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Energy Management through V2G concept with EV Charging/Discharging Strategy

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Abstract: - The integration of Vehicle-to-Grid (V2G) technology has emerged as a promising solution for managing energy demand, enhancing grid stability, and reducing peak loads. This paper explores an advanced V2G-based energy management system that incorporates renewable energy sources (RES), such as solar and wind, to further optimize grid operations. By leveraging bidirectional energy flow between EVs and the grid, combined with real-time forecasting of RES generation, the system addresses renewable intermittency and maximizes energy utilization. A novel algorithm is developed to schedule the charging and discharging of electric vehicles (EVs) based on load demand profiles, EV parking plans, and RES availability. The proposed approach ensures that EVs charge during peak RES generation periods and discharge energy back to the grid during high demand hours, contributing to peak load shaving. A case study is conducted for Gujarat, India, demonstrating the effectiveness of the proposed system in reducing grid stress, improving load profiles, and supporting clean energy integration. The results reveal significant reductions in peak loads and enhanced grid reliability, making this approach a sustainable solution for smart energy management. Future work will explore machine learning-based predictive models to further refine energy scheduling and optimize real-time grid support.

Keywords: integration, contributing, reliability

1. Introduction:

The increasing adoption of electric vehicles (EVs) has transformed the energy landscape, offering a cleaner and more sustainable alternative to conventional transportation. However, the rapid rise in EV usage has introduced new challenges for power grid stability, including peak load management and energy demand fluctuations. Simultaneously, the integration of renewable energy sources (RES), such as solar and wind, into the grid has further exacerbated these challenges due to their intermittent nature. To address these issues, Vehicle-to-Grid (V2G) technology has emerged as a promising solution, enabling bidirectional energy flow between EVs and the grid. Through V2G, EV batteries can act as mobile energy storage units, storing energy during periods of low demand (valley periods) and discharging back to the grid during peak load hours, thereby enhancing grid stability.

While V2G technology alone can optimize energy flow and reduce peak loads, its potential is further amplified when integrated with RES. Solar energy, for example, peaks during midday, while wind energy production often rises at night. By aligning EV charging schedules with these RES generation patterns, excess renewable energy can be stored in EV batteries and utilized when needed. This dual integration not only mitigates renewable intermittency but also reduces the reliance on non-renewable energy sources, promoting a cleaner energy ecosystem.

This paper focuses on an advanced energy management strategy that combines V2G technology with renewable energy integration for smart grid applications. A novel algorithm is proposed to optimize EV charging and discharging schedules based on:

- Real-time load demand profiles,
- EV parking plans, and
- Renewable energy generation forecasts.

The objective is to shave peak loads, enhance energy utilization, and support dynamic grid operations without compromising the driving needs of EV users. A case study for Gujarat, India, is presented, leveraging its significant solar energy potential to demonstrate the benefits of the proposed approach. The results highlight

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improvements in grid stability, reduced peak demand, and increased renewable energy utilization, paving the way for a sustainable energy management framework.

In subsequent sections, this paper discusses the current challenges of peak demand management, introduces the proposed algorithm, and evaluates its performance through simulations. Future directions include exploring predictive machine learning techniques to further optimize energy scheduling for real-time grid applications.

2. Background

3.1 Load Demand and Grid Challenges

Modern power grids face significant challenges in balancing electricity supply and demand. High peak loads occur due to unplanned power plant outages, load forecast inaccuracies, weather conditions, or non-disposable loads. These peaks strain the power system, impacting grid stability, efficiency, and operational costs. The rise in distributed renewable energy sources (RES), such as solar and wind, further adds unpredictability to the system due to their intermittent generation patterns.

To mitigate peak loads and enhance grid reliability, energy storage technologies play a vital role. However, implementing large-scale stationary energy storage systems remains costly. As a sustainable alternative, electric vehicles (EVs) with Vehicle-to-Grid (V2G) capabilities can act as mobile energy storage units. By scheduling charging and discharging during valley and peak periods, EVs can significantly reduce grid stress and support load balancing.

3.1.1 Load demand profile for Gujarat State [3]

The peak Demand and energy requirement during 2022-23 was around 21464 MW respectively. The peak demand observed for the period 2023-24 (as on 31st September 2023) is around 24544 MW. The Daily peak demand of GUVNL for the period 2022-23 is shown below. It is observed that the peak occurs during the month of April-May and during day time [3].

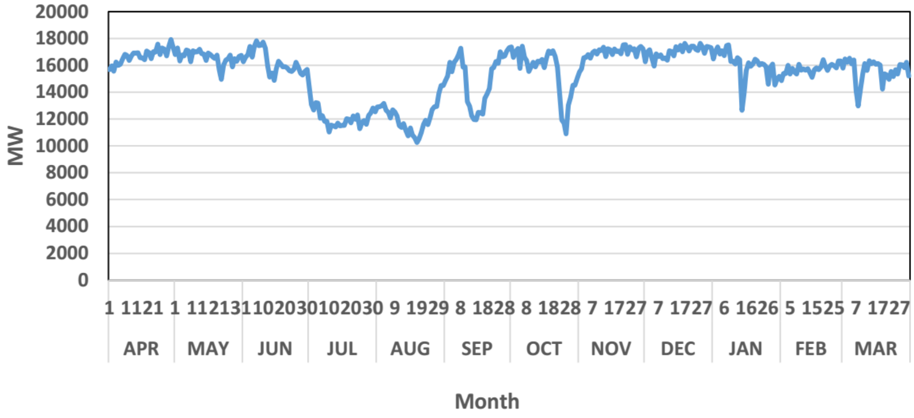


Fig.1 Load demand of gujarat state

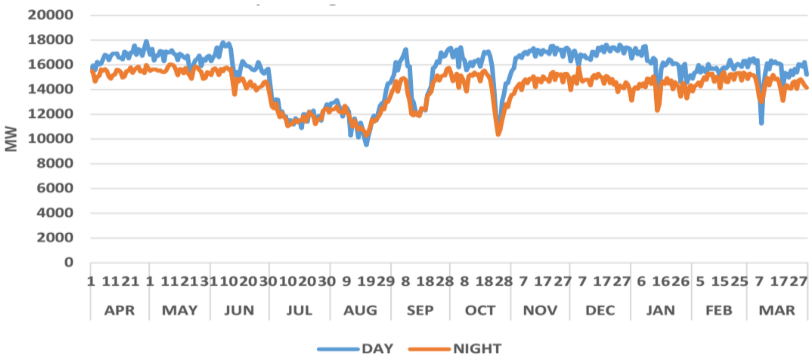


Fig. 2 Day - Night peak demand of gujarat state

The above graph reflects the comparison of the daily peak demand for day time and night time. It can be observed that day peak is higher than night peak for almost all months in a year. Gujarat has taken various initiatives such as feeder segregation and agricultural load shift for shifting the peak demand during day time.

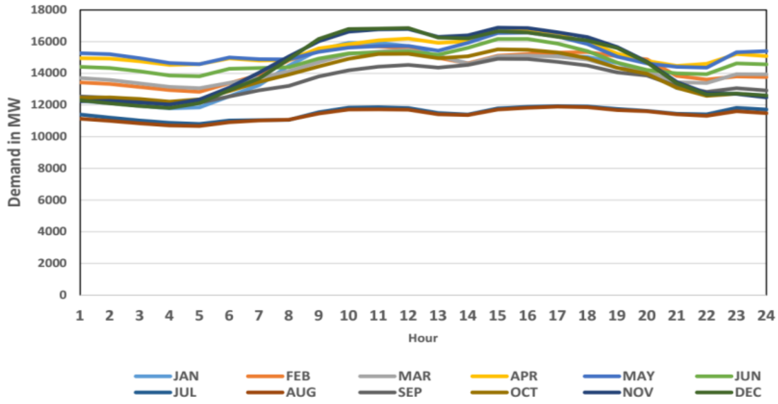


Fig. 3 yearly seasonal demand

From the above the demand pattern, it is evident that peak occurs mostly during day hours and the day and night demand is similar during the month March-June while there is significant difference between night and day demand during other months. The demand pattern during low demand season is flat while demand rises by about 60 % during peak demand months.

3.2 Electric Vehicles as Energy Storage Units

The transportation sector has witnessed a paradigm shift with the adoption of EVs, which offer a cleaner and more efficient alternative to traditional fuel-powered vehicles. Advances in battery technologies and government initiatives have contributed to the increasing number of EVs globally. In India, the rapid growth in EV usage presents an opportunity to leverage EV batteries for grid support through V2G technology.

EV Specifications (Example):

- **Model**: Tata Nexon EV
- **Battery Capacity**: 40 kWh
- **Range**: 465 km
- **Charging Times**:
  - AC: 6 hours at 7.2 kW (10–100%)
  - DC: 50 minutes at 50 kW (10–100%)

3.2.1 EV Charging and Discharging Profile

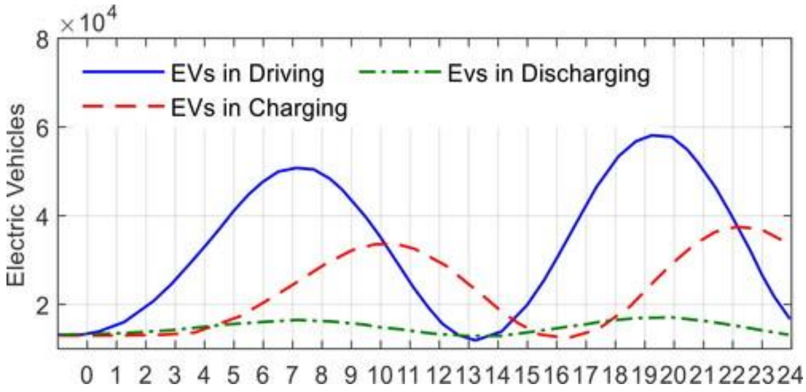


Fig. 4 EV charging discharging demand profile [5]

The graph illustrates the charging, discharging, and driving profiles of electric vehicles (EVs) over a 24-hour period. The number of EVs in driving mode peaks during morning hours (7–9 AM) and evening hours (5–8 PM). This trend reflects typical commute patterns, where EVs are used for transportation during office hours. The charging activity rises significantly during off-peak hours (midnight to early morning, 0–6 AM) and again increases during the daytime (around 6 PM to 9 PM). This indicates a strategic effort to charge EVs during low-demand periods to avoid grid stress. The discharging activity is minimal but increases slightly during peak hours (8–11 AM and 6–8 PM). This shows EVs contributing to grid stabilization through Vehicle-to-Grid (V2G) technology by discharging energy during high-demand periods.

There is a clear inverse relationship between driving and charging patterns, where EVs are primarily charged when not in use. Discharging patterns are aligned with peak grid demand periods, demonstrating the role of EVs in peak load shaving. The graph effectively highlights the potential of EVs in supporting grid stability through optimized charging and discharging schedules.

3.3 Charging Infrastructure and Uncontrolled Charging

The increasing number of EVs requires an extensive network of Electric Vehicle Charging Stations (EVCSs) to support their operation. EVCSs act as intermediaries between the grid and EVs, managing power flow during charging and discharging. However, uncontrolled charging, where EVs charge based on user preferences without considering grid conditions, can exacerbate peak demand issues.

Challenges of Uncontrolled Charging:

- Overloading of grid infrastructure during peak hours.
- Voltage instability and power quality issues.
- Inefficient utilization of renewable energy.

To overcome these challenges, coordinated and optimized charging strategies are necessary. Integrating V2G technology with smart grid systems allows EVs to charge during valley periods (when grid demand is low) and discharge during peak periods, reducing strain on the grid.

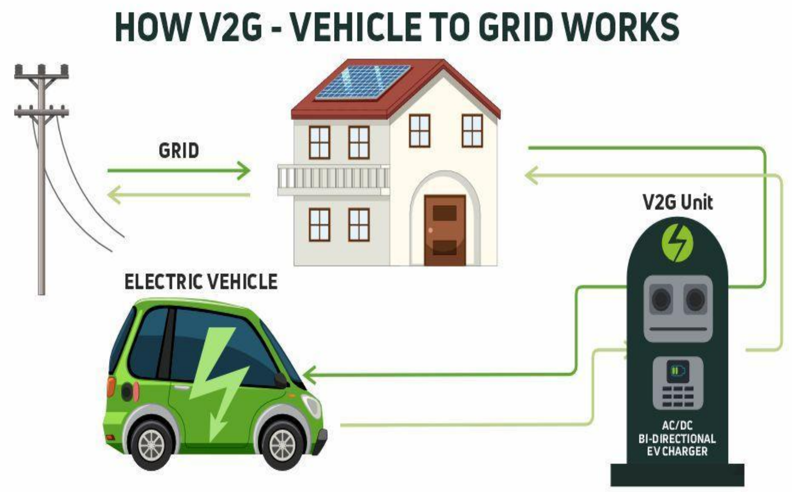


Fig. 5 Vehicle to Grid technology

3. Vehicle-to-Grid (V2G) Technology

A bidirectional power would flow from the power source with the charging device. when charging the battery from the grid to the battery and vice versa when the battery is being discharged to the electrical grid. The integration of bidirectional converters within Vehicle-to-Grid (V2G) technology represents a pivotal advancement in electric vehicle (EV) infrastructure. The schematic diagram illustrates the bidirectional power flow between an EV and the power grid.

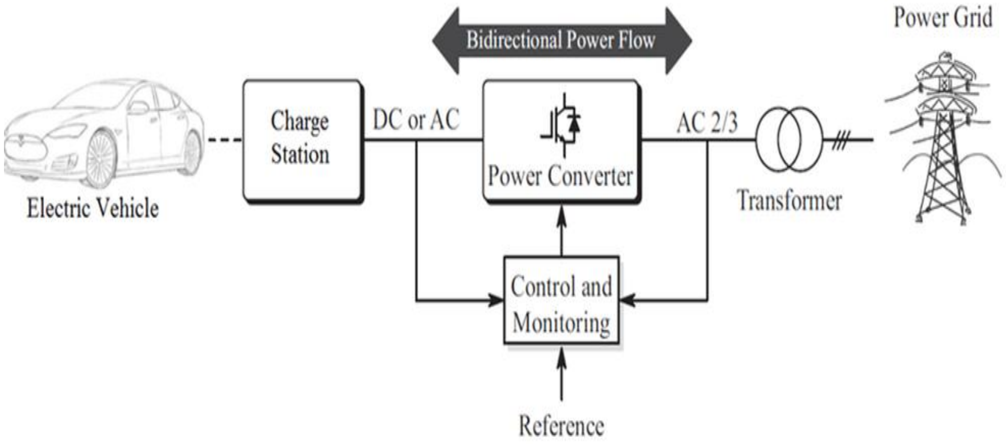


Fig. 6 Bi-directinal power flow for V2G concept [7]

The converter is connected to a transformer, which adapts the voltage levels for seamless integration with the power grid. Central to this system is the control and monitoring unit, which ensures the safe and efficient operation of the power flow. This unit responds to reference signals, dynamically adjusting the power exchange based on real-time grid conditions and EV requirements. However a control algorithm is required to schedule the charging and discharging of the batteries in electric vehicles. Using an appropriate timing of the cycles for charging and discharging, there could be less fluctuations in the peak load needs. A proposed idea adjusts fluctuations in peak load and demand by using the batteries from electric vehicles.

Benefits of V2G Technology

i) Virtual Power Plant: Thousands of EVs are synchronized via V2G technology, which functions as a decentralized energy system. It balances the grid, charges during periods of low demand, and provides power during periods of peak demand. A Virtual Power Plant (VPP) is the name given to this arrangement. In contrast to conventional power plants, virtual power plants (VPPs) combine many energy resources, such as solar panels, batteries, and electric vehicles (EVs), and employ cloud-based software to manage thousands of battery systems to make a virtual big-scale energy storage system.

ii) Grid Stabilization: Electric vehicles may return stored energy to the grid when needed thanks to V2G's ability to permit bidirectional energy flow. Through the balancing of supply and demand changes, this capability aids in grid stabilization, particularly during emergencies or peak hours.

iii) Voltage Support: By supplying the grid with voltage assistance, EVs with V2G capability will ensure steady and reliable voltage levels.

iv) Backup Power: EV that is Bidirectional Grid support is not the only function of the chargers that enable V2G. These robust technologies have power inverters, and the majority of contemporary bidirectional chargers may also activate backup power in case of an emergency or blackout. A bidirectional inverter must first be islanded—that is, disconnected from the grid network—in order to power a home without the need for the grid.

v) Peak Load Shaving: Reduces the peak-to-valley ratio of the grid load curve.

vi) Integration of Renewable Energy: V2G facilitates the incorporation of renewable energy sources into the grid. Electric vehicles can accumulate surplus energy produced from renewable sources such as solar or wind power and provide it when required, thus promoting a cleaner and more sustainable energy portfolio, diminishing overall greenhouse gas emissions, and improving environmental sustainability.

During active hours from 5 AM to 9 PM, electricity is transmitted from renewable sources (wind/solar), while the storage system remains in standby mode. The solar unit is completely active, generating maximum energy during this period and fulfilling the energy requirements at the EV charging station. Figure 7 illustrates the contrast of the aggregated energy from wind and solar sources with the electric vehicle charging station, with many charging points now deemed operational.

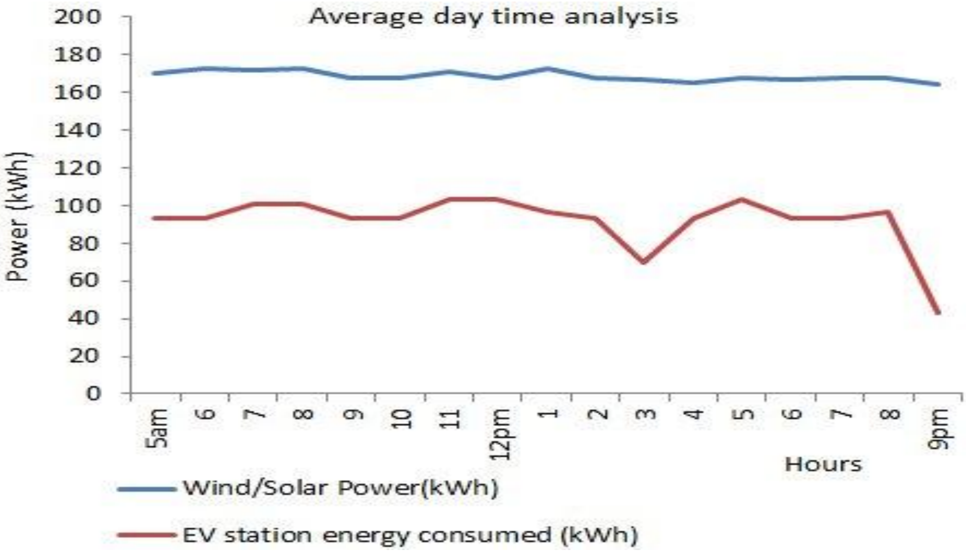


Fig. 7 Energy consumption profile of EV charging station through renewable energy [6]

Figure 7 illustrates that wind and solar energy generation can independently sustain the electric vehicle station from 5 AM to 9 PM.

4. Need for a Coordinated Charging/Discharging Algorithm

To fully leverage V2G technology, a control algorithm is required to schedule EV charging and discharging based on grid load profiles, EV parking plans, and RES availability. The algorithm ensures that:

- Peak loads are minimized through strategic discharging during high-demand periods.
- EVs are sufficiently charged during valley periods to meet user driving requirements.
- Renewable energy sources are employed efficiently to charge electric vehicles, diminishing dependence on grid power.

5.1 Constraints and limitations:

The following presumptions and conditions were taken into account in this study:

- The EV batteries are not presumed to be fully charged to 100% SOC or fully drained to 0% SOC. A battery's performance over time would be significantly impacted by charging it to 100% or draining it to 0%. The reverse of the State of Charge (SOC) is the Depth of Discharge (DOD)[1].
- The algorithm's stated limitation is that the EVs are supposed to be charged when the SOC falls below 10% and continue to be charged until the SOC hits 90%. In a similar vein, they are released only when the SOC equals or exceeds 90% and are released until the SOC hits 10%.
- To make the study simpler, the charging and discharging rates are taken to be linear and equal, based on the power capacity of the EV charging station. Vehicle batteries and charging stations interchange the same amount of energy, which is regarded as equal to the charging station's capacity.

5.2 Proposed Flowchart: V2G Charging and Discharging Optimization

The integration of electric vehicles (EVs) into the power grid through Vehicle-to-Grid (V2G) technology has become a critical component of smart energy management systems. These systems aim to optimize the use of available energy resources, improve grid stability, and promote sustainable energy practices. The scheduling of EV charging and discharging plays a pivotal role in achieving these goals. The flowchart provided illustrates a systematic approach to managing this process effectively.

The flowchart in Figure 5 provides an explanation of the V2G charge-discharge algorithm. It demonstrates the algorithm's step-by-step progression. The peak and valley slots for each vehicle's stay are determined when the parking plan and SOC have been created and imported. The charge-discharge window is then established depending on the scenario conditions and the driving demands of the EV. The EVs are scheduled to charge or discharge based on the power availability in the corresponding valley and peak slots after the charge-discharge window has been established. The charge-discharge window is shortened to the next available slots after scheduling is finished, and scheduling is then continued.

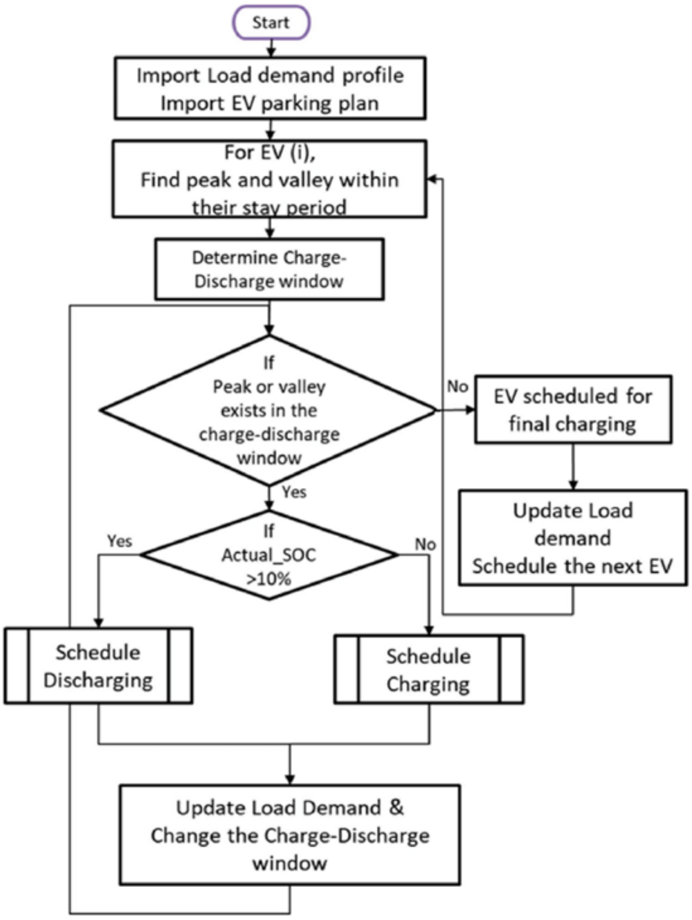


Fig. 8. Proposed algorithm for schedule charging - discharging

This flow chart outlines the process for scheduling the charging and discharging of electric vehicles (EVs) based on load demand profiles and EV parking plans to optimize energy management. A python program has been created to execute this algorithm. Input and output are stated as below.

Input data:

1. Daily Load Demand of Gujarat [2]
2. EV Charging station data with parking plan
3. Initial state of charge (SOC)

Date: 10/12/2024	Daily Load Demand of Gujarat		
Time	Demand (MW)	Time	Demand (MW)
0	13114	12	18238
1	12880	13	18953
2	12779	14	19842
3	12679	15	20086
4	12791	16	19908
5	14085	17	19137
6	15629	18	18227
7	17238	19	16329
8	19789	20	15275
9	20978	21	13982
10	19466	22	13909
11	19294	23	13378

Table: 1 Load demand as an input parameter

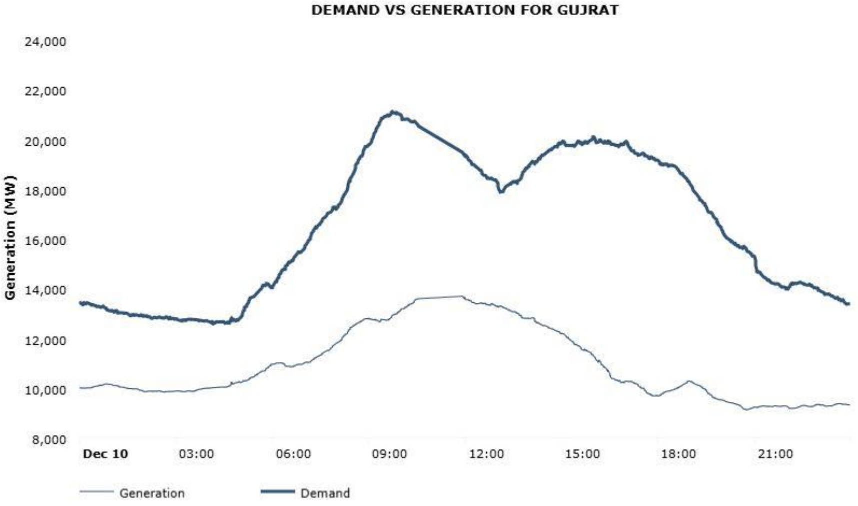


Fig. 9 Difference of Average Demand Vs Generation [2]

Output:

1. Time of charging and discharging
2. Updated SOC
3. Updated load demand

Date: 10/12/2024	Updated Daily Load Demand of Gujarat		
Time	Demand (MW)	Time	Demand (MW)
0	13110	12	18238
1	12850	13	18953
2	12759	14	19842
3	12679	15	20070
4	12791	16	19908
5	14085	17	19020
6	15556	18	18227
7	17198	19	16310
8	19789	20	15190
9	20930	21	13982
10	19285	22	13810
11	19294	23	13222

Table:2 Updated load demand as an output

6. Results and discussions:

Three EV park plan scenarios are simulated using the V2G charge-discharge algorithm, each with three distinct EV population scenarios. This algorithm establishes the EVs' charging and discharging schedule while they are parked. Every vehicle has a specific time slot for charging and/or discharging. This EV charging and discharging schedule is used to modify the load demand profile. When the EV is charging, the load demand rises, and when it is discharging, it falls. Two assessment parameters, such as the load factor and the percentage of peak reduction, are used to compare the load demands before and after V2G scheduling. The effectiveness of peak reduction utilizing V2G in each circumstance is determined by these criteria.

A quantitative indicator of the overall decrease in the peak demand value in a load profile is the percentage of peak reduction. According to Eq. 1, it is the percentage drop in peak demand in the load profile before and after scheduling. It can alternatively be described as the ratio of the peak demand value before scheduling to the peak value reduction after scheduling.

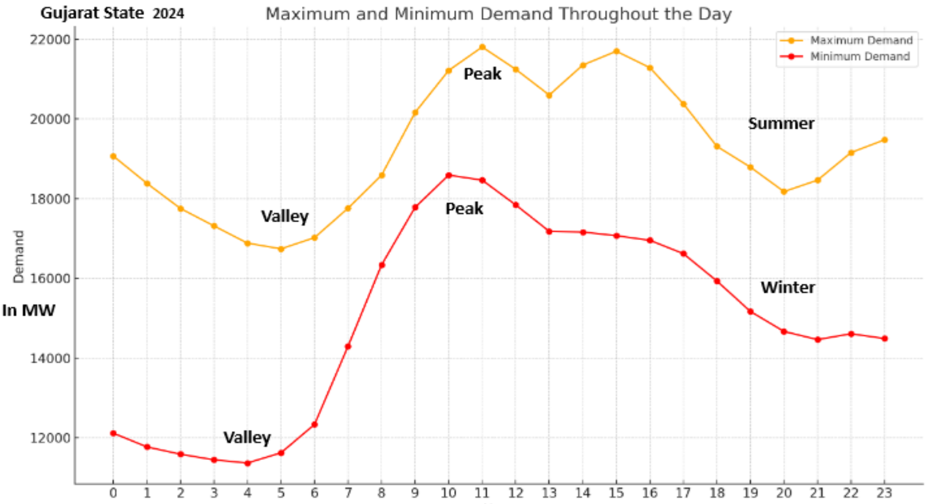
$$\text{Peak\_R.} = \Sigma(\text{Peak\_demand\_b} - \text{Peak\_demand\_a}) / (\Sigma\text{Peak\_demand\_b}) \ast 100 \qquad (1)$$

Peak_R = Peak Reduction

Peak_b = Peak_before

Peak_a = Peak_after

where Peak_demandbefore represents the overall peak demand in the load profile prior to scheduling, and Peak_demandafter represents the entire peak demand following the scheduling of EV charging and discharging as shown in graph.



Data Source: ICED, India

Fig. 10 Load factor without integration Renewable energy [4]

The ratio of the average load demand to the maximum demand over a given time period is commonly referred to as the load factor. The load factor is a measure of the variance in power generation and consumption in load profile analysis. A high load factor indicates that the energy consumption is approximately constant and the load profile has a low peak demand. The load profile has a high peak demand and fluctuating energy usage if the load factor is low. Both before and after the V2G scheduling algorithm is applied, the load factor is computed for the load profile. The load factor difference dictates how well the peak is lowered and how much supply and demand balance is reached as shown in graph. Eqs. (2) and (3) are used to determine the load factors of the load profile before and after scheduling, respectively, which are indicated by the symbols load factor_b and load factor_a.

Load factor_b.= (Average old load demand) / (Maximum peak demand) (2)
Load factor_a.= (Average new load demand) / (Maximum peak demand) (3)
The evaluation factors: Peak_R., Load Factor_b and Load Factor_a are calculated. Considering the variations, due to random parameters in the EV parking plan, the generalized algorithm needs to be made for reliability [1].

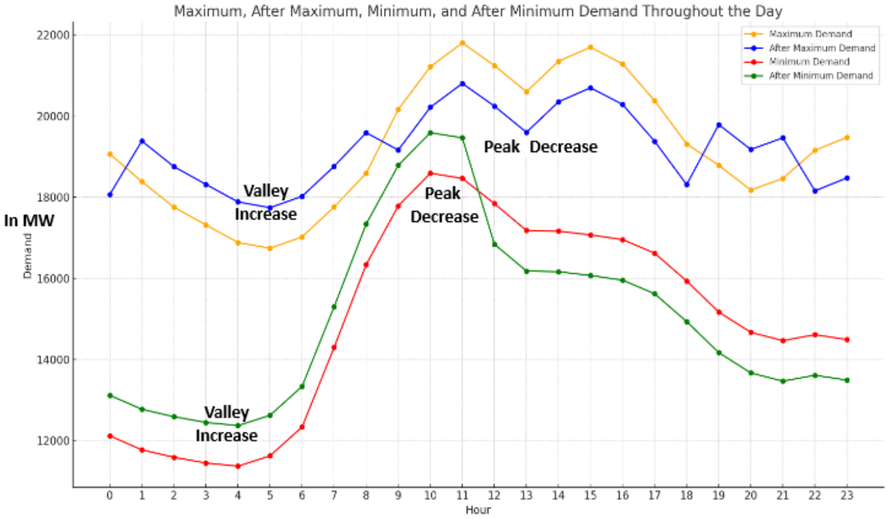


Fig. 11 Load factor with integration Renewable energy and peak load shaving

7. Conclusion:

This research demonstrates the potential of Electric Vehicles (EVs) as mobile energy storage units within the Vehicle-to-Grid (V2G) framework. The study highlights the role of EVs in mitigating grid challenges such as peak load demand, renewable energy intermittency, and grid instability. By strategically scheduling charging during off-peak periods and discharging during peak periods, EVs not only reduce grid stress but also enhance the utilization of renewable energy sources like solar and wind. The proposed coordinated charging and discharging strategy aligns EV activities with grid demands, improving overall system efficiency. The integration of V2G technology with smart grids presents a cost-effective and sustainable solution to meet the growing energy needs of modern power systems while reducing carbon footprints.

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