. 4. Life cycle of power generation sources.

Table 3
Life cycle emission factors of power generation sources.

Power Generation Sources	Emission factor(gCO$_2$-eq/kWh)	References
Coal Power Generation	660–1250	[47–66]
Natural Gas	350–710	[46–48,53,61–64,67]
Oil Based	350–785	[47,48,61,62,68–70]
Hydroelectric	3.5–20	[46,50,55,56,71,72]
Solar	13–90	[46,56,63,68,73–78]
Wind	9–38	[48,50,75,79–81]
Nuclear	7–66	[46,48,49,63–65,74,81,82]
Biomass	14–130	[50,52,57,63–65,83,84]
Geothermal	38–83	[50,63,85,86]

Further, It depends on well to tank (WTT) emissions per unit of fuel ($\widehat{E}_{wtt}$), per unit downstream emission ($\widehat{\mathrm{E}}_d$), combustion efficiency of ICEV($\eta_{comb.}$), exergy efficiency of ICEV($\eta_{\pi,ICEV}$) and efficiency of transmission (η_t).Here, $\widehat{E}_{wtt}$ depends on per unit emission due to the transportation of fuel ($\widehat{E}_t$), emissions due to excavation of fuel ($\widehat{E}_{ex}$) and in the refining of fuel ($\widehat{E}_{ref}$).

Exergy is a maximum theoretical work attained from the particular system when it comes into thermodynamic equilibrium with the environment [87]. The system equilibrium will be achieved when it is chemically, mechanically, and thermally equilibrium [88]. The maximum available work of closed system is a summation of the chemical exergy (Ex_{ch}) and the thermo-mechanical exergy (Ex_{tm}).

Thermo-mechanical exergy (Ex_{tm}) can be described as the maximum extractable work from system under the mechanical and the thermal equilibrium with surrounding. The mathematical equation of this relation comprises Mass potential of species $i(m_i)$, Chemical potential of species $i(\mu_{o,i})$, Reference pressure (P_o), and Reference temperature (K)of the environment, (T_o)as shown in equation (6) [88]:

$$Ex_{tm} = E + p_o V - T_o S - \sum_i \mu_{o,i} m_i \tag{6}$$

where, $\mathrm{E} = \mathrm{U} + \mathrm{E_{kin}} + \mathrm{E_{pot}}$,

The composition difference of initial and final condition of the system can be used to get the additional to achieve the chemical exergy. In this way, The obtained maximum work is called chemical exergy (Ex_{ch}) [88,89]:

$$Ex_{ch} = \sum_i \left(\mu_{o,i} - \mu_i^o\right) m_i \tag{7}$$

If, the initial system is in chemical, mechanical and thermal equilibrium with the environment; by using equations (6) and (7), then the total exergy (Ex) can be calculated as [30]:

$$Ex = Ex_{tm} + Ex_{ch} = E + p_o V - T_o S - \sum_i \mu_i^o m_i \tag{8}$$

The rate of exergy loss or gain by ICEV can be inferred in terms of crank angle degree (CAD). Locations with significant thermodynamic losses can be identified, leading to high emissions. The equation (9) represent the differential form of the rate of exergy loss/gain for engine

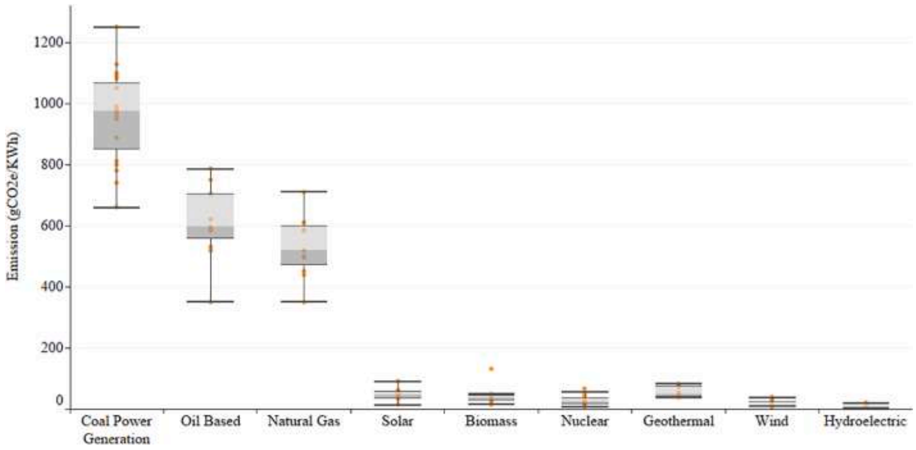

Fig. 5. Life cycle emission factors of power generation sources.

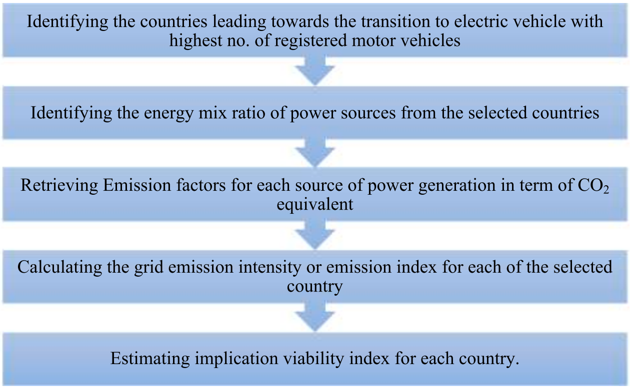

Fig. 6. Methodological Framework.

cylinder [90]:

$$\underbrace{\frac{dEx}{d\Theta}}_{1}=\left(\underbrace{1-\frac{T_o}{T}}_{2}\right)-\underbrace{\left(\frac{dW}{d\Theta}-p_o\frac{dV}{d\Theta}\right)}_{3}+\underbrace{\frac{m_f}{m}\frac{dx_b}{d\Theta}}_{4}-\underbrace{\dot{I}_{tot}}_{5} \tag{9}$$

where,

1. (1) →The rate of change in total exergy of cylinder contents
2. (2) →Exergy transfer with heat
3. (3) →Exergy transfer through indicated work transfer
4. (4) →Burned fuel exergy
5. (5) →Exergy destruction in the cylinder due to combustion and heat transfer

$$\dot{I}_{tot}=T_o\dot{S}_{gen} \tag{10}$$

The entropy balance can be represented as the rate of entropy production in the cylinder due to irreversibility ($\dot{S}_{gen}$), the unburned masses of cylinder contents (m_u) and the entropy values of unburned gas (s_u) as [90]:

$$\dot{S}_{gen}=\frac{d}{d\ddot{I}}(m_u s_u)+\frac{\dot{Q}_b}{T_b}+\frac{\dot{Q}_u}{T_u} \tag{11}$$

where, Q_b and $Q_u$are heat losses from the burned and unburned gasses. T_b and T_u are the temperatures of the burned and unburned gas zones, respectively. The exergy efficiency of the ICEV ($\eta_{\pi,ICEV}$) is advantageous in identifying and estimating the irreversible thermodynamic losses as shown in equation (12), In which, W_{ind} is the indicated work output and E_{max} as maximum extractable exergy.

$$\eta_{\pi,ICEV}=\frac{W_{ind}}{E_{max}}=\frac{W_{ind}}{W_{ind}+\dot{I}_{tot}} \tag{12}$$

The exergy efficiency emphasizes both internal exergy destruction and exergy transfer losses due to irreversibility. Hence, $\eta_{\pi,ICEV}$is a vital parameter that is affecting the degree of viable implication(φ).

3.2. Emission index for electric vehicle (EV)

Electric vehicles (EVs) have zero tail pipe emissions but their emissions depend upon the power generation source used to charge the vehicle. Here, the Emission Index (E.I.) of an EV is a measure of emissions from EVs generated indirectly according to the power generation source. Any country does not only depend on a single power generation source. The power generation system of countries like India, China, Indonesia, and Brazil are majorly dependent on thermal power plants operating with coal. On the other hand, countries like Russia, Italy, Japan, and the United States have a significant share of natural gas power plants. Hence, in this study, different ratios of non-renewable and renewable energy, according to the country's power generation mix, are considered, and the emissions index for the electric vehicles is calculated considering the exergy efficiency of each system.

In this study, detailed literature is reviewed to assess the life cycle impact of thermal power plants which operating on both non-renewable energy sources i.e., oil, coal and natural gas & renewable energy sources, i.e., wind, solar, geothermal, and biomass. The considered activities (extraction of fuel, transportation of fuel, power plants losses etc.) have been already discussed in detail in section 1.3 and Fig. 4. The correlation equations below illustrate a scenario where EV is powered by any non-renewable energy source. The consumption of energy, emissions, and exergy destruction will take place during various activities of the process, i.e. extraction of fuel, transportation of fuel, and operations at power plant. Emission Index of EV (EI_{EV_x}) depends on per-unit emissions generated from upstream activities($\widehat{\mathrm{E}}_{up}$), downstream activities($\widehat{\mathrm{E}}_{down}$), fuel-cycle ($\widehat{E}_{fuel-cycle}$)and operation activities($\widehat{E}_{oper}$), and transmission efficiency of electricity (η_{trans}).

The upstream activity boundary consists of raw material extraction, construction material manufacturing, power plant construction etc. The equation below describes the relation of emissions due to upstream activities ($\widehat{E}_{up}$) which depends upon emissions due to raw material extraction($\widehat{E}_{mat-ext}$), per unit emissions due to construction material manufacturing ($\widehat{E}_{mfg}$), and per unit emissions due to power plant construction ($\widehat{E}_{const}$). The fuel-cycle consists of fuel extraction, fuel processing, transportation, and storage of fuel. The equation depicts the relation of the per-unit emissions from fuel-cycle activity ($\widehat{E}_{fuel-cycle}$) which depends on per unit emissions in fuel extraction$\left(\widehat{E}_{fuel-ext}\right)$, per unit of emissions in fuel processing ($\widehat{E}_{fuel-proc}$), per unit emissions in transporting the fuel to the power plant ($\widehat{E}_{transp}$),per unit emission due to power consumption and energy loss in storing the fuel($\widehat{E}_{storage}$). The downstream includes plant decommissioning, dismantling, and recycling according to the life of power plant. The per-unit emissions from downstream activities is a function of per-unit emissions in decommissioning the power plant ($\widehat{E}_{decom}$), per unit emissions in dismantling the plant ($\widehat{E}_{disman}$), ($\widehat{E}_{maintenance}$) per unit emissions in maintenance of system and per unit of emissions in recycling ($\widehat{E}_{recycle}$).

After that, the operation activity includes power plant operation, power supply losses, and maintenance of the power plant. The per-unit emissions from operation activity is a function of the combustion efficiency of coal (η_{comb}), mechanical efficiency of the turbine ($\eta_{turbine}$), and emissions due to other losses ($E_{l(o)}$) and exergy efficiency of the total power plant ($\eta_{\pi,EV}$). The exergy efficiency of the total power plant ($\eta_{\pi,EV}$) depends on the exergy efficiency of the EV unit(η_u), transmission efficiency (η_t), exergy efficiency due to power generation($\eta_{p,gen,}$) and efficiency of auxiliary component (η_{aux}).

$$EI_{EV_x}=f\left(\sum\widehat{\mathrm{E}}_{EV(x)}\right) \tag{13}$$

$$\widehat{\mathrm{E}}_{EV(x)}=f\left(\widehat{\mathrm{E}}_{up},\widehat{\mathrm{E}}_{fuel-cycle},\widehat{\mathrm{E}}_{oper},\widehat{\mathrm{E}}_{down},\eta_{trans}\right) \tag{14}$$

$$\widehat{\mathrm{E}}_{upstream}=f\left(\widehat{\mathrm{E}}_{mat-ext},\widehat{\mathrm{E}}_{mfg},\widehat{\mathrm{E}}_{const}\right) \tag{15}$$

$$\widehat{\mathrm{E}}_{fuel-cycle}=f\left(\widehat{\mathrm{E}}_{fuel-ext},\widehat{\mathrm{E}}_{fuel-proc},\widehat{\mathrm{E}}_{trans},\widehat{\mathrm{E}}_{storage}\right) \tag{16}$$

$$\widehat{\mathrm{E}}_{down}=f\left(\widehat{\mathrm{E}}_{decom},\widehat{\mathrm{E}}_{disman},\widehat{\mathrm{E}}_{recycle}\right) \tag{17}$$

$$\widehat{\mathrm{E}}_{oper} = f\left(\eta_{comb}, \eta_{turbine}, \eta_{Boiler}, \widehat{\mathrm{E}}_{l(o)}, \eta_{\pi,EV}, \widehat{\mathrm{E}}_{maintenance}\right) \tag{18}$$

$$\eta_{\pi,EV_x} = f\left(\eta_{p,gen,}\eta_u, \eta_{aux}, \eta_t\right) \tag{19}$$

The heat dissipation in terms of heat transfer, chemical reaction, thermal and transmission losses lead to exergy loss. The exergy balance of the system can be expressed as equations (20–22) after neglecting the changes in kinetic and potential energies [91,92]:

$$\begin{aligned}\sum_i \dot{I}_{rev} &= \sum_i \dot{Ex}_{in} - \sum_i \dot{Ex}_{out} \\ &= \left(\sum_i (\dot{m}_i e_i)\right)_{in} + \sum_j \left(1 - \frac{T_o}{T_j}\right)\dot{Q}_j - \dot{W} - \left(\sum_i (\dot{m}_i e_i)\right)_{out}\end{aligned} \tag{20}$$

$$e^{ph} = \int_{(T_o,P_o)}^{(T,P)} \left[x_l\left(\sum x_i H_i^l - T_o \sum x_i s_i^l\right) + x_v\left(\sum y_i H_i^v - T_o \sum y_i s_i^v\right)\right] \tag{21}$$

$$e^{ch} = \left(x_{o,l} \sum x_i e_i^l + x_{o,v} \sum y_i e_i^v\right) \tag{22}$$

The environmental temperature (T_o) and pressure (P_o) are 298.15 K and 1.0 atm for the present study, respectively. The overall exergy efficiency of the electric vehicle powered with thermal power plants is discussed in terms of exergy due to power generation and exergy of the EV unit. According to the exergy balance, the destructive exergy for the thermal powered electric vehicle unit can be expressed:

$$\dot{I}_{tot} = \left(\sum_{k=(fuel,O_2)} \dot{m}_k\left(Ex_{ph} + Ex_{ch}\right)_k\right)_{in} + \left(1 - \frac{T_o}{T_B}\right)Q_{diss} - \left(\sum_{k=(products)} \dot{m}_k\left(Ex_{ph} + Ex_{ch}\right)_k\right)_{out} - V_B I_B \tag{23}$$

Where, Q_{diss} indicates the heat dissipation from the battery of EV to the atmosphere. The consumption of power by the fan, blower, and other electronic components are considered neglected. However, the charging and discharging effects are taken into consideration. The exergy efficiency due to power generation, $\eta_{p,gen}$ can be expressed as [91]:

$$\eta_{p,gen} = \left(\frac{P_{B,dch}}{\frac{P_{B,dch}}{\eta_{battery}}}\right) \times \eta_{convertor} \times \eta_{invertor} \tag{24}$$

The rechargeable battery capacity is affected by several charge/discharge cycles; therefore, the battery degradation model is considered to capture this effect on the battery. For simplicity, $\eta_{convertor}$ and $\eta_{invertor}$ are assumed to be constant. The exergy efficiency of the electric vehicle unit can be expressed in general terms as:

$$\eta_u = \frac{V_B I_B + (Ex)_{out} - \left(1 - \frac{T_o}{T_B}\right)Q_{diss}}{(Ex)_{in}} \tag{25}$$

The exergy efficiency of the auxiliary components, η_{aux} can be characterized as:

$$\eta_{aux} = \frac{\sum_i \dot{Ex}_{out}^{aux}}{\sum_i \dot{Ex}_{in}^{aux}} \tag{26}$$

Therefore, the overall exergy efficiency of the EV can be represented as:

$$\eta_{\pi,EV} = \eta_{p,gen} \times \eta_u \times \eta_{aux} \times \eta_t \tag{27}$$

3.3. Electric vehicle battery degradation model

In the current scenario, electric vehicles predominantly employ lithium-ion batteries. The degradation of batteries can significantly influence the energy consumption and life cycle GHGs. The capacity loss or degradation of the battery affects electric vehicle performance in two aspects: (1) reduction in driving range due to degradation in available capacity, and (2) decrease in the efficiency of battery due to the increased internal resistance. These batteries of electric vehicles also generate GHGs during its life cycle. According to past studies, it releases 57–85 kg CO_2 eq. per kg of battery during an EV's life cycle [93,94]. In this study, a battery degradation model is adopted from the study by Yang et al [30,94]. This battery degradation model is composed of cycling loss and calendar loss.

3.3.1. Cycling loss model

The model includes charge, mass-transfer, and energy transfer processes inside the lithium-ion battery. Theoretically, two charge carriers are present inside a battery: lithium-ions and electrons [95]. The charge balance of battery includes the transport of charge processes in solid materials and liquid electrolyte, which can be formulated by the generic Ohm's law,

$$Solidphase : \nabla^*\left(\sigma_j^{eff}\nabla\phi_{1,j}\right) = i_j^{tot} \tag{28}$$

$$Liquidphase : \nabla^*\left(-k_j^{eff}\nabla\phi_{2,j}\right) + \frac{2RT(1 - t^0)}{F}\nabla\left(-k_j^{eff}\nabla\left(\ln c_j\right)\right) = i_j^{tot} \tag{29}$$

where, σ_j^{eff} and $-k_j^{eff}$ are the effective conductivities in solid and liquid phase respectively; t^0 is the transference number of lithium-ion, F is the Faraday's constant, i_j^{tot} is the total current transferred between the solid electrodes particles and the electrolyte solution, $\phi_{1,j}$ and $\phi_{1,j}$are the potentials in the solid and liquid phases of the battery.

The mass transfer in battery contains the transport processes on solid electrode particles, and in a liquid electrolyte solution, this can be formulated by Fick's second law:

$$Electrodeparticle : \frac{\partial c_J^s}{\partial t} = D_j^S \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial c_J^s}{\partial r}\right) \tag{30}$$

$$Electrolytesolution : \varepsilon_j\frac{\partial c_j}{\partial t} = \frac{\partial}{\partial r}\left(D_j^{eff}\frac{\partial c_j}{\partial x}\right) + \frac{(1 - t^0)\left(i_j^F + i_j^S\right)}{F} \tag{31}$$

where, c_J^s is the Li-ion concentration, D_j^S is the diffusion coefficient in solid materials; ε_j is the electrode porosity, r is the rate of reaction, D_j^{eff} is effective diffusion coefficient.

To take the influence of both battery internal heat production and environmental temperature into consideration, Fourier's law can be applied,

$$\rho c_p\frac{\partial T}{\partial t} + \nabla^*(-\lambda\nabla T) - \sum_i Q_i = Q_{rxn} + Q_{rev} + Q_{ohm} \tag{32}$$

where, $\rho$is the density, λ → heat conductivity, c_p → specific heat capacity, Q_i → heat source term, which is composed of the total reaction heat generationQ_{rxn}, total reversible heat production Q_{rev} and total ohmic heat productionQ_{ohm}. These heat sources can be represented as:

$$Q_{rxn} = \left(i_j^F + i_j^S\right)\left(\phi_{1,j} - \phi_{2,j} - U_j - \frac{(i_j^F + i_j^S)}{S_j}R_f\right) \tag{33}$$

$$Q_{rxn} = \left(i_j^F + i_j^S\right)T\frac{\partial U_j}{\partial T} \tag{34}$$

$$Q_{ohm} = \sigma_{eff}\left(\frac{\partial\phi_1}{\partial x}\right)^2 + k_{eff}\left(\frac{\partial\phi_1}{\partial x}\right)^2 + \frac{2k_{eff}RT}{F}\left(1 - t^0\right)\frac{\partial(lnc)}{\partial x}\frac{\partial\phi_1}{\partial x} \tag{35}$$

where, i_j^F is the Faradaic current in the battery, i_j^S is the electrolyte reduction current, U_j is the battery open circuit potential, R_f is the total SEI film resistance, S_j is the active interfacial area, c is the local Li-ion concentration.

Besides, the battery charging-discharging induced solid-electrolyte interphase generation and $LiMn_2O_4$ active material loss can be simulated by,

$$R_f - R_{f,ini} + R_f(t), \frac{\partial\phi_{pos}}{\partial t} = -r_1 S_{pos} V_0, S_{pos} = \frac{3\phi_{pos}}{R_{p,pos}} \tag{36}$$

where, $R_{f,ini}$ is the initially formed SEI layer resistance, $R_f(t)$ is produced film-resistance in cycling, $r_1$is the side reaction rate, $R_{p,pos}$ is the radius of spherical electrode particles, ϕ_{pos} is the volume fraction of active $LiMn_2O_4$ in the positive electrode, V_0 is the molar volume of $LiMn_2O_4$.

3.3.2. Calendar-loss model

The calendar-loss model is the degradation in the capacity of the battery with time when it stores energy. It is also recognized that calendar loss is mainly caused by the lithium inventory loss during SEI formation at the anode and cathode and self-discharge. Based on the Arrhenius law, battery calendar loss model can be represented as [94]:

$$CL_{calender,n} = A.\exp\left(-\frac{E_a}{RT_n}\right)t_d^{0.5} \tag{37}$$

where, $CL_{calender,n}$ is the calendar loss, A is the pre-exponential factor, E_a is the activation energy, R is the gas constant, T_n is the absolute temperature in K, $t_d$is the no. of days.

3.4. Emission index for electric vehicle powered with mixed energy

The emission index of the electric vehicle when it is powered with mixed energy sources [25]:

$$EI_{EVM} = x_1 EI_{EVS_1} + x_2 EI_{EVS_2} + x_3 EI_{EVS_3} + \cdots + x_y EI_{EVSy} \tag{38}$$

$$\sum_{i=1}^{y} x_i = 1$$

Here,

- EI_{EVM} = *Emission index of electric vehicle when powered with mix energy sources*;
- x_i = *Share power generation Source*
- $EI_{EVS_1}, EI_{EVS_1}, EI_{EVS_1}$, *etc.are emission index of electric vehicle when powered with energy sources*S_1, S_2, *etc.*

3.5. Degree of viable implication

The degree of viable implication, denoted by (φ) is a non-dimensional number, which is the emission index ratio of EV and ICEV [25]. The implication viability of electric vehicles is dependent of power sources used for vehicle charging. It changes in accordance to the power grid mix of a country, being most viable for the countries having more share of renewable energy in their power grid, with a degree of viability less than 1.0.

$$\varphi = \frac{EI_{EVM}}{EI_{ICEV}} \tag{39}$$

Here, a lower degree of viable implication (φ) implies the effective and sustainable implementation of EVs over ICEVs. The viability index is assumed on an ordinal scale [96,97] from 0 to 1, which was further divided into two halves, i.e. 0–0.25, 0.25–0.50, 0.50–0.75 and 0.75–1.0 as shown below.

$\varphi > 1$, *Implimentation of electric vehicle is considered to be not viable*;

$0.75 < \varphi \leq 1$, *Implementation of electric vehicle is considered to be marginally viable*;

$0.50 < \varphi \leq 0.75$, *Implementation of electric vehicle is considered to be viable*;

$0.25 < \varphi \leq 0.50$, *Implementation of electric vehicle is considered to be sustainably viable*;

$\varphi \leq 0.25$, *Implementation of electric vehicle is considered to be most sustainably viable*;

The flowchart for estimating the degree of viability and required data is described in Fig. 7. Also, the study has made a certain assumptions to develop this model.

- The emission factor for different sources has been assumed to be constant for all the selected countries. The factors have been calculated by taking a mean of the available emission data for each of the sources acquired through an extensive literature review.
- The degree of viability has been estimated by considering Volkswagen Golf GTI and Volkswagen e-Golf model as a case vehicle.
- This study has estimated the implication viability of EV in various countries by assuming that the vehicle will be charged on the same grid ratio as currently present.

However, to perform a similar EV implication viability check for a particular region, any available comparable vehicle model can be considered.

3.6. Emissions related to life cycle of vehicle

The life cycle and considered system boundaries of ICEV and EV are presented in Fig. 8. A global perspective is considered for the vehicle's lifecycle and its key components, such as the battery, vehicle

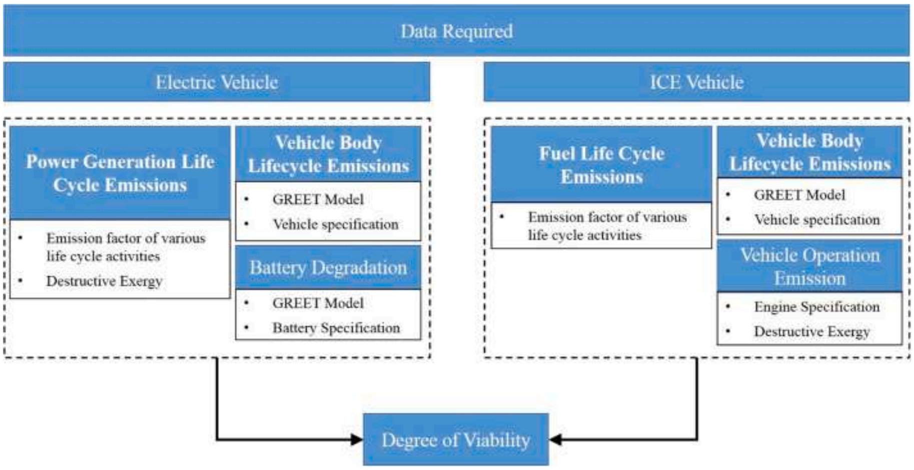

Fig. 7. Flowchart and required data.

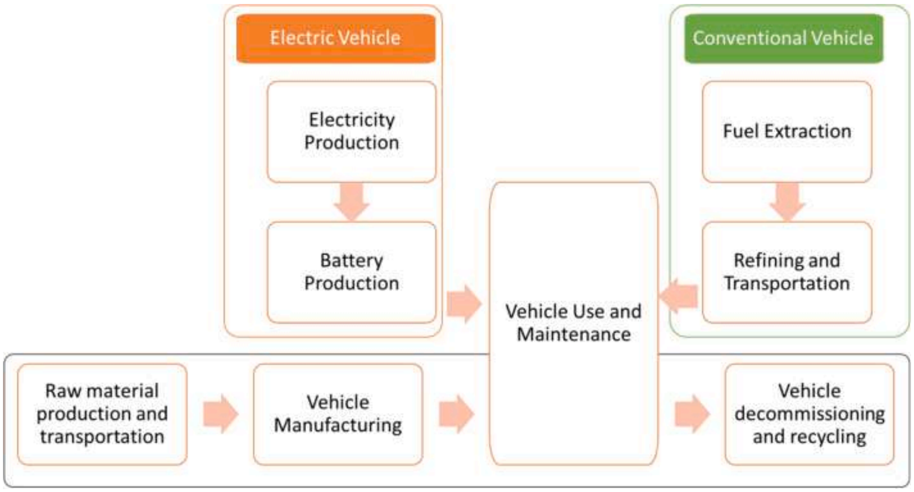

Fig. 8. Life cycle analysis of ICEV and EV.

Table 4
Specification comparison of ICEV and EV.

Specification	Volkswagen Golf GTI (ICEV)	Volkswagen e-Golf (EV)
Length (mm)	4268	4270
Width (mm)	1799	1799
Height (mm)	1442	1450
Kerb Weight (kg)	1348	1615
Mileage	15 kmpl	16.5 kWh/100 km
Car body	Hatchback	Hatchback

components, and electricity generation. Various studies [25,98–100] have performed the LCA for the ICEV and EV. A report on electric vehicles from French officials states that electric vehicle efficiency ranges from 15 kWh/100 km to 25 kWh/100 km, depending upon the traffic speed [101].

In this study, two variants of Volkswagen (Golf GTI and E-Golf) have been considered for comparison. Both variants have similar specifications and dimensions. Volkswagen is a popular brand, which has its sales and market in most of the countries worldwide. In developed nations like USA, China, Russia, France, etc., several Volkswagen models are available. Nations like India, Indonesia, and Brazil are still at a nascent stage in the transition to EV. The EV market is limited. Yet, in the coming future, more industrial players will compete in these nations. That's why Volkswagen's variants are considered as it was in the top 5 EV sales in the U.S. and Europe in 2018.

Table 5
Specification of EV (Volkswagen E-Golf).

Electric vehicle	
Driving range	
Certified range as per NEDC (km)	190
Motor	
Type	Synchronous A.C. Permanent Magnet
Horsepower (SAE), hp	134
Maximum torque, lb-ft	214
Max revs	12000 rpm
Battery	
Rated Pack Energy/Capacity	24.0 kWh / 75.0 Ah
Technology	Lithium Ion
Voltage	323 V
No. of Cells	264
Min/Max Cell Voltage	3.00/4.10 V
Pack Mass/Volume	313Kg, 229.4 L
Drivetrain	
Type	Front Wheel Drive
Gear Ratios	1st: 2.70 Reverse: 2.70 Final: 3.61

The data shown in Table 4, Table 5, and Table 6 are considered in estimating the emissions and losses during the operation of the vehicle. However, there are other emissions as well when we perform a life cycle

Table 6
Specification of ICEV (Volkswagen Golf GTI).

I.C. Engine Vehicle	
Engine	2.0L inline four cylinder, 16 V, turbocharged/ intercooled, TSI
Displacement/Cubic Capacity	1984 cc
Bore × Stroke	82.5 × 92.8 mm
Compression Ratio	9.6:1
Horsepower: Performance	220 @ 4700
Maximum torque, lb-ft @ rpm	258 @ 1500
Transmission Gear Ratios: 1	1st: 2.76 Reverse: 4.55 Final: 2.62

assessment. These activities have already been discussed above. In this study, the GREET-2019 life cycle analysis tool is used to analyze the other off-operation emissions and deriving the emission factor for each activity. The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model) model is an analytical tool that simulates the energy use and emissions output of various vehicles and fuel combinations. The GREET model calculates the total fuel-cycle energy consumption, fossil fuel consumption, petroleum consumption, and all the emissions according to the selected fuel/transportation technology combination [102]. The considered emission factors from different activities are given in Table 7 and Table 8.

4. Results

In this study, an integrated approach combining life cycle assessment with exergy analysis and battery degradation model was developed to assess the degree of viable implication of EV over ICEV in selected countries.

4.1. Power generation energy mix

After identifying the countries with most number of registered vehicles, the power generation scenario of these countries is reviewed. The energy mix grid data is obtained from the International Energy Agency (IEA) website, and the latest available data is considered. As described in Fig. 9, the United States has a versatile energy mix. The U.S. generates electricity majorly by natural gas (34%) and coal (28%) followed by nuclear power generation (19%) and hydropower (7%). The share of other renewable energy like solar, wind, and biomass is comparatively minimal. Countries like China, India, and Indonesia have a significant percentage of coal in power generation, i.e., 68%, 55%, and 58%, respectively, making the energy grid polluted. Germany and Japan also have a significant share of coal, i.e., 38% and 32.5% in their power grid. Natural gas has a substantial stake in Russia, Italy, Japan, U.S.A., and Indonesia, i.e., 53%, 45.5%, 36.5%, 34.3%, and 21.7%, respectively,

Table 8
Gasoline vehicle-cycle related emissions from GREET-2019.

Pollutants	Emissions from components (g/100 km)			
	Power train system	Transmission System	Chassis W/o Battery	Vehicle Body
CO	0.93	0.17	1.06	2.58
NO_x	0.23	57.92	0.29	0.82
SO_x	0.94	0.18	1.13	2.67
CO_2	220	50.85	280	730
GHG	240	56.7	330	860

Table 7
Electric vehicle-cycle related emissions from GREET-2019.

Pollutants	Emissions from components (g/100 km)						
	Power train system	Transmission System	Chassis W/o Battery	Traction motor	Vehicle Body	Battery	Other Parts
CO	0.38	0.47	3.09	0.38	4.47	0.62	0.9
NO_x	0.13	0.14	0.48	0.17	0.9	1.35	0.88
SO_x	1.25	1.45	2.05	2.19	3.94	11.17	2.27
CO_2	86.52	0.13	0.46	130	770	930	1372.89
GHG	96.42	140	490	140	860	1000	903.58

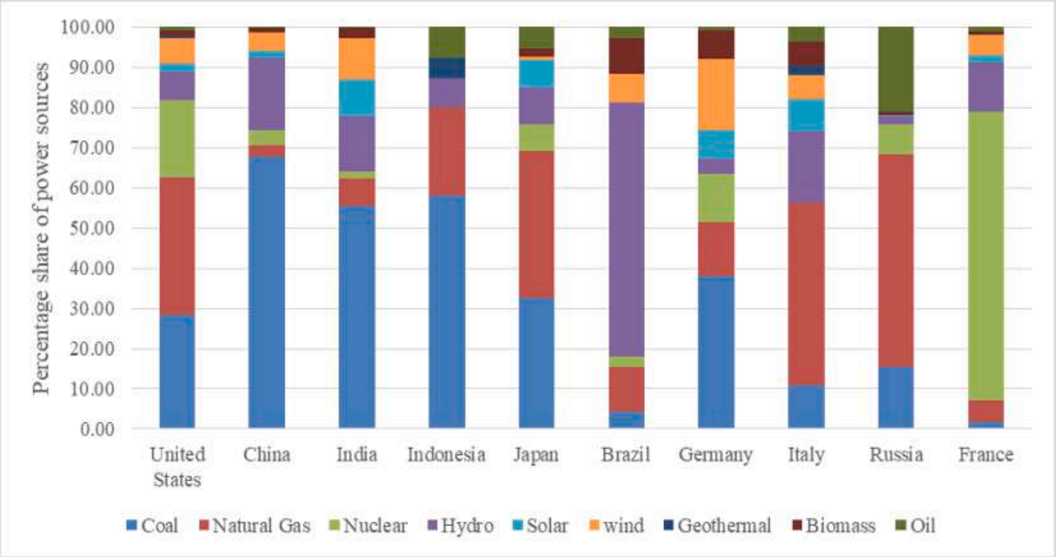

Fig. 9. Energy mix ratio of power sources.

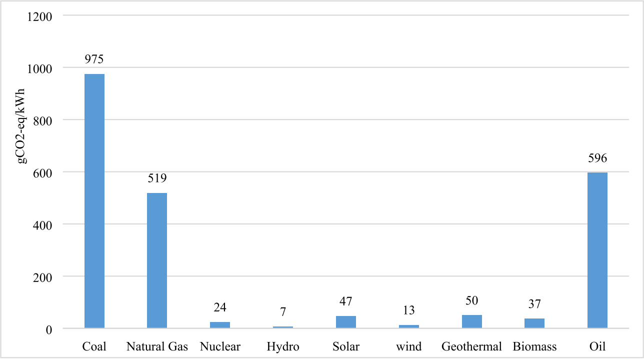

Fig. 10. Estimated average emission intensity of power generation source.

which generates fewer pollutants compared to coal and oil power generation. Brazil and France generate most of their electricity from hydro (63%) and nuclear (72%), respectively, making their energy grid clean and a low-carbon grid compared to other countries.

4.2. Grid emission intensity

In this study, various literature on life cycle assessment of all the power generation sources, i.e. coal, oil, hydro, nuclear, solar, wind, biomass, and geothermal, is reviewed for different periods and different countries. The literature gives a range of emission factors in terms of CO_2-eq, which indicates the effect of various pollutants in a single unit. The median value of emission factors, as obtained from Fig. 5 is considered for calculations moving forward.

Further, these estimated mean emission factors are used in calculating total grid emission intensity. The entire grid emission intensity is indicated in Fig. 10. Countries like France and Brazil have the cleanest grid of 70.75 gCO_2-eq/kWh and 127.39 gCO_2-eq/kWh, respectively among other countries. Russia, Japan, the United States, Germany, and Italy's total grid emission intensity is 543.44, 539.41, 466.37, 451.28, and 374 gCO_2-eq/kWh, respectively, which is considerably cleaner. Countries like China, Indonesia, and India have a total grid emission intensity of 714.45, 666.10, and 575.17 gCO_2-eq/kWh respectively, which is comparatively most polluted among these countries.Fig. 11.

In this study, the viability index for all the selected countries has been estimated, as indicated in Fig. 12. The result shows that the viability index for France and Brazil is between 0.25 and 0.50, which comes on a sustainably viable scale. Therefore, the implementation of electric vehicles in these countries will be able to eliminate at least 50% of their vehicular emissions. Italy's viability index lies between 0.5 and 0.75, which indicates that a minimum of 25% emissions can be eliminated. The viability index of the United States, Japan, Russia, and India comes between the ranges of 0.75–1.0, which indicates that the implementation of electric vehicles in these countries will be marginally viable. The implementation of EVs in these countries can effectively decrease 0–25% of total emissions from vehicles. However, the viability index of Japan, Russia, China, and India is nearer to 1.0, which indicates that even a slight increase of non-renewable sources in the energy mix of these countries may result in bringing them in the not viable category, making EVs insufficient in reducing emissions. According to this study, Indonesia already is in a not viable category. It indicates that the implementation of EVs will not be able to decrease vehicular emission; instead, the emission may increase, i.e., if the energy grid continues to be the same, with the transition to electric vehicles, the emissions will be shifted to power plants. As per the current scenario, in most countries, the power plants are usually located in the periphery of the city. But, with the rapid urbanization taking place, in the future, the probability of urban sprawl engulfing the city peripheries is very high. Hence, the shift in emissions to the fringes, due to electric vehicles' implementation, may adversely affect the residents' health. This is a topic of future research.

The results of the study in Fig. 13 indicate the emission variation according to the country when ICEV and EV are compared. The comparison shows that EV generates less CO_2-eq than conventional vehicles in all considered countries except Indonesia. But if we look into other emissions like SO_x and NO_x, they are higher. The SO_x emissions are much higher where coal power has a significant share like in India, Indonesia, China, and Germany.

5. Conclusion

In the present study, the implication viability index for electric vehicles has been developed for countries with the largest number of registered vehicles. Electric vehicles are being envisioned as a replacement for conventional vehicles to reduce emissions emanating from the transport sector, which is resulting in increased air pollution and degradation of air quality worldwide. The emission reduction potential of electric vehicles largely depends upon the source of power generation. All of the selected countries have mixed power generation sources in different shares, thus generating the need for assessing the viability of shifting to EVs. Several studies were reviewed for the life cycle assessment of all the power generation sources available in these countries. After that, the literature on the life cycle assessment of EV and ICEV

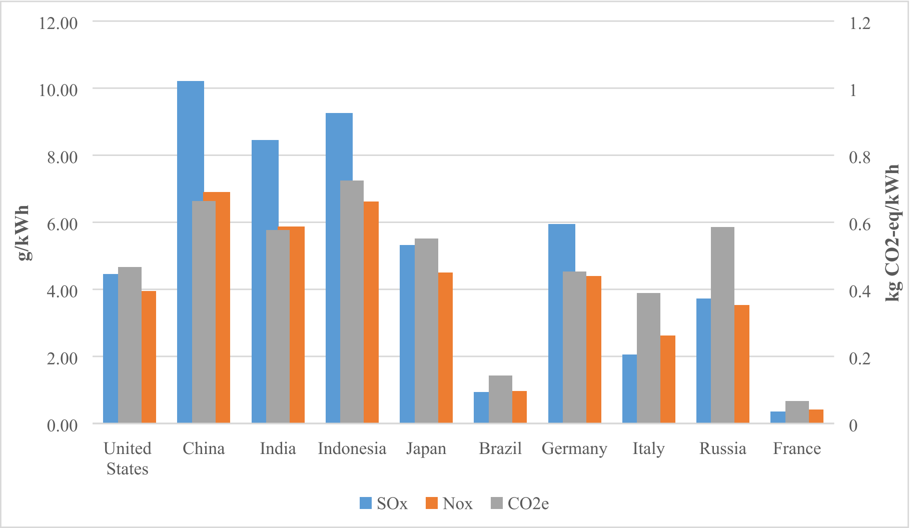

Fig. 11. Total energy grid emission intensity.

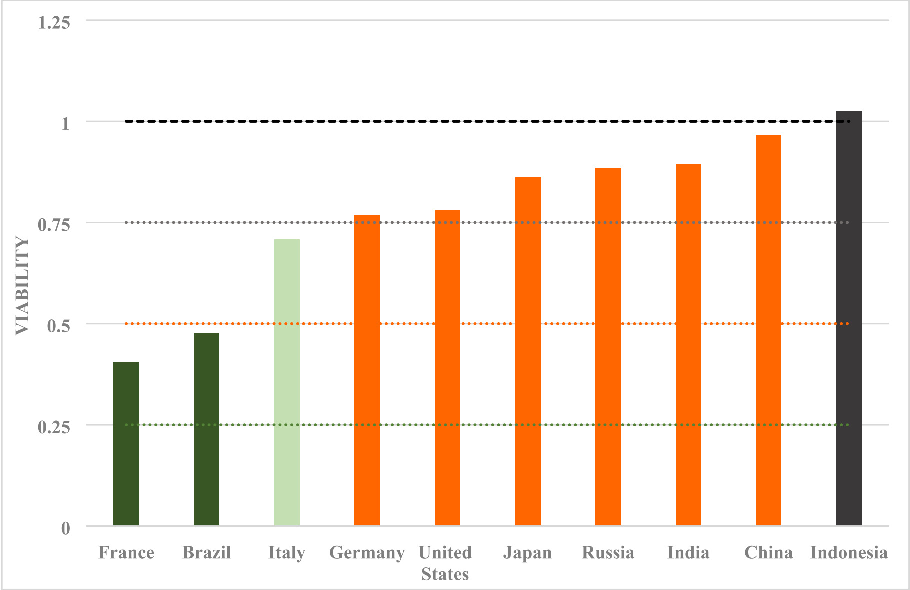

Fig. 12. Electric Vehicle Implication Viability Index.

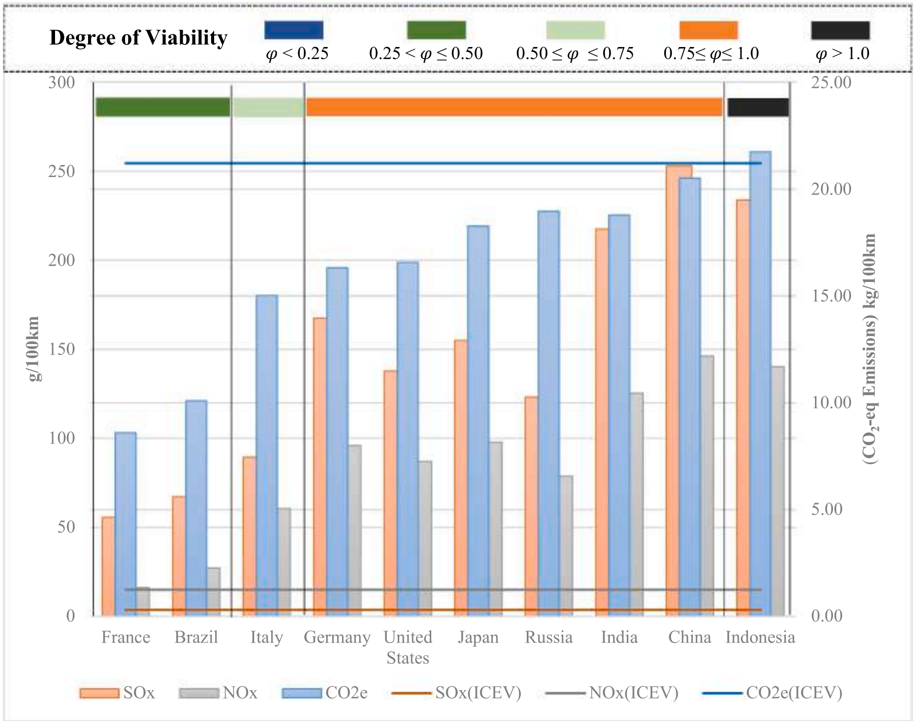

Fig. 13. Emission comparison of EV and ICEV for different countries.

were reviewed. The viability index is calculated by considering the GHG emission factor obtained from the various reviewed literature. The implication viability index of electric vehicle assessment for the abovesaid countries can be concluded with the following points:

- Brazil has the highest share of hydro-electricity in its power generation, whereas France has a high percentage of nuclear power energy. The involvement of both of these energy sources makes the power grid of these countries a clean energy grid. The viability index for Brazil and France lies in a sustainably viable category. Therefore, the implementation of electric vehicles in these two countries is considered to be the most effective among the selected countries. In both countries, EV implementation has the potential to reduce 50%-75% of vehicular emissions.
- Italy has a power grid with mixed power generation sources, where the primary source is natural gas, which is a low emission source. It has only 10% of coal power generation, and the rest are renewable sources. The viability index of the country lies between 0.5 and 0.75, considered a viable category, which has the potential to decrease 25–50% of vehicular emissions due to the shift to an electric vehicle.
- Germany, United States, Japan, Russia, China, and India have a significant share of fossil fuel in their power generation sources. The EV viability index of these nations lies in a marginally viable category. This category indicates that the implementation of electric

vehicles in these countries can reduce up to 25% of vehicular emissions. All of these nations need to focus on either maintaining the same grid mix ratio as present or improving the share of renewable energy to make a sustainable switch to EVs.

- Indonesia has a large share of coal in its power generation. The viability score is above 1, which indicates that the implementation of EVs in Indonesia is likely to be not viable. There will be a net increase in emissions, as on-road vehicular tailpipe emissions will reduce, but emissions at the power plant locations, situated in the peripheries of urban areas, will increase. As such, Indonesia should work towards improving their grid mix ratio in order to sustainably reap the benefits of implementing electric vehicles.

With the rapid urbanization taking place, the growth of vehicular traffic worldwide is also accelerating. This growth in vehicular population is resulting in increasing on-road vehicular emissions, ultimately affecting the air quality of the surroundings. Emissions from automobiles may not be the single most source of air pollution, but it is a significant contributor to the deteriorating air quality worldwide. With the increased emphasis on low carbon development and clean air in infrastructure planning, electrification of the transport sector is gaining popularity, and various nations are taking bold steps in this direction. Although the on-road vehicular emissions could be reduced with the adoption of electric vehicles, the indirect emissions taking place in the production of electricity at power plants may increase. In the future, with increasing urbanization, the probability of urban sprawl is high. Hence, the shift of emissions to the peripheries, where the power plants are currently situated, due to the implementation of electric vehicles is likely to affect residents' health living nearby. Hence, for the sustainable implementation of electric vehicles, it is vital to increase the share of renewable sources of power generation in the energy grid mix worldwide.

This study has estimated the implication viability of EV in various countries by assuming that the vehicle will be charged on the same grid ratio as of present. As a future scope, this methodology can be used to assess the impact of the implementation of electric vehicles for any particular nation, city, or region. This study has assessed the viability based on per unit vehicle. Furthermore, in future research to get a more realistic view, the forecasted number of electric vehicles can be used for viability assessment. Also, detailed energy modelling can be done by considering the share of electric vehicle's energy demand in total electricity consumption for the nation.

CRediT authorship contribution statement

Vikas Nimesh: Conceptualization, Writing - original draft, Methodology, Data curation. **Ranjana Kumari:** Methodology, Data curation, Writing - review & editing. **Neelesh Soni:** Data curation. **Arkopal K. Goswami:** Supervision, Writing - review & editing. **V. Mahendra Reddy:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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