ABSTRACT

This study investigates the impact of integrating 10,000 battery electric vehicles (BEVs) into the electrical grid of Trinidad and Tobago through three charging scenarios: non-incentivized charging, charging at work, and a Vehicle-to-Grid (V2G) program. The results reveal that non-incentivized charging exacerbates peak demand and grid strain, while workplace charging provides only modest peak demand mitigation. In contrast, the V2G scenario significantly reduces peak load impacts and enhances grid stability by leveraging BEVs as dynamic energy storage units that contribute to grid services during high-demand periods. The study proposes a V2G tariff scheme that includes compensation for battery degradation, aiming to incentivize participation and offset potential costs. Economic analysis shows that while V2G involves higher per-MWh costs than conventional storage technologies, it avoids the need for substantial capital investment in static energy infrastructure, presenting a cost-effective solution for energy management in island nations. The findings highlight the potential of V2G technology to facilitate sustainable energy transitions, emphasizing its role in enhancing grid resilience, optimizing renewable energy usage, and reducing carbon emissions. This research underscores the transformative potential of V2G systems as critical enablers of sustainable energy strategies in regions facing similar challenges to Trinidad and Tobago.

Keywords: Electric vehicle charging, Small island developing state, Trinidad and Tobago, Vehicle-to-grid.

1. INTRODUCTION

Battery Electric Vehicles (BEVs) play a crucial role in addressing sustainability challenges like global warming, fossil fuel depletion, and greenhouse gas emissions [1]. They offer zero carbon emissions, higher efficiency, lower maintenance, and regenerative braking, making them environmentally friendly and efficient [2]. EVs can aid in decarbonizing transport and electricity supply by reducing emissions and providing flexibility in energy storage and discharge [3]. Consumer perceptions are vital for EV market acceptance, with attributes like driving range, recharging time, safety, and energy efficiency being key factors influencing consumer satisfaction [4]. Integrating EVs into the smart grid through concepts like Vehicle-to-Grid (V2G) can enhance grid operation and serve as a distributed energy source. Overall, EVs are essential for reducing environmental impact, improving energy efficiency, and advancing sustainable transportation.

The majority of BEV owners prefer to charge their vehicles at home. Studies show that around 90% of EV owners opt for residential home chargers over public charging stations [5]. Home charging is not only convenient but also considered safer, compact, and user-friendly. Additionally, there is a growing interest in smart and intelligent chargers that offer features like mobile application integration, charger management systems, Internet of Things deployment, and charging cost calculations [6]. While curbside charging stations are available, they are often costly, and the need for them is sometimes overestimated, with workplace and shopping facilities being suggested as more incentivized locations for charging infrastructure [7]. Overall, the trend leans heavily towards home charging for electric vehicles due to its practicality and ease of use.
Charging at off-peak times or times of low electricity demand is crucial for various reasons. Firstly, off-peak charging can lead to significant cost savings and energy consumption reductions, as seen in studies on peak shifting strategies in buildings [8]. Additionally, off-peak charging can help alleviate network congestion, improve travel times, and reduce emissions, as highlighted in research on off-peak delivery impacts on greenhouse gases and air pollutants [9]. Moreover, in the context of plug-in hybrid electric vehicles (PHEVs), off-peak charging can be economically incentivized through time-of-use (TOU) rates, although the effectiveness of these rates may vary based on consumer choices and fueling costs [10]. Overall, charging at off-peak times not only benefits individuals and households in terms of cost savings and energy efficiency but also contributes to environmental sustainability by reducing emissions and congestion.

Vehicle-to-grid (V2G) technology enables bidirectional power flow between BEVs and the grid, enhancing grid security and stability by regulated dispatching [11]. V2G facilitates energy exchange between BEV batteries and the grid, offering benefits like load balancing, power grid stabilization, and peak load management [12]. It helps in reducing carbon emissions, optimizing power demand, and increasing smart grid sustainability [13]. V2G also plays a crucial role in mitigating greenhouse gas emissions from the transportation sector and supporting the integration of renewable energy sources into the grid [14]. By utilizing V2G, BEVs can provide auxiliary services to the grid, relieve adverse effects of uncoordinated charging, and contribute to a more efficient and sustainable energy ecosystem.

V2G economics and battery degradation are crucial factors in designing compensation models for BEV owners participating in V2G services. Studies emphasize the importance of realistic battery degradation models [15] and the impact of battery costs on V2G profitability [16]. To address battery aging costs, a two-stage method has been proposed to quantify battery aging and implement health-aware energy management strategies, reducing overall battery degradation expenses [17]. Furthermore, integrating compensation models into demand response (DR) scenarios for EV fleets is essential, where financial compensation should offset battery degradation costs [18]. Optimizing this trade-off can lead to economic benefits for companies while ensuring EV owners are adequately compensated for the wear on their batteries, promoting sustainable V2G practices.

The rise of V2G technology necessitates innovative business models to facilitate consumer adoption. A prime example is Octopus Energy’s, from the UK, Vehicle-to-Grid bundle called Powerloop. This bundle includes a new Nissan LEAF 40 kWh, a Wallbox charger, an App, 100% renewable energy, a Smart meter, and offers £30 cashback every month for £235/month. The package runs on a 4-year contract. Importantly, Powerloop is only available in areas where the local energy grid is managed by UK Power Networks [19].

Government-backed pilot programs play a significant role in exploring the practical implications of V2G implementation. One such example is Electric Nation, a project by Western Power Distribution and CrowdCharge. This trial offers free V2G smart charger installations worth £5,500 to Nissan EV drivers within specific Western Power Distribution license areas. Examining the outcomes of such geographically targeted trials provides insights into both the potential benefits and regional constraints of V2G integration [19]. V2G technology represents a perfect solution for power grids and decarbonizing transportation but challenges exist, such as the small earnings per V2G electric car due to high EV battery costs and low peak-valley electricity price ratios [20]. Additionally, the economic feasibility of V2G technology depends on factors like battery life, charging infrastructure capacity, and tariff structures [21]. These studies highlight the importance of designing effective V2G tariff schemes to optimize grid stability, revenue generation, and EV owner participation.

This study investigates the effects of 10% of the total vehicle population in Trinidad and Tobago, approximately 10,000 vehicles being BEVs and connecting to the electricity grid to charge. Three scenarios are investigated: a scenario that represents non-incentivized charging or business-as-usual, a charging at work scenario and a V2G program. A Nissan leaf is used as the representative BEV for this study and a V2G program with a generous tariff and a battery degradation payment is proposed.

2. Methodology

This study is aimed at investigating the effects of ten percent of the total registered vehicle population being electric and the effect of these vehicles connecting and charging on the local electricity grid. Ten percent of the total number of vehicles registered locally is 10,000 vehicles and, in this study, the total population of BEV is modelled as 10,000 BEVs [22]. The study also presents realistic and relevant mitigation strategies to manage any adverse effects on the power grid. Three charging scenarios are developed and explored, un-incentivized BEV charging, BEV charging at work and the implementation of a vehicle-to-grid program.

The BEVs connecting and charging on the grid are distributed in a discrete normal distribution between the hours of 4 pm and 7 pm. It is assumed that charging would take place at home using level 1 and level 2 chargers with a small and negligible number of BEVs using a public charging network. The distribution of level 1 and level 2 chargers follows a 40% and 60% distribution, respectively. The average distance between the two major cities in Trinidad, the capital, Port-of-Spain, and the second city, San Fernando, is roughly 55 km one way. Fig. 1 illustrates that the population density distribution is also the highest in and on the outskirts of the cities. This study assumes a daily distance travelled to be between 60 km and 180 km, modelling a daily commute between the cities. The study utilizes the parameters of a 2020 Nissan Leaf. The Nissan Leaf is a popular BEV in the Caribbean and Trinidad. The region imports most of its passenger cars used, including BEVs [23]. A 2020 base model Nissan leaf with a 30 kWh battery and a range of 200 km is used in the study. The parameters used for the simulation of the three scenarios are provided in Table 1.
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Fig. 1. Population distribution (inhabitants per 1 km² kilometer). Source: [24].

TABLE I: THE DISTRIBUTION OF BEV CONNECTING TO THE GRID AND THE DISTRIBUTION OF THE DAILY DISTANCE TRAVELLED

<table>
<thead>
<tr>
<th>Time of day</th>
<th>% of BEVs</th>
<th>Distance travelled (km)</th>
<th>% of BEVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 pm</td>
<td>5%</td>
<td>60 km</td>
<td>50%</td>
</tr>
<tr>
<td>5 pm</td>
<td>50%</td>
<td>100 km</td>
<td>40%</td>
</tr>
<tr>
<td>6 pm</td>
<td>40%</td>
<td>180 km</td>
<td>10%</td>
</tr>
<tr>
<td>7 pm</td>
<td>5%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The existing daily electrical demand curve for Trinidad and Tobago is presented in Fig. 2. The peak demand occurs at 7 pm and is 1250 MW, the second highest peak demand occurs at 8 pm and 1200 MW. There is also a daytime peak of 1180 MW that occurs at 1 pm. Power at these peak periods is provided by inefficient simple cycle natural gas turbines that produce the most carbon emissions per kWh or unit of energy produced.

Three scenarios were investigated: non-incentivized charging, incentivized charging, and a vehicle-to-grid program. A custom MATLAB simulation model was developed to evaluate the scenarios that used MATLAB and its various Simulink toolboxes.

3. RESULTS AND DISCUSSION

The results of the scenarios are presented in this section.

3.1. Scenario 1–Non-Incentivized Charging

In this scenario, which would also be considered the baseline scenario, BEVs connect to the electrical grid and charge without being influenced by any tariff or mitigation program. The BEVs follow the behavior outlined in Table I. The result of the simulation is provided in Fig. 3.

The increase in the peak demand at 7 pm is 27 MW, a 2% increase, and 19 MW at the 8 pm peak, a 1.5% increase in demand. The increase in demand at the peak time is inefficient and costly and is the cause of most emissions per kWh of energy produced because single-cycle gas turbines are used to provide the peak demand. Trinidad and Tobago has seen declining natural gas production and there is a concerted focus towards reducing natural usage in the power generation sector and redirecting it to the petrochemical sector [25]. Reducing the peak demand would save natural gas, reduce emissions, and avoid costly and lengthy grid infrastructure upgrades. However, the electrification of transportation and the use of BEV technology has been identified as preferred solution to the decarbonization of transportation [26]. Including the additional electrical demand from BEV’s on the grid when the simple cycle power plants are not in use and the more efficient combined cycle power plant is in use is a cost effective, emission reduction strategy. The combined cycle powerplant is used as baseload and runs throughout the day. Displacing most of the BEV charging load to off-peaks time or times of lower electrical demand would fully utilize the combined cycle power plant, reduce natural gas utilizations, reduce emissions and decrease grid infrastructure upgrades.

3.2. Scenario 2–Charging at Work or During Working Hours

Scenario 1 represents the business-as-usual scenario, where most BEV drivers charge at home after work. This scenario explores charging at work and any noticeable improvement as compared to Scenario 1. In this scenario, 50% of BEV drivers charge at work, and the other 50% charge after working, following the parameters used in Scenario 1. The 50% of BEV drivers that charge at work do so using a level 1 charger, which draws a low power of...
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Fig. 2. Variation in daily electrical demand for Trinidad and Tobago.

Fig. 3. The effect of 10,000 BEV charging on the grid. A 27 MW increase at the 7 pm peak and 19 MW increase at 8 pm.

3 kW. The level 1 charger was used in this scenario as it would require very little electrical infrastructure upgrade at work locations and is cheap to purchase and use. A level 1 charger is provided when you purchase a new BEV. The distribution of the 50% BEV drivers that charge at work is provided in Table II. Scenario 2 aims to simulate a driver of a BEV connecting to charge when they get to work using a charger provided with the BEV.

The results are presented in Fig. 4. Allowing 50% of BEVs to charge at work does reduce the peak demand by 5 MW at 7 pm and 7 MW at 8 pm, but these reductions are relatively small. There is an increase in electrical demand between 9 am and 12 noon due to the work charging, which represents the displaced demand during peak time. The reason for the small decrease in peak demand is because the low power EV chargers that charge the BEVs at work do not fully charge all the BEV during working hours and

<table>
<thead>
<tr>
<th>Charging session initiated at</th>
<th>% of BEV (50% of total BEV population)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 am</td>
<td>40%</td>
</tr>
<tr>
<td>9 am</td>
<td>50%</td>
</tr>
<tr>
<td>10 am</td>
<td>10%</td>
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</table>
top-up or continuing of the charging session takes place at home after work hours.

3.3. Scenario 3--Vehicle to Grid (V2G)

This scenario investigates the use of a Vehicle to Grid (V2G) program to reduce the peak demand associated with BEV charging in the business-as-usual scenario, Scenario 1. To participate in the V2G program, BEV owners must have a V2G enable level 2 charger. Level 1 chargers are unable to participate in the V2G program because they don’t allow for DC charging and the use of CCS and CHAdE MO connectors that enable the V2G capability. In Scenario 1, 60% of the BEV users charge using a level 2 charger. For the V2G Scenario, it is assumed that half of the BEV users with a level 2 charger, have a V2G enabled level 2 charger and participate in the V2G program. The V2G program is as follows:

(a) BEV uses participate daily in the V2G program.
(b) The output from the V2G enable charger is 6 kW.
(c) The V2G program is active or feeds back power to the grid during the period from 6 pm to 9 pm daily. This period captures the daily peak demand and the highest peak period for the day.
(d) Any BEV users that reach a state of charge (SoC) of 20% on the traction batteries of the BEV will be automatically disconnected from the V2G program and begin charging their batteries. This is done to protect the batteries from being completely drained.
(e) All BEV users participating in the V2G program, except for those users who have reached a SoC of 20% on their batteries, begin charging their batteries from 9 pm.

Fig. 5 presents the results of the simulation for the V2G program. The V2G program reduces all the peak demand due to BEV charging and maintains the existing peak demand without BEV charging on the grid. The V2G program delays charging till after 9 pm, this causes a greater power demand between the off-peak period from 12 am to 3 am. Moving electrical load to the off-peak period will ensure efficient utilization of the combined cycle powerplant as it would be operating closer to its rated capacity and not at a lower inefficient capacity.

3.3.1. Vehicle to Grid (V2G) Tariff Scheme

To encourage BEV users to participate in a V2G scheme, a lucrative tariff scheme and compensation for battery degradation should be provided. An electricity tariff that is four (4) times the existing domestic electricity tariff and a daily battery degradation fee of $2.50 USD is proposed for each BEV user participating in the V2G program.

The V2G program would cost the utility $20,100 USD daily for 54 MWh of energy during the peak time or $372.2 USD/MWh. The Levelized Cost of Storage (LCOS) for a utility-scale 100 MW, 1-hour lithium-ion battery bank in 2023 is between $249 and $323 USD. The V2G program is 12% more expensive per MWh than the higher-end LCOS per MWh. The advantage of the V2G program is that the utility is not required to make any capital investment in utility-scale battery storage and its associated electrical infrastructure. The V2G program also allows for energy to be injected into the grid at distributed locations compared to one location, as is the case for a large utility-scale battery bank.

At an electricity tariff that is four times the existing domestic tariff a BEV owner participating in the V2G program gains $3.6 USD daily from the tariff and pays $1.5 USD daily to fully recharge the BEV using the grid. The BEV user has a net profit of $2.1 USD from the tariff and gains an additional $2.50 USD daily as a battery degradation fee. The cost of a new 30 kWh Nissan leaf battery can cost around $4500 USD [27]. At the current V2G battery degradation payment rate a Nissan leaf participant can
change to a new battery in 5 years by using the battery degradation fee.

The levelized cost of energy (LCOE) for a natural gas peaking power plant in 2023 is $221 USD/MWh [28]. The V2G program is 68% more costly than the LCOE for a natural gas peaker power plant. The emissions associated with a simple cycle natural gas peaker power plant is between 0.57 to 0.75 kg CO₂-eq/MWh [29]. The natural gas peaker power plant would produce between 30.78 kg CO₂-eq and 40.5 kg CO₂-eq daily without the V2G program. The emissions per kg of CO₂-eq for a combined cycle power plant is between 0.42 to 0.48 kg CO₂-eq/MWh. Assuming the electricity used to charge the BEVs outside of the V2G program is from the combined cycle powerplant, then there would be an emissions savings of between 8.1 kg CO₂-eq and 14.58 kg CO₂-eq daily.

3.4. Comparative Analysis

The comparative analysis of the three BEV charging scenarios—non-incentivized charging, charging at work, and the Vehicle-to-Grid (V2G) program—reveals distinct impacts on Trinidad and Tobago’s grid efficiency, cost, and environmental sustainability.

3.4.1. Efficiency and Grid Stability

The non-incentivized charging scenario results in increased peak demand, particularly during evening hours, which necessitates the use of less efficient and more polluting single-cycle gas turbines. Conversely, the charging at work scenario partially mitigates peak demand by distributing charging throughout the workday. However, this scenario’s impact is limited by the incomplete charging cycles of vehicles, necessitating additional charging during peak residential hours, thus only modestly alleviating grid stress.

The V2G scenario demonstrates a superior management of energy demand. By enabling electric vehicles to discharge energy back to the grid during peak times, V2G effectively transforms vehicles into mobile energy storage units. This not only stabilizes the grid during high-demand periods but can also optimize the use of renewable energy by absorbing excess generation during off-peak hours and releasing energy during peak demand.

3.4.2. Economic Implications

Economically, non-incentivized charging does not incur additional costs beyond the existing infrastructure but fails to address the inefficiencies and potential costs associated with increased peak demand. The charging-at-work scenario might require a minimal initial investment in charging infrastructure at workplaces but does not significantly alter overall energy consumption patterns.

In contrast, the V2G scenario, while more expensive per MWh compared to other storage technologies, offers significant long-term benefits by reducing the need for investment in additional grid infrastructure and utility-scale storage solutions. The decentralized nature of V2G also means that energy generation and storage are more resilient to localized disruptions, adding an additional layer of security to the energy system.

3.4.3. Environmental Impact

From an environmental perspective, the non-incentivized scenario exacerbates emissions due to the increased use of inefficient power generation during peak times. While the work charging scenario does shift some demand to times when renewable energy might be more available, its overall impact on emissions is limited.

The V2G scenario offers the most substantial environmental benefits by significantly reducing peak demand and allowing for more efficient use of renewable energy sources. By using BEVs as temporary energy storage devices, V2G
can decrease reliance on fossil fuel-based power generation during peak times, thereby reducing the carbon footprint of the energy sector.

3.4.4. Strategic Considerations for Island Nations

The use of V2G technology has significant strategic implications for island nations such as Trinidad and Tobago, which often confront distinct energy issues. In Trinidad and Tobago’s case, these challenges include declining natural gas production and susceptibility to price shocks in the global fuel market. By maximizing nearby renewable energy sources and efficiency by exploiting pre-existing natural gas resources, vehicle-to-grid (V2G) technology not only provides a way to stabilize the grid but also has the potential to improve energy security.

4. Conclusion

This study investigated the potential impact of integrating 10,000 BEVs into the electrical grid of Trinidad and Tobago and proposed mitigation strategies for the resulting increase in peak demand. Three scenarios—unincentivized charging, charging at work, and a V2G program—were explored. The results demonstrated that a well-designed V2G program can successfully mitigate the adverse effects of BEV charging on the grid, even exceeding the benefits achieved through work-based charging strategies. The proposed V2G program with a generous tariff scheme and battery degradation compensation not only reduces peak demand and emissions but also provides financial benefits to BEV owners.

While the V2G scenario showed significant promise, it’s important to acknowledge that real-world implementation presents challenges. Factors like consumer acceptance of V2G technology, the long-term sustainability of the proposed tariff model, and the evolution of grid infrastructure will all influence the feasibility of large-scale V2G adoption. Nonetheless, this study highlights the value of V2G programs as a potential solution for island nations like Trinidad and Tobago, seeking to decarbonize their transportation and electricity sectors.

Future research directions could investigate more sophisticated V2G tariff models, perhaps incorporating dynamic pricing or capacity-based incentives. Additionally, exploring consumer attitudes and preferences regarding V2G participation through surveys and focus groups would offer valuable insights. Ultimately, this work contributes to the ongoing dialogue on integrating electric vehicles into the power grid, emphasizing the unique potential of V2G as a demand management tool and a driver of sustainable energy transitions.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

References


