Electric Vehicle Charging Infrastructure in Bhutan: Performance Analysis, User Experiences, Challenges, and Future Prospects

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Abstract

Electric Vehicles (EVs) have emerged as a transformative technology in the global car market, offering improved performance and environmental benefits over traditional vehicles. However, despite their growing popularity, widespread adoption has been hindered by challenges such as inadequate charging infrastructure and high costs. This study examines the experiences of EV users in Bhutan, focusing on charging habits, battery performance, and user satisfaction. This is the first study in Bhutan to combine both user experience data and technical performance analysis of EV charging infrastructure, providing a complete understanding of the current EV system. The survey was conducted in four Dzongkhags namely Thimphu, Samdrup Jongkhar, Phuentsholing and Trashigang. In addition, this study also includes performance analysis, focusing on power quality measurement at charging station located at Samdrup Jongkhar. By incorporating on-site power quality measurements, this study assesses the impact of EV charging on the local electrical grid. Survey findings reveal significant concerns about charging station availability, limited driving range of EVs and battery degradation, which impact overall user experience. While respondents acknowledge the environmental and economic benefits of EVs, they emphasize the need for more charging stations, better maintenance of EV charging stations and affordable pricing. The findings can guide policymakers by highlighting the need for government action to achieve 70% EV sales by 2035. Future work should focus on optimizing charging station placement, ensuring sustainability through renewable energy integration, and addressing battery performance concerns to ensure a seamless transition to electric mobility.

Key Words: *Electric Vehicles, User satisfaction, Grid impact, Technical performance, environmental impact*

1. INTRODUCTION

Bhutan annually exports a significant portion of its electricity, approximately 75% to India. A considerable proportion of the generated profit is then used to import fossil fuels, primarily for the transport sector (Wangchuk, 2024). This situation highlights the importance of transitioning to electric mobility to reduce fossil fuel dependency and utilize the country's clean energy resources more effectively.

The motivation for electric vehicle (EV) adoption in Bhutan started as early as the 11th Five Year Plan (2013-2018) with the theme 'Self-Reliance and Green Socioeconomic Development.' As of 31st December 2024, there are 576 EVs in Bhutan (Transport Regulatory Division, 2025). As the number of EVs increases, power loads rise significantly, particularly during peak times, which worsens the demand-supply gap and strains the central grid.

This study investigates the experiences of EV users in Bhutan to gain insights into their charging habits, battery performance, and overall satisfaction. By conducting surveys in four key Dzongkhags namely; Thimphu, Samdrup Jongkhar, Phuentsholing, and Trashigang this research provides a comprehensive understanding of the factors influencing user experiences. Additionally, a performance analysis was conducted at a charging station in Samdrup Jongkhar to assess the impact of EV charging on power quality, providing valuable data for infrastructure planning and management.

The findings of this study highlight critical areas of concern, such as the insufficient availability of charging stations, limited driving range, and battery degradation. While users recognize the environmental and economic benefits of EVs, they emphasize the need for infrastructure expansion, better maintenance of charging stations, and more affordable pricing models. These insights are essential for policymakers to develop targeted strategies that support Bhutan's goal of achieving 70% EV sales by 2035 (Norbu, 2022).

2. LITERATURE REVIEW

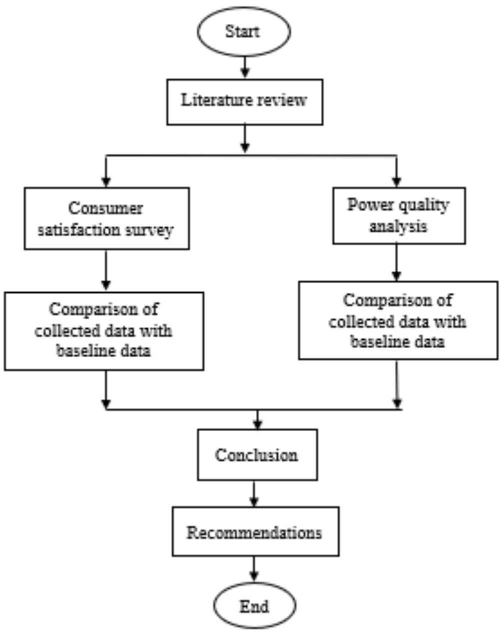
Patel et al. (2020) highlight that current electrical grids are insufficient to support the high-power demands of Level-III EV charging. They recommend grid upgrades, smart charging, and renewable integration to support rapid, cost-effective charging.

A.G. Boulanger, A.C. Chu, S. Maxx, and D.L. Waltz (1999) highlight the significant challenges introduced by the integration of electric vehicles (EVs) into the power grid, particularly increased peak loads that can disrupt grid stability and affect power quality.

Riveros et al. (2012) found that a 0.8% EV load increase could surpass routine generation in Santiago, underscoring the need for smarter grid management and supportive policies.

Rizvi et al. (2018) discuss the transition from fossil fuels to EVs driven by rising energy demand and environmental concerns. They note that EVs support clean energy but raise concerns over grid stability and power quality.

3. METHODOLOGY



4. IMPACT OF EV CHARGING STATION ON GRID

While the electrification of the transportation sector offers numerous advantages such as CO_2 emission reduction, lower environmental pollution, mitigating global warming, cost effective transportation, however the impacts of the EV charger on the power distribution network cannot be neglected. The integration of charging stations affects key operational parameters such as voltage stability, power quality, and transformer lifespan.

To quantify these impacts, power quality measurements were conducted at Samdrup Jongkhar AC EV charging stations using the Fluke 435-II Power Analyzer with a voltage measurement accuracy of ±0.5%. For a typical reading of 230V, the maximum expected deviation is ±1.15V. While the instrument is factory-calibrated, potential limitations include environmental influences, human handling error, and limited measurement intervals that may not fully capture long-term grid fluctuations.

4.1 Voltage Unbalance

Voltage unbalance also known as voltage imbalance refers to the condition in a three-phase power system where the magnitude or phase angle of the voltages in the three phases are not equal. Table 1 and 2 depicts the measured values of no-load and on-load voltage unbalance observed respectively.

Table 1: *No load voltage unbalance*

Time (PM)	Vrms AN Avg	Vrms BN Avg	Vrms CN Avg
12:19:13	228.42	228.34	227.84
12:29:17	229.74	230.35	230.59
12:39:17	229.8	230.3	230.35
12:49:17	231.19	231.02	230.51
12:59:17	230.41	228.92	228.76
01:09:17	229.4	230.2	229.22
01:19:17	230.01	226.89	227.41
01:29:17	229.83	228.59	228.56
Average voltage	229.85	229.32	229.15
Maximum deviation	1.43	2.43	1.74
% Unbalance	0.62	1.01	0.75

The average voltage unbalance = 0.79 %.

The IEC 61000-3-x series give limits for unbalance voltage less than 2%.

$$\%\ voltage\ imbalance = \frac{Maximum\ deviation\ from\ average\ voltage}{Average\ value} \times 100 \quad (2a)$$

Table 2: *On load voltage unbalance*

Time (PM)	Vrms AN Avg	Vrms BN Avg	Vrms CN Avg
03:19:13	231.46	230.66	231.1
03:29:17	232.81	231.65	232.06
03:39:17	230.02	228.01	228.56
03:39:17	230.01	229.29	228.67
03:49:17	229.78	228.49	228.78
03:59:17	228.55	227.17	227.31
04:09:17	228.13	225.85	226.68
04:19:17	230.1	228.54	229.16
Average voltage	230.1	228.71	229.04
Maximum deviation	2.7	2.94	3.5
% Unbalance	1.17	1.28	1.54

The average voltage unbalance = 1.33%.

The voltage deviation is minimum when the charge is not connected to the EV. However, deviations in the voltage levels occur while charging. Comparing the voltage imbalance level with the IEC 61000-3-x series the voltage unbalance is in compliance with the standard limit that is the deviations are below 2%. Table 2 presents the measured values of on-load voltage unbalance observed.

4.2 Power Quality

Power quality is a capability of power distribution network to supply a stable and disturbance free output which is within voltage and frequency tolerances (Bollen, 2000). Here, the power quality issues such as voltage harmonics, current harmonics, and flickering were measured using power quality Fluke 435-series II and the parameters are compared with standards such as IEEE and IEC standards.

a. Voltage Fluctuation

The integration of nonlinear loads, such as EV chargers, into the grid can lead to voltage fluctuations, thereby affecting grid stability and power quality. These fluctuations are typically assessed using short-term (Pst) indices as shown in table 3 and 4, which are measured using a Fluke Analyzer. Short-term flicker index measures flicker severity over 10 minutes. According to IEC6100-3-3 standards, short term flicker (Pst) should be less than 1%

Table 3: *Flicker for No load*

Sl. No	Time	Pst AN	Pst BN	Pst CN
1	03:03:03	0.2	0.18	0.11
2	03:04:50	0.09	0.1	0.08
3	03:05:36	0.09	0.1	0.11
4	03:06:04	0.1	0.11	0.1
5	03:07:21	0.09	0.11	0.11
6	03:08:40	0.14	0.13	0.14
7	03:09:12	0.1	0.12	0.11
8	03:10:36	0.12	0.13	0.13

Table 4: *Flicker for on load*

Sl. No	Time	Pst AN	Pst BN	Pst CN
1	01:35:20	0.14	0.13	0.13
2	01:36:05	0.11	0.1	0.11
3	01:37:09	0.16	0.16	0.16
4	01:38:40	0.19	0.17	0.17
5	01:39:46	0.1	0.11	0.1
6	01:40:51	0.13	0.11	0.11
7	01:41:43	0.1	0.09	0.08

b. Harmonics

As nonlinear devices draw current, harmonics are emitted in short pulses. The harmonics in load current can often lead to overheated transformers, overheated neutrals, blown fuses and the discharged circuit breakers. Harmonic power-waveform distortion occurs when the first, second, third, and other harmonics are mixed.

i. Voltage harmonics

Voltage harmonics were measured during EVCS operation. As per IEEE 519-2014, harmonics up to the 50th order are considered, but levels above the 25th order were negligible. Thus, analysis focused on harmonics up to the 25th order, assessing voltage harmonic content and total harmonic distortion (THD)as shown in figure 1 and 2. The result was compared with IEEE standard (HARMONICS, 2014)

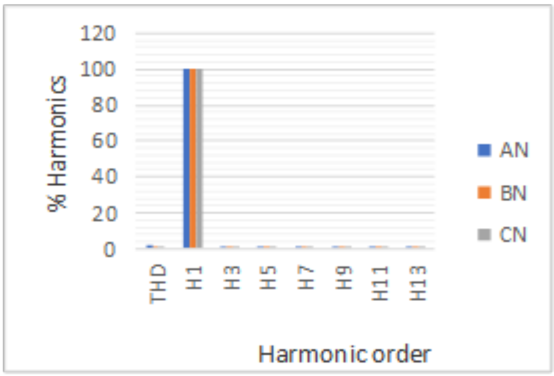


Fig.1: *Harmonics for Voltage NO load (THD =1.533%)*

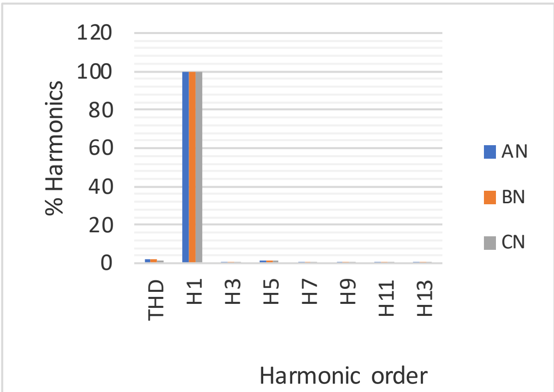


Fig.2: *Voltage Harmonics for ON load (THD =1.88%)*

ii. Current Harmonic

The current harmonics are generated in the source more significant compared to the voltage harmonics. The figure 3 and 4 current harmonics measured at no-load and on-load is compared with the IEEE standard (HARMONICS, 2014).

$$I_{full\ load} = \frac{kVA}{\sqrt{3}V_{s(L-L)}}$$

$$I_{sc} = \frac{I_{full\ load}}{z}$$

$$I_L = \frac{P}{\sqrt{3}*V(L_L)*\cos\emptyset} \quad (2b)$$

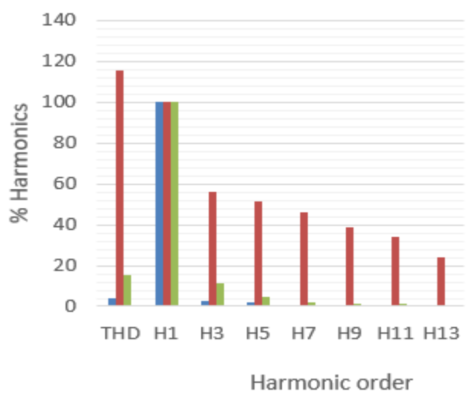


Fig.3: *Current harmonics at no Load*

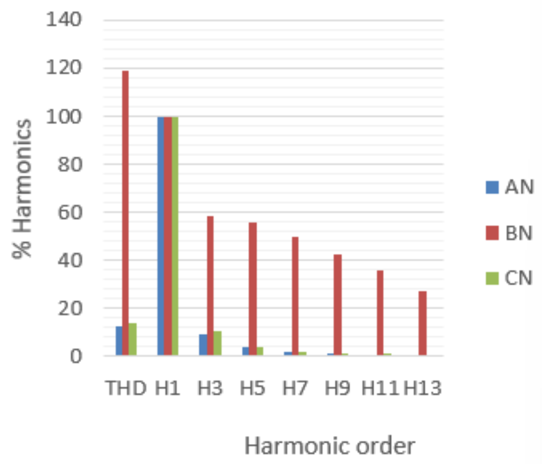


Fig.4: *Current harmonics at load*

c. Transformer Lifespan

Widespread EV deployment increases stress on distribution transformers, significantly reducing their lifespan. Increase in load causes increase in hot spot temperature of the transformer as reported in (Radu Godina, 2015). The transformer lifespan depends on the health of the winging insulation. The charging of EVs cause increase in load which in turn causes increase in hot spot temperature. It also produces stress on the transmission lines and uneven distribution of current in the transformer winding, which leads to a decrease in the life and efficiency of the transformer (Tulika Bhattacharjee M. R., 2024).In (Quanyi Gong, 2012)the researcher concluded that uncoordinated charging accelerates the ageing of transformers.

To avoid transformer overloading, EVs may be charged at different times and the studies show that the adverse effects of EV charging on the life of the transformer can be offset by integration of rooftop PV (Tulika Bhattacharjee M. R., 2024).

5. TECHNICAL PERFORMANCE

In assessing the technical performance of EV charging stations, our study focused on five key areas. First, we examined grid impact, including voltage instability, power quality issues, transformer overloading, and the aging of grid infrastructure due to increased charging demand. We then analyzed charging efficiency, which is affected by the performance of internal components as electrical energy passes through multiple conversion stages. Station downtime was also assessed, with our findings showing it was primarily caused by external disruptions rather than technical faults. Additionally, we considered charging speed, which plays a crucial role in user convenience and system throughput. Lastly, we assessed the fault occurrence rate, defined as how frequently technical issues arise, typically measured as faults per month. These indicators collectively provide a comprehensive view of the reliability and effectiveness of EV charging infrastructure in Bhutan.

5.1 Station Downtime

EV infrastructure plays a critical role in enabling the adoption of sustainable transport systems. However, the efficiency and reliability of EV charging stations are highly dependent on their uptime. Station downtime percentage is a common metric used to assess the performance and reliability of EV charging stations. This case study evaluates the downtime of both DC and AC EV charging station located in Samdrup Jongkhar, Bhutan, using the standard formula:

$$Downtime\ \% = \left(\frac{Downtime\ duration}{Total\ operating\ time}\right) \times 100 \tag{3a}$$

The charging station was installed in 2021 and has accumulated a total operating time of 35,064 hours till date. The station includes both DC and AC charging units. However, the DC charging station experienced two major downtimes: one in the year of 2024, due to environmental factors specifically rain and lightning. Resulting in a complete shutdown for three months. The second instance was in early 2025 when an excavator, during construction activities, accidentally severed the underground power cable that connected the charging stations, and it is still under operation. Additionally, the AC charging station also experienced a simultaneous disruption during the 2025 incident. Collectively, these two events amount to a total downtime of four months or approximately 2,920 hours.

Applying the station downtime percentage formula

$$Station\ Downtime\ \% = \left(\frac{2920}{35064}\right) \times 100 \approx 8.33\%$$

Around 8.33% downtime indicates that the station was non-operational for over one month per year on average. While this may appear to be a moderately acceptable rate, it surpasses the generally recommended threshold of 5% downtime for public infrastructure (Mobley, An introduction to predictive maintenance (2nd ed.)., 2002). Although the station remains under partial operation, the damages from the latest disruption in 2025 have not yet been fully resolved for Dc charging station. This presents a concern for users and infrastructure planners, as consistent availability is essential to maintain consumer trust and ensure seamless EV adoption.

5.2 Charging Efficiency

The charging efficiency of an EV charging station refers to how efficiently electrical energy is transferred from the grid to the electric vehicle's battery. The efficiency of an EV charger is influenced by the efficiency of multiple internal components since electrical power undergoes several conversion stages (Kieldsen, Thingvad, Martinenas, & Sørensen, 2016). The efficiency of the charger is calculated by measuring power at both input and output sides. According to (Milushev, 2021), the charging efficiency is calculated as

$$\eta_{CS}(\%) = \frac{E_C^{max}}{E_G^{max}} \times 100.$$

$$= \frac{P_C \times time}{P_G \times time} \times 100 \tag{3b}$$

Where: E_C^{max}= Energy from the charger (kWh) and E_G^{max} =Energy from the charger (kWh)

The grid power and charging station power measured are given in the table 5 and 6.

Table 5: *Grid power (P_G)*

Power	Phase A	Phase B	Phase C	total
kW	0.01	0.02	0.01	0.03

Table 6: *Charging station power (P_C)*

Power	Phase A	Phase B	Phase C	total
kW	0.006	0.01	0.006	0.022

Time recorded = 3minutes = 0.05hr

$$\eta = \frac{P_C \times time}{P_G \times time} \times 100$$

$$= \frac{0.022 \times 0.05}{0.03 \times 0.05} \times 100$$

$$=73.33\%$$

5.3 Charging Speed (kW or kWh/min)

Charging speed refers to the rate at which electrical energy is delivered to an electric vehicle's battery by the charging station. According to (power-sonic, n.d.), time required to charge an EV is given by

$$Charging\ speed = \frac{Battery\ capacity\ (kWh) - Remaining\ capacity (kWh)}{charging\ time\ (min)}.$$

$$= \frac{Total\ energy\ transfered\ (kWh)}{Charging\ time\ (\text{min})}$$

The details of charging power and the time taken to charge the EV and the calculation for average charging speed is given in the table 7. (3c)

Table 7: *Charging speed analysis*

charging power (kWh)	time (min)	speed (kWh/min)
0.08	1.25	0.064
0.7	12.45	0.05622
2.65	41.4	0.064
4.2	65.45	0.06417
Average charging speed		0.04611

6. USER EXPERIENCES AND CHALLENGES

6.1 Survey Design and Data Collection Approach

This study employed a mixed-methods research design, combining both quantitative and qualitative approaches to gather comprehensive insights into the experiences and challenges faced by EV taxi drivers in Bhutan. The primary data collection tool was a structured online questionnaire created using Google Forms, complemented by face-to-face and telephonic interviews. The survey was shared through Facebook forums, and interviews were conducted during academic vacations with EV taxi drivers in Thimphu, Phuentsholing, Samdrup Jongkhar, and Trashigang. For the remaining Dzongkhags, responses were gathered online or via phone. The target population included all EV taxi drivers in Bhutan, estimated at 201 out of 576 EVs, according to BCTA. Using purposive and convenience sampling, the study received 107 valid responses, achieving a response rate of approximately 53%, which is statistically sufficient for analysis. Data collection took place over a six-month period from October 2024 to March 2025.

6.2 EV Drivers' Satisfaction Survey

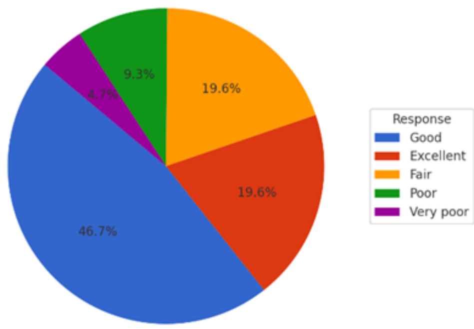


Fig.5: *Overall Experience with EV User*

Fig. 5 represents the overall EV user satisfaction. Most drivers rated their experience as Good or Excellent, indicating that many EV users express greater satisfaction with electric vehicle than with traditional fuel-based car. This is largely because the EV users benefit from free electricity for charging and exempt from paying parking fees. However, 30% of users rated their experience as Fair, Poor, or Very Poor, reflecting significant room for improvement. In terms of user-friendliness in usage of charging station, majority that is around 57% found the charging process User-friendly. However, nearly 19% found it Somewhat challenging indicating that while the system works for many, barriers remain in accessibility. Another significant concern among EV drivers in Bhutan was regarding the availability and compatibility of charging stations.

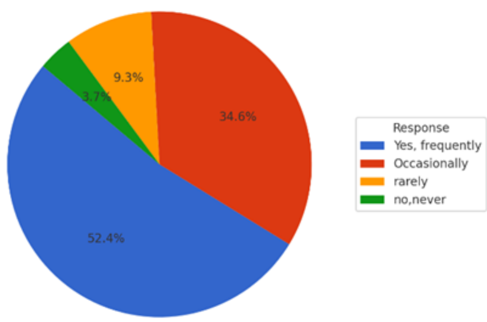


Fig.6: *Issues with Charging Station Availability*

A majority of respondents reported

encountering issues either frequently or occasionally, highlighting the inconsistency and unreliability of the current charging infrastructure as highlighted in figure 6. This has become a recurring barrier, especially for taxi drivers who rely on timely and accessible charging for their daily operations. Many EV drivers, when asked, strongly emphasized the need for more charging stations across the country particularly in remote or underserved Dzongkhags. Their feedback reveals a pressing demand for expanding the charging network to reduce wait times, avoid station congestion, and ensure smoother travel for all EV users.

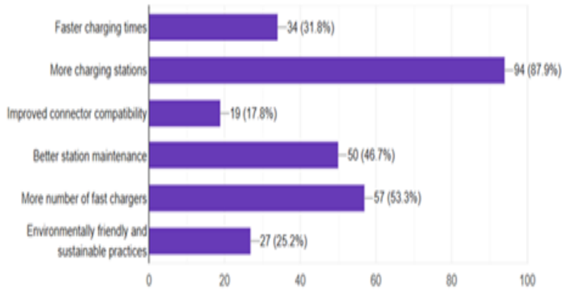


Fig.7: *EV Users Charging Improvement Request*

Further, figure 7 clearly shows a strong collective demand for more charging infrastructure. A staggering 87.9% of EV drivers indicated that more charging stations are needed, making it the most requested improvement among all options. The consistent demand across different survey questions reflects the growing pressure on Bhutan's current EV infrastructure. As more drivers adopt EV particularly in high-usage sectors like taxis, the expansion of reliable and accessible charging stations has become a top priority for users across the country.

6.3 Challenges Faced by the EV Drivers

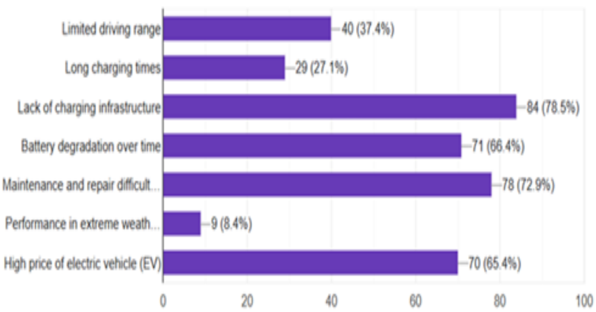


Fig.8: *Challenges faced by EV Drivers in Bhutan*

Fig. 8 depicts various challenges faced by EV drivers in Bhutan. Some of the major challenges faced are as mentioned below.

a. Limited driving range and Battery Degradation Over Time

EV drivers in Bhutan expressed concerns regarding the limited driving range and battery degradation over time. Many EV users reported experiencing reduced battery efficiency after prolonged use, which negatively impacts the overall driving experience. For example, one of the EV taxi drivers said that the driving range has decreased from 353 miles to 300miles after charging in just one year.

b. Maintenance and Repair Difficulties

High maintenance costs are also one of the primary concerns among the EV drivers. According to the Bhutanese news and forum, Executive Director of the Bhutan Taxi Association (BTA) expressed the issues. Since EV technology and software are still new, repairs often take months, leaving vehicles unusable for long periods. The cost of maintenance can also be extremely high, sometimes reaching Nu 1.2 million. Additionally, Bhutan Power Corporation (BPC) lacks the expertise needed to handle EV-related issues, leaving owners with limited options for repairs and support. The cost of spare parts for EVs is significantly higher, and unfortunately, these parts are not readily available in our country. The need to import them from other countries further adds to the expenses. Unlike traditional fuel-powered vehicles, EV owners have limited options for seeking repairs, often relying on the same company for spare parts and services, making it expensive. According to kuensel, Bhutanese first electric bus has been out of service for months due to lack of technicians.

c. Lack of Charging Infrastructure

Charging stations are installed in all 20 dzongkhags, but the problem arises when vehicles travel long distances without access to a charging station. Currently, most charging points are placed within a range of 250 to 300 km. In some dzongkhags, there is only one charging station available, which typically consists of a single slow charger and a fast charger. If either of these chargers encounters a technical issue or malfunction, it can leave the entire dzongkhag without functioning charging infrastructure. The reliability of these stations is crucial, as any breakdown could disrupt the availability of charging services for residents and travelers, leading to inconvenience and potentially leaving vehicles stranded without power. One of the EV drivers in Samdrup Jongkhar expressed the need for EV charging station in Samdrup Jongkhar, Ngalam, Wamrong and Sengkhor.

d. Long Charging Time

Charging time is one of the most critical factors in the adoption and practical use of EVs. Unlike conventional vehicles, which can refuel quickly at gas stations, EVs require time to charge their batteries, which can vary depending on several factors, including the type of charger, the battery size, and the current state of charge. increasing the number of fast chargers along highways and in urban areas is critical for making long trips more feasible.

7. ENVIRONMENTAL IMPACT

7.1 CO_2 Emission Reduction

In 2015, transport sector in Bhutan has been identified as primary source of GHG emission, accounting for approximately 424,830 metric tonnes CO_2e which represented 11.14% of the country's total emissions (3,814,000 metric tonnes) (Wangchuk, 2024). The net carbon emission reduction by the adoption of EVs in Bhutan is calculated by comparing Baseline Emissions (BE) and Project Emissions (PE). The Baseline Emission act as a reference point to measure how much a project has helped in cutting down emissions. Project emissions are the carbon emissions released while building and running a project designed to reduce emissions.

The equation for the calculation of Baseline Emission as per (Milushev G. , 2021) is

$$BE_y = \frac{\sum_{i,f} ED_{i,y} \times EF_{j,f,y} \times 100 \times ITF_Y^{y-1}}{AEC_{i,y} \times MPL_{j,y}} \tag{5a}$$

Where:
BE_y= Baseline emissions in year y (tCO_2e)
$ED_{i,y}$= Electricity delivered by project charging systems serving applicable fleet i in project year y (kwh)
$EF_{j,f,y}$= Emission factor for the fossil fuel f used by comparable fleet vehicles j in year y (tCO2e/gallon)
ITF_Y^{y-1}=Technology improvement rate factor for applicable fleet i
$AEC_{i,y}$= average electricity consumption by the applicable fleet i (kWh/100km)
$MPL_{j,y}$= average mileage of comparable fleet j using fossil fuel (km/l)

The equation for the calculation of Project Emission as per (Milushev G. , 2021) is

$$PE_y = \sum_{i.y} EC_{i,y} \times EFP_{i,y} \tag{5b}$$

Where: PE_y= Project emission in the year y ((tCO_2e)
$EC_{i,y}$ = Electricity Consumption by project chargers i in the year y (kWh)
$EFP_{i,y}$= Emission factor for source electricity in Bhutan ($kgCO_2$/kWh).
The net emission reduction can be obtained by $ER_y = (BE_y - PE_y) \times Dy$. Where: ER_y = Emission reduction in the year y *and* Dy = Discount factor applied in the year y.

The data required for calculation of carbon emission reduction are given in the table 8 below.

Table 8: *CO_2 calculation data*

Parameters	Value
Electricity delivered, $ED_{i,y}$	1370000kWh
Emission factor of Diesel, $EF_{j,f,y}$	2.64CO_2e/L
Average Electricity Consumption, $AEC_{i,y}$	21.2kWh/100km
Average Mileage for diesel engine, $MPL_{j,y}$	24.07km/L
Electricity Consumption by project chargers, $EC_{i,y}$	1370000kWh
Emission factor for source electricity in Kerala, $EFP_{i,y}$	0$kgCO_2$/kWh
Improvement in Technology factor for one year, ITF_Y^{y-1}	1
Discount factor, Dy	1

The results obtained from the above data and equations are:
Baseline Emission (BE) = 708,781.7764tCO2e
Project Emission (PE) = 0
Emission Reduction (ER) = 708,781.7764tCO2e/708,781,776.4kgCO2e

Since the electricity in Bhutan is primarily produced by hydropower, the grid emission factor is zero (Settlements, Ministry of Work and Human, 2017), hence the Project Emission is 0 tCO_2e, resulting in a net emission reduction of 708,781.7764 tCO_2e. This demonstrates the effectiveness of EV adoption in reducing transport sector emissions.

8. CONCLUSION

This study highlights key challenges in Bhutan's EV adoption, including limited infrastructure and grid issues. One major challenge for EV owners in Bhutan is the lack of trained technicians for repair and maintenance. To address this, EV-specific training should be introduced in technical institutes and engineering colleges to build local expertise. Additionally, integrating solar energy into EV charging infrastructure can help stabilize voltage levels and diversify Bhutan's hydropower-reliant energy mix.

Despite these, users value environmental benefits from zero-emission electricity. Strategic expansion, improved maintenance, and policy support are essential to meet Bhutan's 2035 goal of 70% EV sales and sustainable transport.

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