Economic and Environmental Impact of Vehicle-to-Grid (V2G) Integration in an Intermittent Utility Grid

Hayder Ali
Dept. of Electrical Engineering, SBASSE,
Lahore University of Management Sciences, (LUMS)
Lahore, Pakistan
hayder.ali@lums.edu.pk

Sajid Hussain
Dept. of Electrical Engineering, SBASSE,
Lahore University of Management Sciences, (LUMS)
Lahore, Pakistan
18060013@lums.edu.pk

Hassan A. Khan
Dept. of Electrical Engineering, SBASSE,
Lahore University of Management Sciences, (LUMS)
Lahore, Pakistan
hassan.khan@lums.edu.pk

Naveed Arshad
Dept. of Computer Science, SBASSE
Lahore University of Management Sciences, (LUMS)
Lahore, Pakistan
naveedarshad@lums.edu.pk

Irfan Ahmad Khan
Marine Engineering Technology in joint appointment with Electrical and Computer Engineering
Texas A&M University
College Station, Texas, USA
irfankhan@tamu.edu

***Abstract*—The importance of vehicle-to-grid (V2G) power transfer is increasing due to increased penetration of electric vehicles (EVs) along with an increasing focus on reducing fossil fuel emissions. The V2G feature of EVs has the potential to increase grid stability and optimize power flows at the distribution scale for many developed regions. However, in many developing regions, the grid is mostly intermittent, and the role of EVs must be redefined in many unique scenarios. In line with this rationale, this paper assesses two scenarios; 1, the role of V2G in reliable utility grid (a typical case in developed countries), and 2, the role of V2G in intermittent utility grid (a common scenario in developing countries). Assessment is based on the role of V2G in operational kWh cost reduction and CO_2 emission reduction with tangible benefits of V2G operation as compared to business as usual.**

Keywords—CO_2 emission; Intermittent utility grid; kWh cost; PV systems; and V2G

I. Introduction

There is an increasing interest in energy self-sufficiency through sustainable means to mitigate global warming concerns [1]. For many developing countries such as Pakistan, energy self-sufficiency is a major political and social concern, with over 70% of the imported fuel utilized for transportation purposes [2, 3]. This high reliance on fossil fuels adds to many unwanted environmental hazards, with two cities of Pakistan being ranked in the top 10 polluted cities in the world [5]. A significant reason for the condition is the high amount of CO_2 emission from internal combustion engines in cars and bikes. Therefore, the need is to reduce dependence on fossil fuels and introduce new environment-friendly transport technologies [6, 7].

Electric vehicles (EVs) are one of the emerging and accessible technologies in the transportation sector to decrease CO_2 eruptions and oil demand. Other advantages of this technology are zero noise pollution, low maintenance cost, safety improvement, energy security, and vehicle-to-grid (V2G) power flow opportunity to reduce peak costs and increase grid stability [8, 9]. V2G refers to a feature of EVs in which the battery storage system can also feed energy back to the grid when it is required. V2G power transfer has been under investigation for more than a decade because of its potential of effectively a grid-level storage without many conventional overheads for large scale storage [10]. Many authors studied V2G feature of EVs, concerning CO_2 emission reduction, cost reduction, renewable integration, and grid support perspective in the scenario of developed countries under a steady utility grid [11, 12]. However, the evaluation of EVs V2G operation in intermittent grids is not investigated in detail with many establishments in developing countries having a back-up generation as well as solar to replace the grid during an outage.

In many developing countries, the utility grid is largely intermittent due to generation shortfall or transmission and distribution constraints [13, 14]. This results in many domestic and commercial consumers resorting to diesel-based back-up solutions, which are a) costly and b) have a considerable impact on CO_2 emissions. This is where the V2G operation of EVs can play a significant role where the power is backed up from V2G operation instead of diesel generations for many of the rolling blackouts. This paper presents a case study of Lahore University of Management Sciences (LUMS), which has a conventional utility grid backed up with diesel generation system. In the first part of the case study, the V2G impact on the steady (non-intermittent) utility grid is simulated on PVSOL (a state-of-the-art commercial software) to show economic and environmental benefits, followed by the benefits of V2G in an intermittent grid scenario. The findings of this study can be key in efficiency improvement, and CO_2 emission reduction in many developing countries and policies could be aligned to allow higher penetration of EVs, which is required to carry out this operation in the future.

The rest of the paper organized as follows: Section II compares various topologies in practice from the power consumption perspective, followed by Section III, which outlines the case study for the impact of V2G operation in two selected scenarios, followed by the conclusions in Section IV.

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II. Structures of a Typical Grid Operation in Regions with Intermittent Grid

There are four broad categories of consumers with regards to power usage options based on their needs and economic strength, i.e., consumers with:

1) Utility Grid supply only
2) Utility Grid and (grid-connected) PV System
3) Utility Grid, PV System and Storage
4) Utility Grid, PV System and Generators

A. Utility Grid supply only

Utility Grid supply only is the conventional topology where the utility grid provides for all the loads, as shown in Fig. 1 (a). There are no other sources of energy (i.e., diesel generator or solar PV) integrated with the system. This is most common for the regions with stable grids but it is not typically a case for developing countries where the grid is mostly intermittent, resulting in rolling blackouts of few hours every day, even in major cities.

B. Utility Grid and (grid-connected) PV System

Due to decreasing PV systems cost, this topology is now becoming very popular due to suitable economics. Solar PV complements the grid and effectively reduces the overall basket price of the units consumed. So, there is a bidirectional power flow with the utility grid and is shown in Fig. 1 (b). Solar modules are typically mounted on the rooftop or in the neighboring land depending on the availability of space. For domestic/commercial settings, the main principle is to produce electricity through sunlight, and the excess energy is delivered to the utility grid in surplus condition. The financial modalities of these systems depend on constraints like grid electricity price, provision of storage, grid feed-in-tariff, and net-metering requirements [15, 16].

C. Utility Grid, PV System and Storage

To cater for outages, the utility grid with a PV system may be integrated with storage for reliable supply. However, with storage still significantly costly, this type of arrangement is not very common where entire building loads are backed up through storage. In this topology, net-metering may or may not be available depending on consumer type and basic setup of such a system is shown in Fig. 1 (c). In essence, batteries store excess energy generated by the PV system and deliver to the load when it is required or to reduce dependence on the grid at the time of peak tariff [17].

D. Utility Grid, PV System and Generators

The utility grid with a PV system and generator is a very common topology, which is mostly used in small and medium enterprises having substantial (MW scale) load. Battery banks are not feasible for these enterprises due to large storage requirements and high cost (initial and replacement) of batteries. As a result, large consumers use back-up generators (with significantly lower upfront costs) in place of batteries, as shown in Fig. 1 (d). This topology provides higher reliability, but there are many other disadvantages, e.g., the high running cost of generator units, CO_2 emission, and limitation on PV system generation due to direct tying with the generator [18].

Due to the variety of topologies available, it is essential to redefine the V2G role in these circumstances, especially in CO_2 emission and cost reduction perspective.

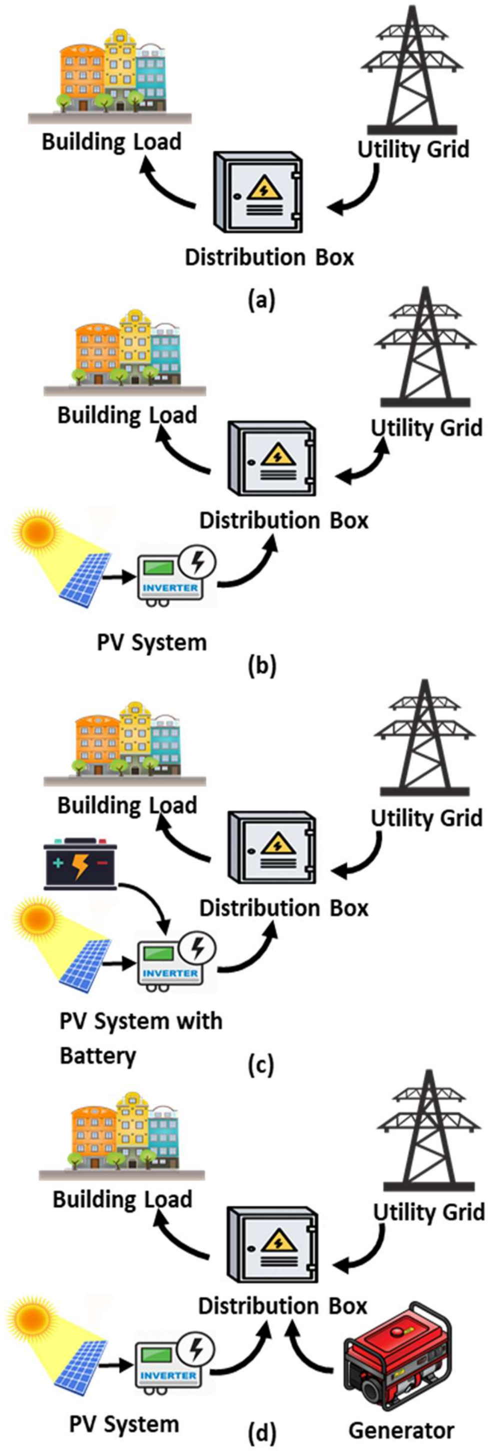

Fig. 1. Utility grid structure present in Pakistan (a) utility grid supply only (b) utility grid with (grid-connected) PV system (c) utility grid with PV system and storage (d) utility grid with PV system and generators.

III. Results and Discussions

V2G can potentially be a significant factor in modern grid storage with the availability of vehicle storage in case rolling blackouts in intermittent grids. In this section, we evaluate two cases:

Case 1: Role of V2G in reliable utility grid (a common case in developed countries)

Case 2: Role of V2G in intermittent utility grid (a common scenario in developing countries)

The first case is presented through the effect of V2G in a domestic consumer household case with an EV and solar generation. The second case presents our evaluation for LUMS with intermittent grid, diesel back-up, and rooftop solar.

Case1: Role of V2G in reliable Utility Grids

To identify the role of V2G in a steady system, a simulated case study on PVSOL is performed for a household with 15 kWp PV system, three electric cars with V2G capability and an appliance/auxiliary load (household load) of the annual energy demand of 3880 kWh. The typical structure is shown in Fig. 2 with detailed specifications of the EVs, also shown in Table 1.

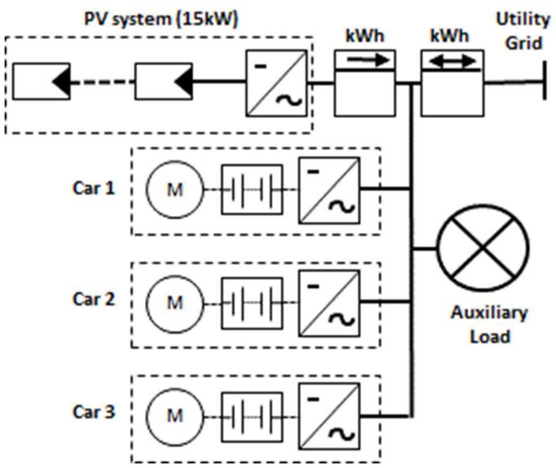

Fig. 2. Structure of a domestic home system with a reliable grid along with PV and three EVs.

TABLE I. Technical Specification of a Typical Electric Car [19]

Technical Specification	**Value**
Engine Output	107 kW
Battery Capacity	23 kWh
Consumption	12.1 kWh/100 km
Distance cover in a complete charge cycle	162 km
Charging Type	AC Type 1

The power flow diagram for the whole year is shown in Fig. 3. Results show that the PV system provides 22,381 kWh annually while the annual energy required for EVs charging and appliance load is about 8,416 kWh and 3893 kWh, respectively. The energy needed for the appliance load is taken by the PV system and the V2G feature of EVs. The load share of the PV system and EVs is 1,775 kWh and 2,032 kWh, respectively, and the surplus 12,192 kWh is fed to the grid, as shown in Fig. 3. It also observed that 89 kWh of energy is also received from the utility grid, which is very low as compared to the total energy utilization. In this case, V2G helps to reduce 13429 kg/year in CO_2 emission and also provides the level of self-sufficiency (LSS) of 99.1%, calculated by (1). Where C_{grid} represents consumption covered by the grid, and C_{total} represents total consumption. These results show the effectiveness of the V2G role in the reliable grid. [20].

$$LSS = \left(1 - \frac{C_{grid}}{C_{total}}\right) \times 100 \quad (1)$$

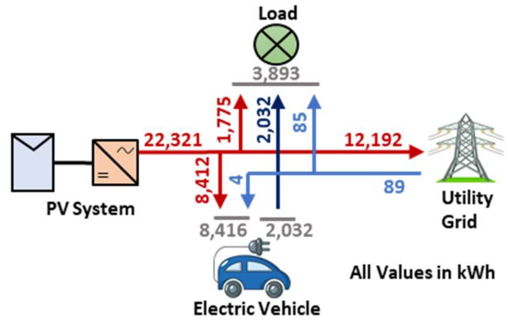

Fig. 3. Annual energy flow diagram of a domestic home system with a reliable grid.

Case 2: Role of V2G in Intermittent Utility Grid

To examine its role in the intermittent utility grid backed up with diesel generator, we have considered the utility structure of LUMS. The primary sources of energy are utility grid, 400 kWp PV system, and diesel generators, as shown in Fig. 4. Details about the PV system specifications are already presented in our earlier work [21, 22]. Due to the sizeable local load, the PV system is not capable of supplying energy back to the grid. In this case study, a scenario is assumed where EVs replace all cars and bikes in LUMS and support the V2G feature (as shown in Fig. 4). Detailed specifications of both motor cars are already given in Table I with typical bike aspects shown in Table 2. All EVs are considered to have an up to allowed 50% SOC discharge.

TABLE II. Technical Specification of Electric Bikes

Technical Specification	**JE-70**	**JE-125**
Motors	48V, 1500W	72V, 5000W
Motor Power	2 HP	6.8 HP
Battery Power	30AH	40AH
Distance Cover in One Full Charge	50-60 km	110-120 km
Top Speed	50 km/hr	80 km/hr
Charging Time	5 hr	8hr
Unit Consumed	1.5 units	3.5 unit

For the year 2017, the consumption of energy units and the cost of those units paid to the utility company by LUMS are shown in Fig. 5 (a) and (b), respectively. It is observed that the monthly energy demand and the corresponding cost exceed from 1000 MWh and $170,000, respectively, for October. In addition, the CO_2 emissions by the back-up diesel generator for this month are about 200 Mg, which is calculated by (2).

$$ECO_2(kg/month) = 2.68 \times \alpha\ (liter/month) \qquad (2)$$

Where ECO_2 represents CO_2 emissions per month, α represents diesel consumption of generators per month, and 2.68 factor represents CO_2 emission per liter of diesel. The CO_2 emission profile for the whole year is also presented in Fig. 5 (c) [23].

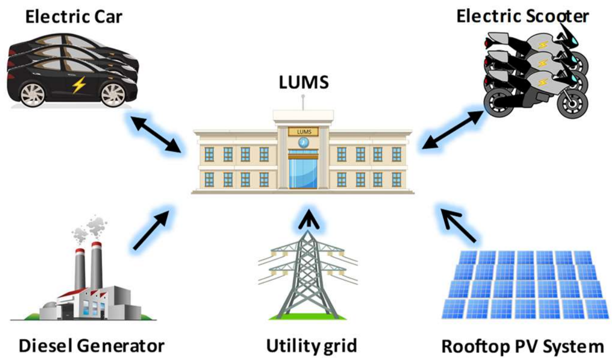

Fig. 4. The utility grid structure of Lahore University of Management Science (LUMS).

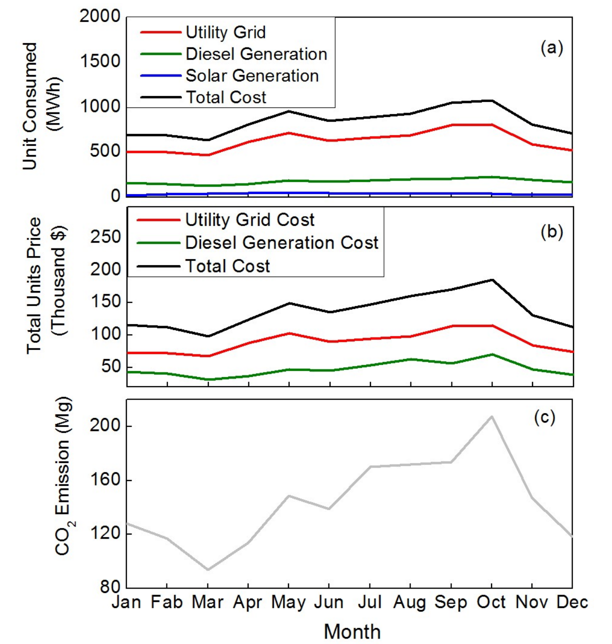

Fig. 5. LUMS energy data (a) the number of units consumed (b) cost of the units consumed and (c) CO_2 emission by the diesel generators.

Along with the energy consumption, it is also essential to evaluate the peak load demand for the evaluation of the maximum demand index. The demand for summer and winter is about 3MW and 1.5MW, respectively, as shown in the average load profile of LUMS in Fig. 6 (a). Due to the various curricular activities on the campus of LUMS, the number of cars and bikes available in the institute varies throughout the day, as shown in Fig. 6 (b). It is observed that on a typical working day, the maximum number of E-bikes and E-cars are 500 and 800, respectively. The corresponding energy available from the EVs throughout the day is shown in Fig. 6 (c).

Maximum energy available through all EVs is around 3.8MWh, which occurs at 12^{th}hour, as shown in Fig. 6 (c). By taking the daily load profile, energy availability from EVs, and the conversion losses of 10%, a back-up time graph for the whole day is obtained, which is presented in Fig. 6 (d). It shows that if the utility grid is interrupted (due to a rolling blackout), then what levels of supply can be maintained through EV storage without the need for high-cost diesel generators. For example, if the utility is interrupted at 11th hour, then the EV back-up time is around 60 min for winter and up to 45 min for summer, which allows lower dependence on costly diesel generation as the energy units produced by diesel generator have almost twice to that of the grid. [24]. Cost and CO_2 emission reduction is about 12% and 25%, respectively, as shown in Fig. 7.

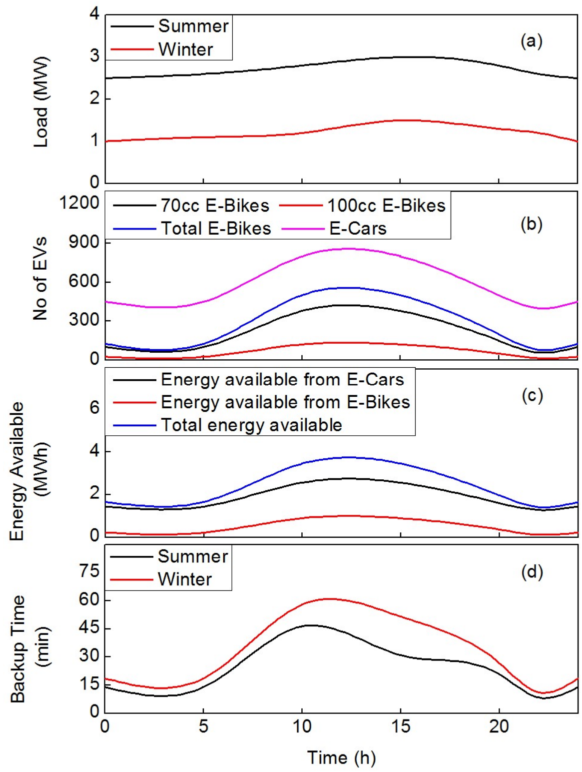

Fig. 6. Variation of parameters at LUMS throughout the day (a) load profile (b) EVs availability profile (c) energy available from EVs and (d) back-up time.

These numbers are likely to vary from one setting to another but gives a general framework for future conversion to EVs or incentivizing these schemes for employees and visitors to use EVs instead of IC engines-based vehicles. From a policy perspective, the reduction in cost and CO_2 emissions become more prominent in the countries where the share of renewable energy resources in the energy mix is high. Furthermore, V2G also support high penetration of PV system due to the storage capability. One of the limitations of V2G is that it decreases the life of EV batteries, so an attractive incentive plan should be composed where EV owners must be provided high incentives for subscribing to V2G plans. The assessment provided in this paper will, therefore, be beneficial for policymakers as well as for a large number of consumers to plan their back-up energy resources for cost and CO_2 emission optimization.

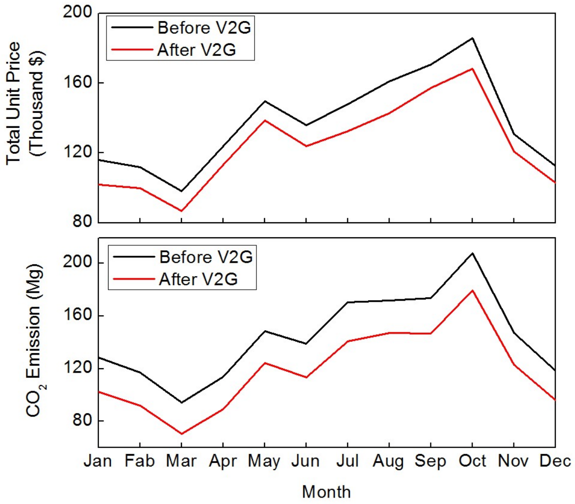

Fig. 7. Reduction of the unit cost and CO_2 emissions before and after incorporation of V2G.

IV. Conclusion

This paper evaluates the benefits of V2G in two scenarios a) non-intermittent grid and b) intermittent grid V2G. For a domestic setting in stable grids, V2G can reduce CO_2 emission 13,429 kg/year with the self-sufficiency of 99.1% with net-metering. However, the case is different for larger enterprizes with higher loads and grid intermittency. In this case, the intermittent grid is backed up with a diesel generator, and V2G can play a critical double role by a) providing the emergency back-up of 45-60min and b) reducing the use of costly and environmentally unfriendly diesel generator. Results show that the cost of electricity units consumed and CO_2 reduction is up to 12% and 25%, respectively, after the incorporation of the V2G feature. These benefits become more prominent when the share of renewable resources in the energy mix increases. Besides, V2G also supports more solar installation and reduces the number of back-up generators due to the high storage capacity. This information is beneficial for EV policymakers to incentivize EVs to allow higher penetrations and reduce reliance on fossil fuels.

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