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Abstract—Air pollution has led to global temperature increases and health hazards. Emission reduction is a global mission, and countries worldwide are working towards this goal. Transportation network electrification is a possible solution. Electrifying only transit systems will not have much impact without energy policy evolution and renewable source share enhancement. Since transportation needs rise with increasing population, emission intensity reduction steps should be implemented soon to affect global emission reduction. This work proposes reducing the share of vehicles with high per-passenger emissions and replacing them with mass transit systems under a generation scenario. It primarily establishes emission trends under the current vehicle scenario with only fossil fuel-burning vehicles and electric vehicle (EV) scenarios. It also considers different fuel mixes and finally compares all vehicle and fuel mix combinations. Results reveal that the proposed transport and fuel mix options help to reach the target set by India under the Paris Agreement.

1 INTRODUCTION

Air pollution has been a global concern for over 30 years, and the rapidly increasing air pollutant levels have resulted in air quality deterioration [1]. In 2018, countries such as India, Bangladesh, and many others worldwide recorded the lowest air quality [2]. The poor air quality due to air pollutants such as NO_x, SO_x, and particulate matter (PM) results in cardiovascular diseases and increases the risk of cancer [3]. In 2018, the World Health Organization (WHO) reported that air pollution resulted in six hundred thousand deaths every year [4]. The report further stated that the number of deaths in 2018 also included children under the age of 15 [4].

In addition to environmental health risks, one of the primary air pollutants, i.e., greenhouse gases (GHGs), also results in global warming [5]. In regard to GHG emissions, specifically CO₂, the highest growth was recorded in 2018 over the 2011 level [6]. The global CO₂ emissions in 2018 reached 55.6 Gt of CO₂, which is 43% higher than the 2000 level [6]. As a result of the increase in CO₂ emissions, in 2018, the warmest year was recorded in Europe, the Middle East, New Zealand, and parts of Asia [6]. Similarly, a report by the International Energy Agency (IEA) has revealed that India emitted 2,299 million tons of CO₂ in 2018 [7], which is 4.8% higher than the 2017 level [6].

Among the various sources of air pollution that cause health hazards and global warming, the transport sector accounts for 70% of the total air pollution [8]. An in-depth study has stated that 73% of the emissions from the transport sector are due to the combustion of the liquid fossil fuels used in motor vehicles [9]. In this regard, an emission report on European Union countries has indicated that the internal combustion engine (ICE) accounts for 77% of the total air pollutants [6]. Within this proportion of 77%, 50% is attributed to pollutants such as SO_x, NO_x, and PM, and the remaining 27% is attributed to CO₂. Similarly, in India, the emissions from ICE vehicles reached record levels among global megacities, and Delhi recorded the highest PM emissions [10].

It has been projected that the global motor vehicle population is expected to reach 2.6 billion by 2030 compared to 1.7 billion in 2020 [11], which translates to a 53% global vehicle population increase. The resultant emission estimate increases from 12,548 Mt in 2020 to 16,053 Mt in 2030 [12], which is 28% higher than the 2020 level. The conditions in India will be worse as the motor vehicle population is expected to increase by more than 84% [13], i.e., from 271 million in 2020 to 498 million in 2030. The corresponding emissions are projected to increase from 790 Mt in 2020 to 1,241 Mt in 2030, i.e., a rise of 57% over 10 years [12]. However, emissions will increase but not proportionally to the vehicle increase due to new emission regulations, such as the Bharat stage VI [14]. Emission regulations help to mitigate emissions to a certain extent, but these regulations are insufficient.

Addressing the issue related to the increase in vehicular emissions necessitates a paradigm shift towards an environmentally sustainable system. One way would be to electrify the urban transportation system (TS) and invest in mass public TSs. Countries worldwide have implemented electricity-based TSs, such as trams, metro rail systems, monorail systems, and trolleybuses [15-16], which have proved efficient in reducing city-level pollution [16]. In addition to trams and metros, electric buses (E-buses) have also been added to the list for reducing vehicular

emissions [17]. Countries such as the USA, and China have adopted battery-based electric vehicles (EVs) after successful trial runs in cities over a decade [18-19].

Similar to the battery-based E-bus, decision-makers in various nations have chosen to adopt plug-in and hybrid EVs. In this regard, these two EVs (plug-in and hybrid) have reached market shares of 29%, 6%, and 1.5% in Norway, the Netherlands, and China, respectively [20]. California, Japan, France, and Germany have followed the same trend of adopting plug-in EVs [21]. Apart from studies related to the adoption and promotion of EVs [22-23], studies have also focused on emission analysis [24]. Analysis results have revealed that the tailpipe emissions from EVs are lower than those from ICE vehicles. The well-to-tank emissions from EVs, on the other hand, are higher than those from ICE vehicles [25]. Studies [17] have investigated the sources of emissions in the case of EVs and have concluded that the source of electricity generation impacts the emissions from EVs.

In India, approximately 70% of its electricity generation comes from fossil fuel-based power plants [26], which are the major contributors to air pollution [17]. Hence, under the given energy generation scenario, the increasing penetration of EVs will lead to an increase in pollution from power plants. The Government of India (GoI) has plans to enhance electricity generation from renewable sources [27] to promote low-emission generation. Additionally, in 2015, India set a target of reaching GHG emissions 33% to 35% below the 2005 level under the Paris Agreement [28]. In this regard, the critical question that has to be addressed is, "Is it possible to meet the Paris Protocol by shifting to E-mobility, and if not, what needs to be addressed?"

Addressing the above question requires analysis of the impact of E-mobility on reducing the pollution from the transport sector. The analysis further necessitates a thorough study of the emissions under the present and future trends of vehicle and energy mix options. In this regard, the following subsidiary questions arise:

- a. What is the present road transport emission level?
- b. What is the projected target emission level?
- c. What is the energy generation mix used for electricity generation?
- d. What will be the impact of the efficiency change in the E-mobility system?
- e. If the vehicle mix changes, will this impact emissions?

The answers to the above subsidiary questions will help to analyze the present transport emissions, in terms of how far the current emission level is from the target emission level, how emissions depend on the energy mix, and what the possibilities are of reaching the target emission level. In this regard, a detailed emission analysis of the transport system is necessary, and the following are the emission analysis steps:

- Energy calculation for EVs to drive 1 km- this will help to evaluate the emissions from the generation of the required energy.
- Impact of system efficiencies on the required energy from the generating plant for the different EVs to drive 1 km- this will help to generate the emission projections under present and future trends (while generating the required energy), considering the improvement of the models of the subsystems used.
- Emission analysis under the following combinations:

Generating system scenarios- these will help to produce the emission projections from generating power plants based on the contribution of individual fuel mix options.

1. G-1, coal-dominant case: the present energy mix (NITI Ayog) whereby fossil fuel plants dominate.
2. G-2, RES-dominant case: the future energy mix pursued by India (NITI Ayog), where the share of RESs is greater.
3. G-3, proposed scenario: the assumed energy mix targeting the phasing out of coal by 2030.

Vehicle scenarios- these will help to evaluate the energy requirements of EVs based on the number of EVs on the road, and, hence, the emissions from generating the required energy.

1. V-1: vehicle mix considering the GoI target of reaching an EV proportion of 30% by 2030 [29].
2. V-2: assumed vehicle mix considering a 20% growth in EVs each year over five years.
3. V-3: assumed vehicle mix considering a 25% growth in EVs every five years.

Emission analysis of various combinations of the above generation and vehicle mix options is performed, and the results are compared to the target set under the Paris Agreement. The analysis results reveal that the combination of G-3 and V-3 delivers the best results. The work further analyses the characteristics of G-3 and V-3 by maximizing the number of buses (thereby eliminating an equivalent number of private vehicles), which indicates that this improves the emission projections. Thus, the work concludes that maximizing the mass transit system by reducing the number of passenger vehicles (cars and two-wheelers (TWs)) will impact emission reduction and help to reach the target sooner.

2 SYSTEM MODEL

A growing economy will result in transportation growth as well, and this will make meeting the Paris Agreement a challenge because the current TS is based entirely on fossil fuels. However, by judiciously re-engineering the TS and by changing the fuel mix used in a given country, it is possible to meet the targets set under the Paris Agreement. The judicious re-engineering of the TS essentially means that society has to move towards a public-based TS, and this has to be electrified. Mere electrification will not be sufficient because it also has to be ensured that the generation of electricity itself is environmentally friendly, sustainable, and predominantly RES-based. This raises the question of which fuel mix should be applied in India for sustainable electricity generation in addition to the kind of vehicles that should be adopted. In the following subsections, the above two questions will be systematically investigated. These subsections also sequentially answer the five subsidiary questions asked in the Introduction section.

2.1 Vehicle scenarios

The GoI has implemented measures for the reduction in emissions from the transport sector. One of these steps is to electrify the urban transit system [30]. In this regard, the GoI plans to reach an EV proportion of 30% by 2030 [29]. This subsection describes the current vehicle scenario and, based on the growth rate of vehicles, simulates future scenarios. These vehicle projections will help to determine the emissions under the various vehicle scenarios. The number of registered vehicles includes categories such as small commercial vehicles (SCVs), taxis, TWs, cars, small-goods vehicles (SGVs), large-goods vehicles (LGVs), and buses. The number of registered vehicles in India from 2001 to 2015 is obtained from reference [31]. From reference [31], it is observed that the total number of registered motor vehicles increased from approximately 57.28 million in 2000 to 120.69 million up to 2015. The aforementioned study also elaborated the composition of the registered vehicles and reported that SCVs, taxis, TWs, cars, SGVs, LGVs, and buses accounted for 2.58%, 1.37%, 75.71%, 13.32%, 2.48%, 1.98%, and 1.07%, respectively, of the total registered motor vehicles in India.

Since this work conducts an emission analysis from 2020-2040, an estimate of the number of registered vehicles is necessary. The evaluation of the estimated registered vehicles considers the growth rate trend of the registered number of vehicles (all ICE vehicles) (from 2001-2020) in India. The number of registered vehicles is obtained from the literature (2001-2020) [31], and the corresponding growth rate is evaluated and provided in Table 1 (Part A, pink shade). The growth rate of vehicles (except cars) shows a decreasing trend over time, although the rate of change in the growth rate is different for the different vehicles. From these numbers, it is concluded that the Indian population is moving towards private vehicle ownership. With a similar growth rate trend, the growth rate of vehicles from 2021-2040 is assumed and listed in Table 1 (Part A). Based on the assumed vehicle growth rate, Table 1 (part B) summarizes the estimated number of vehicles from 2021-2040 (business as usual (BAU)). The values in part B indicate that there has been a continuous increase in the number of registered motor vehicles in India. It is evident from these numbers that the registered motor vehicles will increase from approximately 153.75 million in 2020 to 209.58 million in 2040 [13].

Based on the estimated registered vehicles (all ICE), it is deduced that the emissions from these vehicles will increase in the future with increasing vehicles. In this regard, the GoI has designed initiatives to implement environmentally sustainable vehicle models (such as EVs). The GoI has set a target to reach an EV proportion of 30% of the total registered vehicles [29] by 2030. Considering the total registered vehicles (Table 1, part C) and the GoI target for EV implementation, part C describes the estimated vehicle scenario with the combination of ICE vehicles and EVs. This work generates estimated vehicle projections, assuming that the growth rate of EV penetration is 15% every five years. For the emission analysis of the different vehicle scenarios, this work assumes two more vehicle mixes as case scenarios. These case scenarios are the vehicle mixes considering the BAU state and the number of EVs increasing (a) at a rate of 20% every five years and (b) at a rate of 25% every five years. Hence, the vehicle scenarios in this work are as follows:

1. Vehicle mix considering the GoI target of 30% EVs by 2030 (Fig. 2(a))- V-1
2. Vehicle mix considering a 20% growth in EVs every five years (Fig. 2(a))- V-2
3. Vehicle mix considering 25% growth in EVs every five years (Fig. 2(a))- V-3

From the numbers in Fig. 2(a) derived from Table 1, part B, it is observed that V-2 represents the vehicle mix considering a 20% growth in the number of EVs every five years. Here, in case V-2, at this growth rate, the number of EVs will reach 40% of the total registered vehicles by 2030, i.e., 10% more than the GoI target. By 2040, the

TABLE 1: Growth rate, estimated registered vehicles in India (2020-2040) and vehicle scenarios for emission analysis

Part A- Growth rate (2001-2020) and projected growth rate (2021-2040) of the registered number of vehicles in India							
Year	SCVs	Taxis	TWs	Cars	SGVs	LGVs	Buses
2001 to 2005	10%	10.2%	13%	10.9%	8.26%	8%	8.88%
2006 to 2010	9.3%	9.8%	10.3%	11.24%	7.9%	9.8%	8.3%
2011 to 2015	8.8%	9.23%	9.1%	11.66%	7.5%	9.34%	7.8%
2016 to 2020	7.91%	8.52%	8.56%	11.7%	7.08%	8.90%	7.4%
2021 to 2025	7.23%	7.86%	7.69%	12.28%	6.65%	8.48%	7.02%
2026 to 2030	7.01%	6.89%	7.34%	12.98%	6.22%	8.09%	6.69%
2031 to 2035	6.81%	6.39%	7.17%	13.77%	5.79%	7.72%	6.41%
2036 to 2040	6.52%	5.94%	6.85%	14.69%	5.37%	7.37%	6.18%
Year	SCVs	Taxis	TWs	Cars	SGVs	LGVs	Buses
Part B- Number of vehicles (estimated) in India (in millions) (business as usual (BAU)) (all ICE)							
2020	4.00	2.33	120.19	18.32	3.58	3.68	1.66
2025	4.29	2.51	129.63	20.57	3.82	3.99	1.78
2030	4.59	2.68	139.15	23.24	4.06	4.32	1.90
2035	4.90	2.85	149.12	26.44	4.29	4.65	2.02
2040	5.22	3.02	159.34	30.34	4.52	4.99	2.14
Part C- Energy required at the plug point by EVs to drive 1 km (without AC) (kWh)							
Particulars	SCVs	Taxis	TWs	Cars	SGVs	LGVs	Buses
Rolling resistance	0.27	0.34	0.25	0.36	0.42	1.23	1.14
Aerodynamic force	0.086	0.097	0.068	0.08	0.12	0.17	0.14
Acceleration resistance	1.58	1.71	1.47	1.87	1.88	6.49	6.49
Energy recovered during braking	0.72	0.75	0.69	0.81	0.79	2.23	2.26
Energy required to travel 1 km (EV(km)) at the plug point	0.27	0.31	0.24	0.33	0.36	1.25	1.22
Part D-Annual energy required by the EVs from the generating station in case V-1 (TWh)							
Year	SCVs	Taxis	TWs	Cars	SGVs	LGVs	Buses
2020	0.45	0.19	4.50	1.33	0.75	3.88	1.31
2025	7.05	3.03	71.03	21.94	11.76	61.69	20.61
2030	14.57	6.26	147.37	47.93	24.14	128.93	42.51
2035	22.82	9.78	231.61	80.03	37.48	203.76	66.39
2040	32.12	13.68	325.78	121.11	52.14	288.58	92.95

number of EVs will reach 80% of the total registered vehicles (BAU level) in the case of V-2. In case V-3, the number of EVs will reach 50% of the total registered vehicles by 2030 (20% more than the GoI target) and 100% of the total registered vehicles by 2040.

In summary, this subsection presented the different vehicle scenarios for the emission analysis representing the BAU state and estimated projections to reach the GoI EV target. Since the generation source impacts the emissions from EVs, it is important to analyze various generation scenarios in India.

2.2 Energy generation scenarios

Presently, 70% of the electricity is generated by coal power plants [26], although India has plans to consider renewable sources for electricity generation in the future [27]. The GoI has developed various models to promote energy generation from renewable energy sources (RESs) [32] to reduce emissions and reduce the dependency on fossil fuels [33]. Based on these models, this work considers two generation scenarios: coal-dominant (the present generation mix) and RES-dominant scenarios (based on the GoI model to promote RESs). The total energy generation demand (estimated) is also retrieved from the literature and is as follows: 2020-1213 TWh; 2025-1377 TWh; 2030-1645 TWh; 2035-1912 TWh; and 2040-2185 TWh [28].

Fig. 1 (a) shows the coal-dominant case, and the bar graph shows the percentage contribution of each fuel mix to the total energy generation. Thus, Fig. 1 (a) shows the energy generation percentage from 2020-2040 with coal dominating. The contribution of coal-based power plants to the net energy generation is the highest under this scenario. However, the contribution from coal from 2025-40 decreases at a low rate from that in 2020. Since coal-based power plants contribute the most to atmospheric emissions, this case will help to study the worst-case scenario

in terms of environmental pollution.

Fig. 1: (a) Generation scenarios: Coal dominant (current generation scenario of India), RES dominant (plan according to the planning commission, India), NEW scenario, which represent the G-1, 2, and 3 respectively. These further represent the contribution of each fuel mix and how it varies through the years in case of these scenarios. (b) System model of the EV representing the energy pathway of the system from well to wheel. The model shows the subsystems used for energy flow, where the efficiency of the subsystems helps to calculate the energy requirements of the EV system.

Similarly, Fig. 1 (b) shows the energy generation percentage from 2020-2040 with RESs dominating energy generation. Careful observation reveal that in comparison to the coal-dominant case, the contribution of RESs is growing in this case. Additionally, the contribution from coal from 2025-40 decreases at a higher rate over that in

2020. The changes in the generation scenario will impose an impact on emission reduction from power generation. In terms of emissions, RESs are eco-friendly sources of energy, and hence, the emission analysis of this scenario will present the best-case scenario.

Though comparing both these energy generation scenarios, the contribution of coal-based plants exceeds those of the other systems even in the RES-dominant case. Hence, the impact on emission reduction by shifting to the RES-dominant case might not be sufficient. A special report on global warming considering an increase of 1.5°C by the Intergovernmental Panel on Climate Change (IPCC SR 1.5) has suggested that the contribution of coal should be reduced to 80% below the 2010 contribution by 2030, and coal should be phased out before 2040 [34]. In this regard, assuming that India will phase out coal by 2040 and extensively use RESs (solar energy), a generation mix is considered for the emission calculations. Fig. 1 (c) shows the assumed generation mix named the NEW scenario.

Thus, this subsection elaborates on the energy mix used for the emission analysis in this work. The next subsection presents the energy requirements and the factors that influence these energy requirements.

2.2.1 Energy requirements of the EVs

The various energy generation scenarios and analysis will help to project emissions in case policymakers suggest EV implementation. Evaluating the emissions under the various vehicle and energy mix scenarios requires evaluation of the energy requirements of EVs. In this regard, it is necessary:

1. To analyze the energy generation mix, which will help compute the emission projections (from the well).
2. To analyze the energy requirements of EVs to evaluate the emissions (from the tank).

The earlier subsection has presented the energy generation projections to evaluate point number 1. This section shows the energy requirements of the different EVs and the factors influencing the energy requirement of these vehicles. The energy pathway of the EV is necessary to evaluate the energy required. Therefore, Fig. 1 (d) shows the well-to-wheel energy flow pathway of the EV system. The model indicates the subsystems used for energy flow, and these subsystems are numbered to represent the pathway of energy flow. The energy calculation involves two steps:

1. Calculation of the energy required by a vehicle to drive 1 km.
2. Calculation of the energy required from the generating plant to ensure the energy needed (to drive 1 km) at the plug point.

Calculation of the energy required by the vehicle to drive 1 km:

The parameters that are necessary for the calculation are the driving pattern (in terms of the average speed and traffic pattern) and the vehicle specifications (applied in the motion model to determine the work done to travel 1 km).

The Methods section provides details of the above calculations performed for all vehicle categories. Moreover, the following energy calculation assumptions apply:

- The values in Table 2 (part A) are calculated for the different vehicles using various resistive forces (equations 1-5 in the Methods section).
- The work considers the driving pattern [35] of a tier-II city in India for the energy calculations.

Table 1 (Part C) summarizes the energy required by an EV to drive 1 km, and the energy calculations consider non-AC EVs. Based on the values in the table, it is observed that the energy requirements vary for the different vehicles. The values also reveal that the energy requirements of TWs are the lowest, and those of LGVs are the highest, which indicates that the energy required depends on the vehicle size/weight.

Calculation of the energy required from the generating plant to ensure the energy needed (to drive a vehicle 1 km) at the plug point:

The calculation steps to evaluate the energy obtained from the generating plant rely on the subsystem efficiency in the system model (Fig. 1 (b)). The equations used for the calculation are provided in the Methods section, and the corresponding analysis from 2020-2040 is summarized in Table 1 (Part D).

The system efficiency η_1 includes the efficiency of the various subsystems (from the charging station to the EV). The subsystem efficiencies are obtained from reference [36-40]. As efficiency values are available for recent years only, the values remain the same throughout the study period. The transmission and distribution efficiency (T&D efficiency), η_2 , is obtained from references [41-43]. The GoI has implemented initiatives to mitigate the T&D losses, and the literature have shown that the GoI has launched programs to lower the T&D losses at present and in the future. Hence, η_2 varies from 2020 to 2040 and indicates that efficiency increases over time.

Fig. 2: (a) Total registered number of vehicles (ICE+EV) for vehicle scenarios V-1, 2, and 3. (b) Annual energy required from the generating station by the EVs in case of V-1, 2, and 3. (c) Total emissions for the fuel mix G-1 in the case of V-1, 2, and 3. (d) Total emissions for the fuel mix G-2 in the case of V-1, 2, and 3. (e) Total emissions for the fuel mix G-3 in the case of V-1, 2, and 3. The total emissions represent the emission caused by the energy mixes of that respective generation scenario.

Fig. 2 (b) shows the total energy required from the generating plant by the EVs under the three vehicle mixes of V-1, V-2, and V-3, respectively. The numbers in Fig. 2 (b) are derived from the portion of Table 1 (parts C, and D respectively). The evaluation of the annual energy required by the EVs relies on equation 8 (Methods section), which calculates the average distance traveled by an EV in a day (D). The D value is different for the different vehicles, such as 64 km for SCVs, 41 km for taxis, 24 km for TWs, 34 km for cars, 90 km for SGVs, 164 km for LGV, and 100 km for buses [44]. Shifting towards EVs will necessitate higher energy demand, and the numbers in the table also support this. However, comparing the aggregate energy requirements for all the vehicles to the total energy generation reveals that the former falls within the generation limits of India.

Thus, this subsection discusses the energy requirements of EVs, which is later employed for the emission calculations. The next subsection briefly discusses the emission analysis of the EV system.

2.3 Emission analysis

The emissions from EVs include well-to-tank emissions (since EVs are known for their zero tailpipe emissions). Hence, for the emission analysis of EVs, an energy requirement study of EVs is essential and is presented in the earlier subsection. This subsection presents the emission analysis for the following categories:

1. Emissions under vehicle scenario G-1 considering generation scenarios V-1, V-2, and V-3.
2. Emissions under vehicle scenario G-2 considering generation scenarios V-1, V-2, and V-3.
3. Emissions under vehicle scenario G-3 considering generation scenarios V-1, V-2, and V-3.

The emission analysis is conducted from 2020-2040, and the various vehicle and generation scenarios from 2020-2040 are described in earlier subsections. The emissions from ICE vehicles are based on BS-6 norms [14].

The results in Fig. 2 (b-d) reveal the total emissions from the registered vehicles under the three vehicle mixes (V-1, 2, 3) and fuel mixes (G-1, 2, and 3). The numbers in Fig. 2 (b-d) are evaluated from portions of Tables 1 and 2. The following are the observations from the numbers provided in Fig. 2 (b-d):

1. The emissions from ICE vehicles are independent of the generation scenarios (G-1, G-2, and G-3).
2. The emissions from EVs in 2020 do not change/improve much by the generation scenarios. The reason is that the generation mix under these scenarios is similar to that in 2020. In addition, the number of EVs is very small and, therefore, does not greatly affect the emission analysis.
3. From 2025 onwards, the impact of the generation scenarios becomes more notable, and the NEW scenario extensively uses RESs. Hence, the emissions, in this case, are much lower than those in the remaining two cases.
4. The emissions from EVs increase with the increasing number of EVs from 2025 to 2035. However, in 2040, the emissions from EVs have decreased from the 2035 level (though the number of EVs has increased).
5. Additionally, the difference in emissions (from EVs) from 2030-35 is smaller than that from 2030-25. This may occur because the growth in vehicles, as well as in emissions, decreases over time.

The primary observations from Fig. 2 (b-d) indicate that the emissions from ICE vehicles decrease over time because of the implementation of upgraded models and the reduction in the number of vehicles. Compared to vehicle scenarios V-1 and V-2, vehicle scenario V-3 constitutes a high penetration of EVs. Based on Fig. 2 (b-d), the total emissions (ICE+EV) in 2040 under G-1 and G-2 are higher in case V-3 than those in cases V-1 and V-2. Moreover, the total emissions in 2040 under G-3 decrease with the vehicle scenario, i.e., lower in V-2 and V-3 (from the V-1 level).

The emission projections depicted in Fig. 3 (a, b, c) further elaborate on the emission analysis. The emission projections in Fig. 3 are compared to the Paris Protocol emission target. The Paris Protocol emission target is depicted as a baseline for all emission categories as shown in Fig. 3. Fig. 3 (a) shows the emissions to reach the GoI EV target, i.e., vehicle mix V-1, where the number of EVs increases by 15% every five years. The total emissions under G-1 and G-2 do not intersect the baseline, and G-3 intersects the baseline approximately in 2040.

Fig. 3 (b) shows the emissions under vehicle mix V-2, where the number of EVs increases by 20% every five years. G-3, in this case, intersects the baseline in 2037. Similarly, Fig. 3 (c) shows the emissions under vehicle mix V-3, where the number of EVs increases by 25% every five years. The emissions under G-3 intersect the emission baseline in 2035. Fig. 3 (a, b, c) reveal that the emissions under G-1 and G-2 increase from 2020 onwards due to the increasing number of vehicles (not much change in the energy mix though). Under G-3, the emissions increase up to 2025 for the same reason as under G-1 and G-2. However, the emissions under G-3 gradually decrease thereafter, which reveals the impact of the notable reduction in the fossil fuel contribution to the energy mix.

Further, close observation of these graphs (Fig. 3 a, b, and c) indicates that cases G-1 and G-2 are incapable of reaching the target set under the Paris Protocol. The total emissions under G-3 in cases V-1, V-2, and V-3 intersect the emission baseline only after 2035. V-3 reaches the target the earliest in 2035 under G-3, and a few more characteristic changes in the vehicle mix, in this case, may help to assess whether it could impose greater impacts on emission reduction.

2.4 Impact of the change in vehicle mix under V-3

Among the emissions under V-1, V-2, and V-3 considering fuel mixes G-1, G-2, and G-3, the emissions under V-3 and G-3 reach the emission baseline the earliest in 2035. Hence, a further change in vehicle mix V-3 might result in a greater emission reduction. This subsection elaborates on the impact of the changes in vehicle composition under V-3. The basis of the change in composition is as follows:

1. From the registered vehicle growth rate and composition, it is evident that the percentage contribution of TWs and cars is greater than that of buses. The reason is that people opt to shift more towards private vehicles than towards public transport.
2. The passenger capacity of buses is higher than that of both TWs and cars, and based on the evaluations done, the numbers reveal that the energy requirements of TWs and cars are higher than those of buses. Therefore, one might

Fig. 3: (a) Emissions under V-1 and for the generation scenarios G-1, 2, and 3 with the baseline (the Paris Protocol target). (b) Emissions under V-2 for the generation scenarios G-1, 2, and 3 with the baseline (the Paris Protocol target). (c) Emissions under V-3 for the generation scenarios G-1, 2, and 3 with the baseline (the Paris Protocol target). (d) Characteristics of V-3 and G-3 towards the emission reduction target.

conclude that the per-passenger energy requirements of cars and TWs are much higher than those of buses.

Hence, an essential conclusion from the above is that private vehicles will result in higher energy consumption provided that India implements steps to shift towards EVs. In the case that policymakers design a vehicle composition shifted more towards public transport, replacing TWs and cars with an equivalent number of buses might produce major results. This work, therefore, assumes replacement levels of 3% and 5% of TWs and cars, respectively, with an equivalent number of buses.

The reason for considering these specific percentages is that the impact imposed by the change in the resultant number should reflect the results for the maximum possible change given the maximum vehicle production. This work, therefore, calculates the projected growth rate in both these cases and the resultant number of vehicles, as listed in Table 2. The numbers reveal that as a result of replacing TWs and cars, the growth rate of TWs and cars decreases (compared to the numbers provided in Table 1) while that of buses increases. The impact of these changes on the energy requirements also shows that although the energy requirements of buses increase (compared to the data in Fig. 2), the per-passenger energy requirements of buses remain lower than those of TWs and cars.

Fig. 3 (d) shows the emission analysis results for these two characteristics. The graph in Fig. 3 (d) shows that in the case of a 3% replacement of cars and TWs (with an equivalent number of buses) every five years, the target could be met by 2034. However, replacing cars and TWs at 5% (with an equivalent number of buses) every five years meets the goal by 2032 (approximately). Thus, it can be concluded that maximizing the mass transit system by reducing the passenger vehicles (cars and TWs) will impact emission reduction and help to reach the target sooner.

TABLE 2: Projected growth rate, number of vehicles, and annual energy required for the change in vehicle composition under V-3.

Part A-Projected growth rate(2021-2040)in the case of a 3% replacement of cars and TWs														
Year	SCVs		Taxis		TWs		Cars		SGVs		LGVs		Buses	
2021 to 2025	7.23%		7.86%		4.86%		9.33%		6.65%		8.48%		18.07%	
2026 to 2030	7.01%		6.89%		4.31%		9.89%		6.22%		8.09%		16.33%	
2031 to 2035	6.81%		6.39%		4.40%		10.86%		5.79%		7.72%		15.79%	
2036 to 2040	6.52%		5.94%		3.47%		11.89%		5.37%		7.37%		14.39%	
Part B- Projected growth rate (2021-2040) in the case of a 5% replacement of cars and TWs														
2021 to 2025	7.23%		7.86%		2.47%		6.67%		6.65%		8.48%		22.33%	
2026 to 2030	7.01%		6.89%		1.69%		7.03%		6.22%		8.09%		21.48%	
2031 to 2035	6.81%		6.39%		1.22%		7.45%		5.79%		7.72%		19.00%	
2036 to 2040	6.52%		5.94%		0.57%		8.00%		5.37%		7.37%		18.71%	
Part C- Resultant number of vehicles in the case of a 3% replacement of cars and TWs														
Year	SCVs		Taxis		TWs		Cars		SGVs		LGVs		Buses	
	ICE	EV	ICE	EV	ICE	EV	ICE	EV	ICE	EV	ICE	EV	ICE	EV
2020 (ICE-99%, EV-1%)	3.96	0.04	2.30	0.02	118.98	1.20	18.14	0.18	3.54	0.04	3.64	0.04	1.64	0.02
2025 (ICE-75%, EV-25%)	3.22	1.07	1.88	0.63	94.52	31.51	15.02	5.01	2.86	0.95	2.99	1.00	1.47	0.49
2030 (ICE-50%, EV-50%)	2.29	2.29	1.34	1.34	65.73	65.73	11.01	11.01	2.03	2.03	2.16	2.16	1.14	1.14
2035 (ICE-25%, EV-75%)	1.23	3.68	0.71	2.14	34.31	102.93	6.10	18.30	1.07	3.22	1.16	3.49	0.66	1.98
2040 (ICE-0%, EV-100%)	0.00	5.22	0.00	3.02	0.00	142.00	0.00	27.30	0.00	4.52	0.00	4.99	0.00	3.02
Part D- Resultant number of vehicles in the case of a 5% replacement of cars and TWs														
Year	SCVs		Taxis		TWs		Cars		SGVs		LGVs		Buses	
	ICE	EV	ICE	EV	ICE	EV	ICE	EV	ICE	EV	ICE	EV	ICE	EV
2020 (ICE-99%, EV-1%)	3.96	0.04	2.30	0.02	118.98	1.20	18.14	0.18	3.54	0.04	3.64	0.04	1.64	0.02
2025 (ICE-75%, EV-25%)	3.22	1.07	1.88	0.63	92.36	30.79	14.66	4.89	2.86	0.95	2.99	1.00	1.52	0.51
2030 (ICE-50%, EV-50%)	2.29	2.29	1.34	1.34	62.61	62.61	10.46	10.46	2.03	2.03	2.16	2.16	1.23	1.23
2035 (ICE-25%, EV-75%)	1.23	3.68	0.71	2.14	31.69	95.06	5.62	16.86	1.07	3.22	1.16	3.49	0.73	2.20
2040 (ICE-0%, EV-100%)	0.00	5.22	0.00	3.02	0.00	127.47	0.00	24.27	0.00	4.52	0.00	4.99	0.00	3.48
Part E- Annual energy required by EVs from generating stations in the case of a 3% replacement of cars and TWs (TWh)														
Year	SCVs		Taxis		TWs		Cars		SGVs		LGVs		Buses	
2020	0.45		0.19		4.50		1.33		0.75		3.88		1.31	
2025	11.74		5.05		115.09		35.61		19.60		102.81		36.99	
2030	24.28		10.43		232.03		75.66		40.23		214.88		82.60	
2035	38.04		16.30		355.26		123.09		62.47		339.60		137.01	
2040	53.54		22.80		483.88		181.59		86.89		480.96		206.57	
Part F- Annual energy required by EVs from generating stations in the case of a 5% replacement of cars and TWs (TWh)														
Year	SCVs		Taxis		TWs		Cars		SGVs		LGVs		Buses	
2020	0.45		0.19		4.50		1.33		0.75		3.88		1.31	
2025	11.74		5.05		112.46		34.74		19.60		102.81		39.27	
2030	24.28		10.43		221.04		71.90		40.23		214.88		92.20	
2035	38.04		16.30		328.11		113.37		62.47		339.60		161.05	
2040	53.54		22.80		434.38		161.45		86.89		480.96		252.11	

The starting question was: can India meet the emission target set under the Paris Protocol. The answer is that to meet the set target, it is necessary to adopt a vehicle mix consisting of more than 60% of vehicles such as EVs and a fuel mix extensively using RESs. Phasing out all fossil fuel-based energy generation is a challenge as currently, the contribution of fossil fuels to energy generation is greater than 60%. However, this will create new opportunities for job growth and clean energy. Moreover, this is a matter of policy in terms of how countries formulate strategies so that the above transportation and power generation conditions can be met.

3 METHOD

This section includes a detailed description of the EV system model and mathematical steps involved in the entire analysis conducted in this work. The system model helps to identify the energy flow path (from well to wheel), and by identifying the subsystems and efficiencies of the system, the energy requirements of EVs can be calculated. The energy requirements and emissions from the generation plant to produce the energy required will help to study the emissions from EVs. The subsections below describe the system model, vehicle scenarios, energy calculation steps, and a mathematical model to analyze the emissions.

3.1 System model

This subsection elaborates on the system model adopted to identify the subsystems involved in the energy pathway of EVs and thus evaluate their emissions. Fig. 1 (d) shows the EV system model, including the generating power plant, transmission system, distribution system, charging station, and EV. The details of each subsystem of the system model are as follows:

Power plant: The electric energy generation of India includes the generation from a fuel mix (coal, oil, gas, nuclear energy, hydro-energy, and RESs). This work presents the contribution of the fuel mix of 2020 to the emissions in 2040 and under the various scenarios.

Transmission and distribution: The electric grid in this work involves a section of the actual electrical distribution network of a typical tier-II city in India. The electricity grid constitutes 320, 220, and 132-kV feeders, and the distribution side has a 33-kV substation with 11-kV outgoing feeders. These substations supply electricity to both 11-kV and 440-V (11-kV/440-V) systems.

Charging station: The charging station comprises a rectifier, high-capacity battery, inverter, and charger. An 11/0.44-kV transformer feeds each charging station, and the electric energy thus received is stored in the high-capacity battery. The stored energy in the battery is later used to charge EVs. This work focuses on the environmental impacts of EVs, and therefore, it does not describe the corresponding specifications.

The following assumptions are considered:

1. The work does not consider detailed models of the subsystems (transformer, rectifier, inverter, and motor). For example, it does not consider the pulse-width modulation (PWM) scheme of the inverter nor the entire electromagnetic model of the transformer. Detailed models are necessary to analyze a dynamic system model but are not essential for energy flow analysis.
2. The battery module installed at the charging station is charged by the grid during grid off-peak hours. As the grid of Indian cities is already weak due to the increasing demands, battery charging during grid off-peak hours will not further stress the grid with the TS demand.
3. The efficiencies of the subsystems have been obtained from the literature along with their technological developments.
4. The energy pathway presented herein spans from well to wheel. The work has not considered the path for fuel to reach the generating power plant.

Thus, this subsection elaborates on the system, and the following subsection examines the vehicle scenario considerations.

Vehicle scenarios:

The registered number of vehicles from 2001 to 2020 is retrieved from the literature [31], and the growth rate of each vehicle type from 2001-2020 is calculated by:

$$N_{RV}^y = N_{RV}^{(y-1)}(1 + \%G_r) \quad (1)$$

where N_{RV}^y is the number of registered vehicles for a given year, $N_{RV}^{(y-1)}$ is the number of registered vehicles in the previous year, and $\%G_r$ is the growth rate of individual vehicles. The work considers the growth rate trend from 2001 to 2020 and assumes the growth rate from 2021-2040 to calculate the estimated number of vehicles in this interval. The GoI has set a target to reach an EV share of 30% by 2030. Based on this target, this work considers three vehicle scenarios as follows:

1. A 15% growth in EVs after every five years,
2. A 20% growth in EVs after every five years, and
3. A 25% growth in EVs every five years.

The number of vehicles under the three vehicle mixes is calculated by using equation 1 for the period of 2020-2040, and the results are listed in Table 1 (parts C, D, and E, respectively). The next section elaborates on the energy calculation steps.

Energy requirements:

The energy calculation for EVs involves two steps:

1. Energy calculations to determine the energy required to drive vehicles 1 km.

The steps include calculating the work conducted against the resistive forces [35] as follows:

a. Rolling resistance

$$F_{(ro)} = f_r \times Mg \quad (2)$$

where M is the mass of the vehicle, g is the gravitational acceleration constant, and f_r is the rolling resistance coefficient.

b. Aerodynamic resistance

$$F_{(ae)} = \frac{A_f C_d \rho V^2}{2} \quad (3)$$

where ρ is the density of air, A_f is the frontal area of the vehicle, C_d is the drag coefficient, and V is the velocity of the vehicle.

c. Acceleration resistance

$$F_{(ac)} = \alpha M \frac{dv}{dt} \quad (4)$$

where α is the rotational inertia constant, M is the mass of the vehicle, and dv/dt is the acceleration of the vehicle. Evaluating the work conducted against the resistive forces, the work achieved by the prime mover is calculated by:

$$workdone(W_A) = \int f(ds) = \sum (f)_j (d)_j \quad (5)$$

where f is the force, and ds is the distance. Now, the total energy required to travel 1 km can be calculated by:

$$E_{EV(km)} = W_A - W_B \quad (6)$$

where W_B is the energy recovered during braking. This work considers that 30% of the kinetic energy in braking is recovered by regenerative braking [15]. $E_{EV(km)}$ is calculated and provided in Table 2 (part A).

2. The energy required from the generating plants to drive EVs

Considering the energy needed by a vehicle to drive 1 km, the amount of energy that should be generated can be calculated by the following:

$$E_{EVGP} = \frac{E_{EV(km)}}{(\eta_1 \times \eta_2)} \quad (7)$$

where E_{EVGP} is the energy required from the generating plant to drive 1 km (Table 2, part B), $E_{EV(km)}$ is the energy required by the EV to drive 1 km, η_1 is the T&D efficiency, and η_2 is system efficiency. Furthermore, the evaluation of the annual energy required by the EVs from the generating plant is:

$$E_{EV(annual)} = E_{EVGP} \times 365 \times D \quad (8)$$

where $E_{EV(annual)}$ is the total annual energy required by EVs from the generating plant, and D is the average distance traveled by EVs per day.

The work also elaborates on the impact on emissions when the ratio of vehicles under vehicle mix V-3 (which provides better results) changes. It considers replacing cars and TWs with buses via the following expressions:

$$x = \frac{E - bus_{AO}}{TW_{AO}} \quad (9)$$

$$z = \frac{E - bus_{AO}}{Car_{AO}} \quad (10)$$

where x is the number of TWs replaced by one E-bus, $E - bus_{AO}$ is the average occupancy of an E-bus, which is equal to 50 [112], and TW_{AO} is the average occupancy of a TW, which is equal to 1.5 [112]. Similarly, z is the number of cars replaced by one E-bus, and Car_{AO} is the average occupancy of a car, equal to 3.18 [112]. Thus, evaluating these values in the equation results in an x value equal to 33 and a z value equal to 16. Hence, one E-bus replaces 33 TWs and 16 cars.

Emission calculation:

The work analyzes the emissions from EVs, and since the tailpipe emissions are zero in the case of EVs, the emission calculation is performed to determine the electric energy required to drive EVs. Considering $E_{EV(GP)}$, the emission from the generating plant is:

$$EM_{GP} = \sum (EM_{CO_2(FM)} + EM_{NO_x(FM)} + EM_{SO_x(FM)} + EM_{PM_{2.5}(FM)}) \quad (11)$$

where EM_{GP} are the total emissions from the generating plants to generate the energy required to drive a vehicle 1 km, and $EM_{CO_2(FM)}$, $EM_{NO_x(FM)}$, $EM_{SO_x(FM)}$, and $EM_{PM_{2.5}(FM)}$ are the CO_2 , NO_x , SO_x , and $PM_{2.5}$ emissions, respectively, from the fuel mix. The levels of these emissions can be calculated as follows:

$$EM_{CO_2FM} = E_{EVGP} \times \%_{GFM} \times EM_{CO_2FM}^{kWh} \quad (12)$$

$$EM_{SO_xFM} = E_{EVGP} \times \%_{GFM} \times EM_{SO_xFM}^{kWh} \quad (13)$$

$$EM_{NO_xFM} = E_{EVGP} \times \%_{GFM} \times EM_{NO_xFM}^{kWh} \quad (14)$$

$$EM_{PM_{2.5}FM} = E_{EVGP} \times \%_{GFM} \times EM_{PM_{2.5}FM}^{kWh} \quad (15)$$

where E_{EVGP} is the energy generated by power plants to drive a vehicle 1 km, $\%_{GFM}$ is the percentage generated from the fuel mix, and $EM_{CO_2FM}^{kWh}$, $EM_{SO_xFM}^{kWh}$, $EM_{NO_xFM}^{kWh}$, and $EM_{PM_{2.5}FM}^{kWh}$ are the CO_2 , NO_x , SO_x , and $PM_{2.5}$ emissions, respectively, when producing 1 kWh from the fuel mix. The baseline of the total emissions from the transit system is:

$$TS_{T_{EM_{bl}}} = AnnualT_{EM(dieselin2005)} \times (1 - 0.33) \quad (16)$$

where $AnnualT_{EM(dieselin2005)}$ are the annual total emissions in 2005 [111], and $TS_{T_{EM_{bl}}}$ is the emission level that India has to reach by 2030 under the target set. Moreover, this work considers the following assumptions to determine the baseline: by 2030, India aims to realize a 33% to 35% CO_2 emission intensity from the 2005 level.

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Figures

Figure 1

(a) Generation scenarios: Coal dominant (current generation scenario of India), RES dominant (plan according to the planning commission, India), NEW scenario, which represent the G-1, 2, and 3 respectively. These further represent the contribution of each fuel mix and how it varies through the years in case of these scenarios. (b) System model of the EV representing the energy pathway of the system from well to wheel. The model shows the subsystems used for energy flow, where the efficiency of the subsystems helps to calculate the energy requirements of the EV system.

Figure 2

(a) Total registered number of vehicles (ICE+EV) for vehicle scenarios V-1, 2, and 3. (b) Annual energy required from the generating station by the EVs in case of V-1, 2, and 3. (c) Total emissions for the fuel mix G-1 in the case of V-1, 2, and 3. (d) Total emissions for the fuel mix G-2 in the case of V-1, 2, and 3. (e) Total emissions for the fuel mix G-3 in the case of V-1, 2, and 3. The total emissions represent the emission caused by the energy mixes of that respective generation scenario.

Figure 3

(a) Emissions under V-1 and for the generation scenarios G-1, 2, and 3 with the baseline (the Paris Protocol target). (b) Emissions under V-2 for the generation scenarios G-1, 2, and 3 with the baseline (the Paris Protocol target). (c) Emissions under V-3 for the generation scenarios G-1, 2, and 3 with the baseline (the Paris Protocol target). (d) Characteristics of V-3 and G-3 towards the emission reduction target.