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Research Article

High penetration of rooftop photovoltaic system in distribution grid – Feeder specific analysis

Brijesh M. PATEL[1,*], Nikunj R. PATEL[2], K. L. MOKARIYA[3]

[1]*Gujarat Technological University Ahmedabad, Gujarat, 382424, India*
[2]*Department of Electrical Engineering, Ganpat University, Kherva, Gujarat, 384012, India*
[3]*Department of Electrical Engineering, Government Engineering College Valsad, Gujarat, 396001, India*

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ABSTRACT

The worldwide industries including Indian Renewable energy industries has been expecting a significant growth in the photovoltaic system deployments in their respective power system grid. To identify the amount of penetration and accordingly make the modifications in view of supply side management and demand side management will be a key area to be focused. This study primarily aimed to explore the impact of PV (photovoltaic) penetration and enhance the utilization of renewable energy at the distribution level for electric vehicle (EV) charging. The goal was to reduce the carbon footprint and increase the adoption of green energy in transportation. Developed algorithm and its results are discussed with actual field data for a selected case study of Feeder 24, Palanpur city of UGVCL Distribution Company. The simulated results with the proposed algorithm show the percentage PV penetration on the feeder on an hourly and daily basis when 282 rooftop consumers are connected to the feeder and this also shows the PV penetration forecast in the future. The proposed algorithm tested on real data of whole city distribution network and the result shows that in the future, when the distribution system will deal with EV load and high PV penetration, finally developed Feeder specific PV penetration-based EV load management system can help to minimize issues due to high SPV penetration and increase renewable energy power for charging of EV for any distribution grid feeder. the approach applying in real-time applications for Palanpur city its result is shown. By expandingacross multiple cities at the state or national level it makes easy and stable operation for distribution company, improve overall national grid stability. It enhances the environmental benefits of EVs, contributing to zero-emission transportation.

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INTRODUCTION

The demand for renewable energy has been increasing due to the depletion of fossil fuel reserves and concerns about greenhouse gas emissions and global warming. Solar photovoltaic (PV) and wind energy are the most widely adopted renewable energy sources. Among them, PV

*Corresponding author.
*E-mail address: bmpgp1412@gmail.com

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power generation has gained significant popularity due to its suitability for residential and commercial applications, along with the decreasing cost of solar panels in the market. Globally adoption rate of the PV systems growing rapidly [1].

High PV penetration introduces operational challenges for grid specifically during low load power demand. Studies show high PV power generation can lead increase power losses, voltage instability, reverse power flow, tripping of protection system [2,3,]. Also continuous over voltage can reduce life of appliances and, some cases, cause PV inverter to cut out from grid cause power losses [4,5].

Several research has been done to understand technical effect of high PV penetration and its possible solutions like use of energy storage, use of smart inverters, demand side load management, and dynamic reactive power control [6,7]. But existing study mainly focused on large size PV integration and specific technique, leaving a gap to understanding the combine effect of various solutions techniques for distribution grid with high residential PV penetrations.

This study aims to minimize gap by analytical study of the effect of high PV penetration at power distribution level and finding potential solutions. The results of said study can help distribution company and policy maker to develop future ready grid management system for accommodation of high PV generation [8].

Table 1 gives an overview of solar PV electricity power install and generation in India, showing the increasing share of PV in the total energy mix [9].

This study is in aligns with two national targets, firstly EV target 30 percent EV sale by 2030 (EV 30@30) and 500 GW generation of power from renewable power generation sources [11,12]. With higher adoption of EV and increasing utilization of renewable energy for charging of EV by integrating EV charging with solar energy, overall system will reduce charging cost for consumer, improve grid stability and reduce carbon emission. Higher utilization renewable energy for charging of EVs lead to reduction of CO_2 emissions, as in line with government of India and international projections. Dynamic EV charging rates depend on solar PV power generation and feeder loading conditions, lead to cost saving of consumers, reduce grid stress, make EV adoption more environment friendly, also economics benefits such as reduce fuel imports, more job creation in renewable energy and EV areas. By shifting EV load to periods of high solar generation or off-peak hours, the system ensures annual grid cost savings of Rs 3–5 crore per MW load shift, contributing to more efficient energy management. This proposed approach as discussed in subsequence section will offer a clearer picture of their overall sustainability. Such an integrated approach will help policymakers refine strategies to maximize both environmental benefits and economic growth. Regulatory Implications recommendations for Feeder specific, PV penetration-based EV charging load management system also discussed in this study.

Recent literature addresses PV penetration and PV-EV coordinated charging. Some of studies have explored EV coordinated charging and pricing mechanisms within the power grid. Table 2 presents a comparative analysis of PV penetration studies, while Table 3 focuses on EV charging load management studies, highlighting research gaps and recent advancements.

The computational performance of the proposed algorithm has been optimized to handle large datasets and extended feeder networks efficiently. It is designed such easy to apply for large scale, its make it utilize for any number of feeders for multiple cities.

The algorithm mainly focusing on maximizing renewable energy (RE) utilization within low-tension (LT) distribution networks at feeder level. It ensuring that electric power generated by PV plant at the distribution level is consumed locally, it improves overall grid stability.

Its scalability and efficiency enable real-time decision-making, ensuring optimal EV charging strategies even for complex and extensive urban power networks.

SPV GROWTH IN INDIA

In India, energy consumption has more than doubled since 2000 [21]. In 2021-22, the country's total electricity generation was 1356 billion units (BU). It shows an increase of about 9.83% of the actual generation of last year. The gross per capita electricity consumption in 2021-22 was 1255 kWh. The increase in renewable capacity to 500 GW by 2030 is expected to likely account for around 44.7% of total gross electricity generation in 2029–30. All the characteristics of power generation in India are shown in the Figure 1[22].

In country residential SPV systems are typically a few kilowatts in size, while commercial and utility systems are

Table 1. Statistics for solar PV power Install and generation in India [9,10] [adopted by author]

Statistics	2022	2024
Installed PV power capacity	60.81 GW (14.91%)	97.86 GW (22.09%)
Total power installed capacity	407.79 GW	442.85 GW
Total power generation capacity	1484.33 TWh	1,948.95 TWh
Share of PV on total power generation	73.48 TWh (4.9%)	102.10 TWh (5.2%)

Table 2. Comparative analysis of PV penetration studies

Ref.	Focus Area	Findings	Research Gap
[13]	Mitigating the duck curve in high-PV penetration grids using pre-cooling strategies.	Tested pre-cooling impact on system net demand in California and Texas.	Potential integration of EV load as an alternative to pre-cooling for duck-curve mitigation.
[14]	Reverse power flow (RPF) challenges in LV networks with high PV penetration.	RPF increases with PV penetration, leading to relay miscoordination and nuisance tripping Thermal loading limit sat 80% PV penetration.	Include modelling solar radiation variability.
[15]	Safe PV penetration limits and voltage regulation in LV networks.	Voltage violations occur at 2.5% localized PV Penetration, while distributed PV can reach 110%, but voltage control becomes challenging above 20% PV capacity.	The economic impact of voltage control mechanisms.
[16]	Hosting capacity analysis and optimization for PV-grid integration.	Developed a framework for determining location-based hosting capacity.	Integrating real-world case studies

Table 3. EV charging load management studies

Ref.	Focus Area	Findings	Research Gap
[17]	Real-time electricity tariff estimation for EV charging using day-ahead forecasting.	Analyzed different energy mix scenarios: fossil fuel, solar PV + fossil fuel, and solar PV + hydrogen storage. - Identified cost variations based on energy mix.	Developed system by considering whole grid scenario, Analysis can be done for distribution network.
[18]	Demand-side management (DSM) of EV charging stations using deep learning-based forecasting.	Demonstrated that EV charging stations help in peak load saving and managing microgrid by connected EV stations.	Incorporate pricing and economic impact analysis.
[19]	Optimal power-sharing and scheduling for EV charging stations using distributed consensus-based optimization.	sharing among different EV charging stations. - improve energy economics and cost efficiency.	Can explore renewable energy integration.
[20]	Optimal placement of solar powered EV charging stations for reliability improvement.	Compared system reliability with and without PV integration.	Can be consideration existing Solar rooftop system.

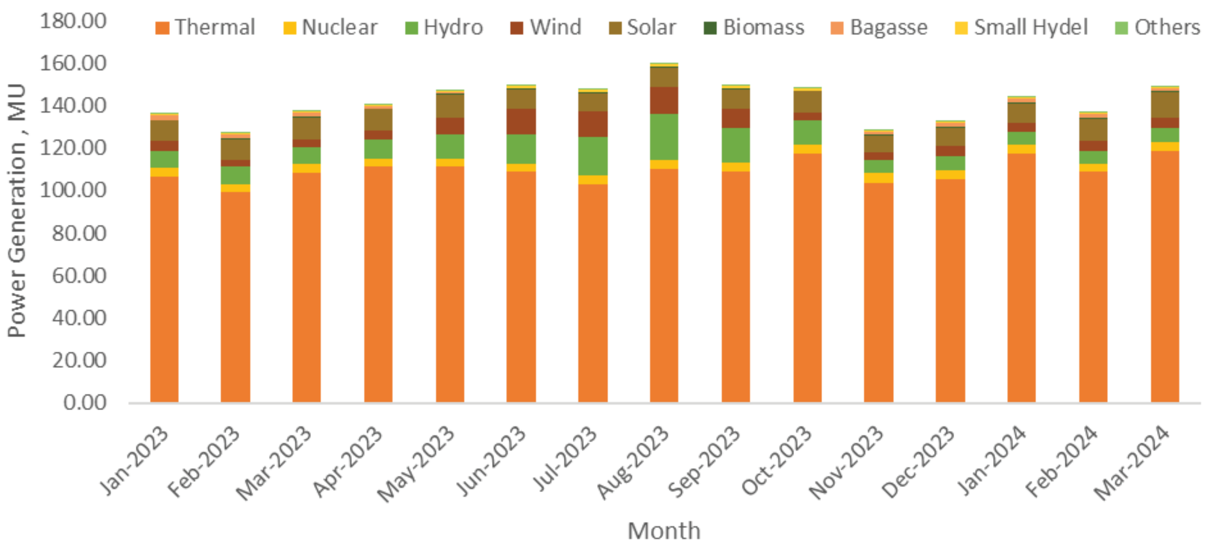

Figure 1. All India Power Generation Growth [23] [adopted by author].

generally on the megawatt scale. The integration of renewable energy sources such as residential photovoltaic systems into Low Voltage (LV) distribution feeders helps to increase the level of energy production in the system without additional large generation and transmission units that require high costs [8].

The Indian government aims to install 100 GW of grid-connected solar power by 2022[24]. However, at the current rate, only 38% of the target is expected to be achieved. To achieve this goal, the Indian government has launched a number of schemes to promote solar power generation in the country, so name it Solar Park Scheme, Central Public Sector Undertaking (CPSU) Scheme, Viability Gap Financing (VGF) Schemes, Channel Bank and channel top Scheme, Grid Connected Solar Rooftop Scheme etc [25].

India has reached the 4th position in the world in solar power installation. As of November 2022, solar projects with a capacity of 61.97 GW have been commissioned in the country [10]. With the development of new technologies, economics and reduction in prices of solar cells/modules, solar tariff is now viable in India. The annual results of the solar power project are shown in Figure 2 [26].

In FY2022, 10.1 GW utility scale solar capacity with 2.2 GW roof top capacity was added by India. In country top three states were Rajasthan, Gujarat and Uttar Pradesh with 6, 1.9, 0.5 GW capacity respectively. For the FY2023, however, 3.5 GW roof top solar projects and 16.5 GW utility solar scale projects are to be commissioned [27].

INDIAN DISTRIBUTION NETWORK AND SOLAR ROOF-TOP TOPOLOGY

Distribution network is the most important network in the whole power sector. It is the only interface between utilities and consumers, it's a cash register for the entire sector [28].

The distribution network conducts electricity from the transmission termination point, at the 66/33 kV level. The standard voltages on the distribution side are 11 kV and 0.4 kV/0.230 kV [29]. Standard supply voltage at consumer end, i.e. Single-phase voltage 230/240V, and three phase voltage 400/415V [30].

The Government of India is rolling out rooftop solar program Rooftop for a total 40,000 MW capacity by Rooftop Solar Projects by 2022 (Table 4,5). Residential rooftop installed and connected to the distribution grid.

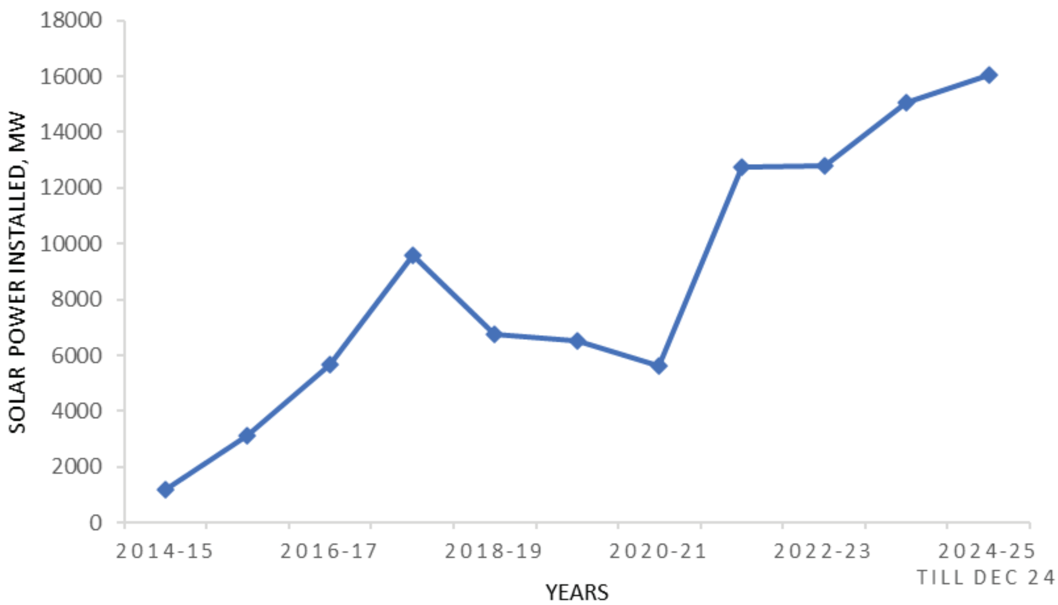

Figure 2. All India grid tie SPV installation growth [25] [adopted by author].

Table 4. The rated voltage A.C. supply distribution network [31] [adopted by author]

Category	System Voltage Level
For All installations up to and including 6KW Connected Load.	230 Volt Single Phase
For All installations above 6KW and up to 100 KVA/KW of Connected Load.	400 Volt Three Phase

Table 5. Permissible voltage variation limits in distribution network [30] [adopted by author]

Standard voltage level at consumer end (India)	Permissible limit
230 Volt, 50 Hz, Single Phase	±6% Upper Limit= 243.8V, Lower Limits= 216.2 V
400 Volt , 50 Hz, Three Phase	±6% Upper Limit= 424 V, Lower Limits= 376 V

Inverter is connected with SPV plants to convert direct current to alternating current as per frequency level of grid. An inverter designed to synchronize with the grid so that the generated power from the module can be injected into the grid [32].

INVERTER AND GRID SYNCHRONIZATION

Inverter is very most important part of SPV grid tie roof top system

SPV system Inverters are classifying as below:

a) Grid Tie Inverter
b) Off Grid Inverter
c) Hybrid Inverters

Single-phase grid-tied inverters provide an output of 220–240 VAC, single-phase, 50 Hz, while three-phase inverters deliver an output of 415–440 VAC, three-phase, 50 Hz [33]. The solar PV grid connection levels are outlined in Table 6 [34].

Each inverter of the rooftop solar PV system must be equipped with an automatic synchronizing device, the operation of the PV system should not cause voltage flicker exceeding the limits specified in the relevant parts of the International Electrotechnical Commission (IEC) series 61000[24] The voltage and frequency set point in Grid tie Inverter is shown in Table 7.

A rooftop solar photovoltaic system synchronized with the electrical distribution network must be equipped with the following protection functions [37].

1. Overvoltage and under voltage protection if the voltage rises above 110% or below 85% considering 02 second clearing time.
2. Protection against over or under frequency with clearing time of 0.2 second.
3. The inverter of the rooftop solar PV system should be able to withstand 220% of the rated voltage.
4. The total distortion of the harmonic current at the output of the converter must not be greater than 5% [38].
5. Voltage flicker: The operation of the photovoltaic system should not cause voltage flicker [35].

PROBLEMS WITH HIGH PHOTOVOLTAIC PENETRATION

In a grid type inverter if the grid voltage is higher, the inverter tries to increase its output voltage to meet the requirement to export energy to the grid [39].The inverter has set low and high voltage values as shown in Table 5, and accordingly inverter starts supplying the grid or will get disconnected from service [35].Therefore, LV distribution networks must evolve to accommodate the increased penetration of photovoltaic in order to reap the maximum benefits from green energy sources. There are various technologies in the literature that focus on solving voltage regulation problems [8]. Table 8 shows the summary of Key Penetration issues on distribution networks.

As a study on real LV outlets, several investigations have been carried out to determine the effects of high PV

Table 6. Solar PV grid connectivity level [35] [adopted by author]

S.r. No.	Consumer connected load	Level of Connectivity
1	Up to 6kW	240V, Single Phase
2	Above 6kW and upto18.65kW	415V, three phase
3	Above 18.65 kW and up to 100KW/ kVA	High Tension (HT)

Table 7. Voltage and frequency set point (Cut off) in grid tie inverter [35,36] [adopted by author]

	Frequency Min	Frequency (Max)	Voltage (Min)	Voltage (Max)
Single Phase System	49.2 Hz	50.3 Hz	184V	253V
Three Phase System	49.2 Hz	50.3 Hz	320V	440V

Table 8. Summary of key PV penetration issues on the distribution network [9] [adopted by author]

Sr. No	High PV penetration possible issues	Action to be taken
1	Tripping of PV systems during system voltage drop/ up events	May effect consumer equipment's distribution transformer voltage regulation.
2	LV distribution system voltage Management	Distribution transformer voltage regulation.
3	Reverse power flow	Issue may rise in protection system.
4	Harmonic injection	Not considered an issue for Grid tied Inverter.
5	PV system islanding	Distribution transformer voltage regulation.

Installations effect on distribution network. These study shows adverse effect on voltage level and distribution power losses [40,41]. Mainly need for a more intelligent network for effective monitoring [42]. Other study shows how line impedance, length and short circuit resistance of distribution transformer plays significant role in determining the voltage level effect [43]. Other relevant literature has shown how OLTCs, solar inverter and distribution network connected batteries can maintain the voltage, by Tap changing transformer, [44,45].

POSSIBLE SOLUTIONS FOR HIGH PHOTOVOLTAIC PENETRATION

Possible solutions to overcome Problems with high photovoltaic penetration includes batteries connected in distribution network, Inverters connected in system, DSTATCOM, export power limit, Reconductoring and rearrangement distribution line is as follow [7].

Battery Energy Storage System

Storing the PV generated energy in the battery gives answers to number of questions a raised, but depth of discharge, day of autonomy needs to be carefully selected.

Solar Inverters

By enabling the Volt-VAR mode of solar inverter to support reactive power, it is either necessary to reduce the actual energy production or to increase the size of the inverter[34].

Sale Power Limit:

To overcome the problems due to the high penetration of PV, introduce export limits to limit excessive energy backflow.

DSTAT-COM:

During peak periods of PV power generation can use

Distribution static compensators (DSTATCOM), but at low voltage level of distribution level R/X ratio is high, reactive power compensation is not good solution.

Re-conductring:

Replacing old grid conductors with larger conductors with a large area (to increase load capacity) it can make grid more capable for high PV power generation without voltage rise/low problem.

CASE STUDY

Uttar Gujarat Vij company limited (UGVCL)is one of the big distribution companies in Gujarat and in Palanpur city. In Palanpur city with distribution network residential consumers and industries are connected some of consumer connected in network with Rooftop SPV system with different installed capacity as shown in below Table 9.

The UGVCL distribution network in Palanpur city is with high penetration of grid tie PV system in some of feeders, below table shows number of consumer with Rooftop PV system connected with different feeders of Palanpur City.

Table 9. Statistics for solar PV electricity generation and demand, feeder24 of Palanpur City

Statistics	Value
Installed PV Capacity.	1076.65 KW
Total PV Generation Capacity per day.	4875.62 Units
% Share of P.V.	28.19 %
Total Electricity. Demand per day with SPV Roof-top.	12420 Units
Total Electricity demand per day without SPV Roof top.	17295.62 Units
Average size of Rooftop SPV.	3KW

Table 10. Summary of rooftop SPV consumers connected on distribution network.

Feeder labels	Number of customer	Installed solar load KW
Feeder - 1	6	18.38
Feeder –2	242	879.78
Feeder –3	110	384.97
Feeder –4	85	327.61
Feeder –5	1	2.6
Feeder –6	46	148.13
Feeder –7	6	17.94
Feeder –8	55	191.55
Feeder –9	134	492.25
Feeder –10	2	5.94
Feeder –11	27	100.93
Feeder –12	125	405.21
Feeder –13	18	153.3
Feeder – 14	73	304.97
Feeder – 15	125	459.96
Feeder – 16	32	134.57
Feeder – 17	2	5.94
Feeder – 18	1	2.99
Feeder – 19	2	10
Feeder –20	26	199.37
Feeder –21	66	271.59
Feeder –22	39	281.3
Feeder –23	180	664.9
Feeder –24	282	1076.65
Feeder –25	7	48.96
Feeder - 26	127	448.51
Grand Total	**1819**	**7038.3**

Above Table 10 shows total 1819 consumer of Palanpur city with average size of 3 KW Rooftop PV is synchronize with distribution network and total install SPV capacity is 7038 KW.

PROPOSED ALGORITHM AND RESULTS WITH FIELD DATA

The proposed algorithm is designed to compute solar PV penetration on any distribution feeder based on the number of rooftop SPV consumers connected. It calculates and plots total PV generation per day or per year for connected rooftop plants and provides results at both individual consumer and feeder levels. The algorithm was tested using real data from the 11 kV distribution feeder number 24 of Palanpur city, where 282 consumers have rooftop SPV installations, total 1076 kW.

This algorithm not only determines the solar PV power generation characteristics of each consumer but also enables analysis for any number of feeders and consumers within a distribution network. It estimates PV penetration over different feeders and also analyses load factor of each feeder with and without PV power. It will facilitate grid stability study for integrating PV power generation with EVs charging load, we will discuss in upcoming section.

The developed algorithm allows for analysis of large-scale data for scaling up to entire city or multiple urban areas, make it more efficient tool for large scale grid stability improvements. Additionally helps stake holders like policy makers, grid operators to take decisions on renewable power integration and grid optimization.

Load Profile

Proposed algorithm first compute load profile of selected feeder. The Measured load data at sending end point of feeder at 66/11Kv substation as shown in Figure 3,

Mathematical model as follow to calculate actual load energy on feeder:

$$PL_n = PL_a - P_s \tag{1}$$

Where,

PL_a and PL_n show the actual and net load energy on the feeder respectively.

P_s is annual or daily Energy produced by SPV Rooftop system,

PV Generation

Automatically estimate total SPV energy generation on feeder and SPV energy generation by individual consumer from the installed Rooftop SPV system data of each consumer on feeder shown in Figure 4. The daily PV generation of the studied networkfeeder24 for fixed mount module tilt at 45-degree angle, for south facing module is around 4.5 KWh per day from 1KW system.

Proposed Algorithm

The detail flow chart of proposed algorithm is shown in Figure 5. The details of steps are as under.

1. Read The feeder Load Data (KWh) and Installed Solar Rooftop (KW) Capacity on feeders.
2. Compute SPV power generation for each customer on feeder for selected time period (Yearly or Daily).
3. Repeat step 2 for all solar Rooftop systems on feeder, generate data sheet for each.
4. Estimate the total SPV power generation on feeder.
5. Estimate actual load on feeder and plot data.
6. Compute PV penetration on feeder hourly, daily and yearly.
7. Repeat process for N number of feeders.

PV Penetration on Feeder No. 24 and at Different Area of City

This algorithm was implemented using Python code for a balanced operational state of the network. The above

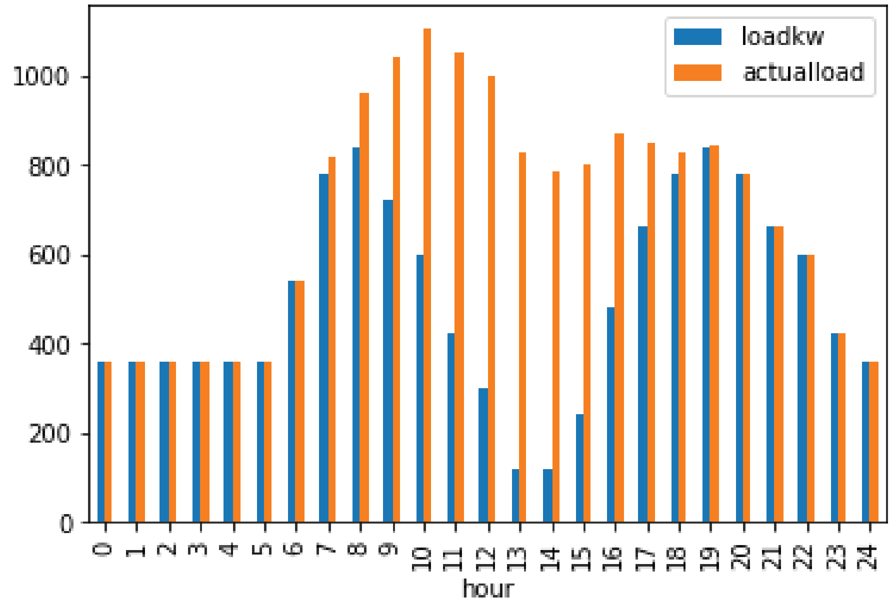

Figure 3. Computed actual load (KWh) and net load (KWh) (Feeder 24) on 15, January,2022.

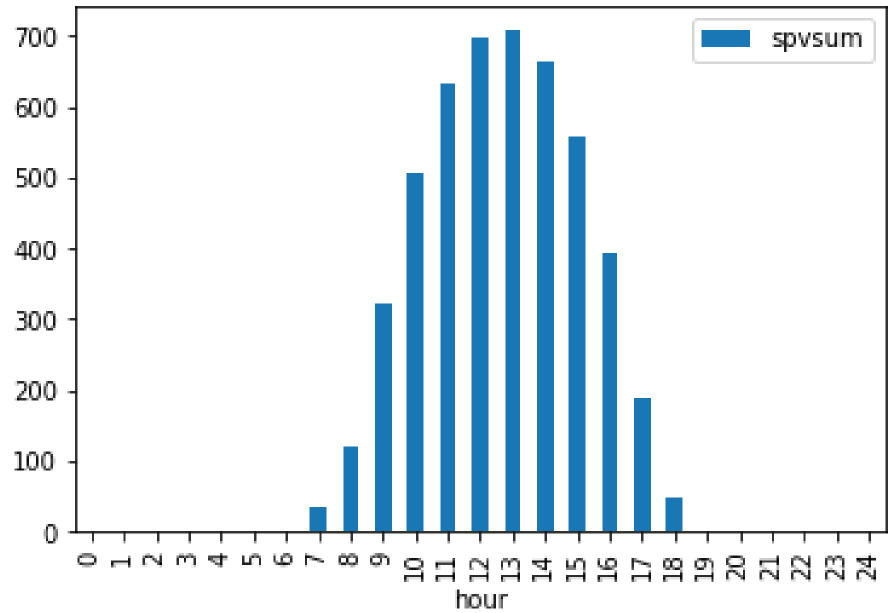

Figure 4. SPV rooftop power generation (KWh) on feeder-24 per Day on 15, January, 2022.

proposed algorithm was tested with actual data of distribution feeder24 of Palanpur city and calculated solar power generation data and graph for the entire feeder, for individual consumers and accordingly estimated the actual load profile of selected feeder 24to estimate the PV penetration on the feeder24 and comparative analysis of PV penetration across different areas of city.

PV penetration present day (15th January,):

PV penetration (PV_{pen}) is defines as the amount of yearly load electric energy injected by solar PV. Math's model , as:

$$PV_{pen} = \frac{P_s}{PL_a} \tag{2}$$

PL_a, Actual load on feeder per day = 17295.62 KWh
P_s, Solar PV power generation per day = 4875.62 KWh

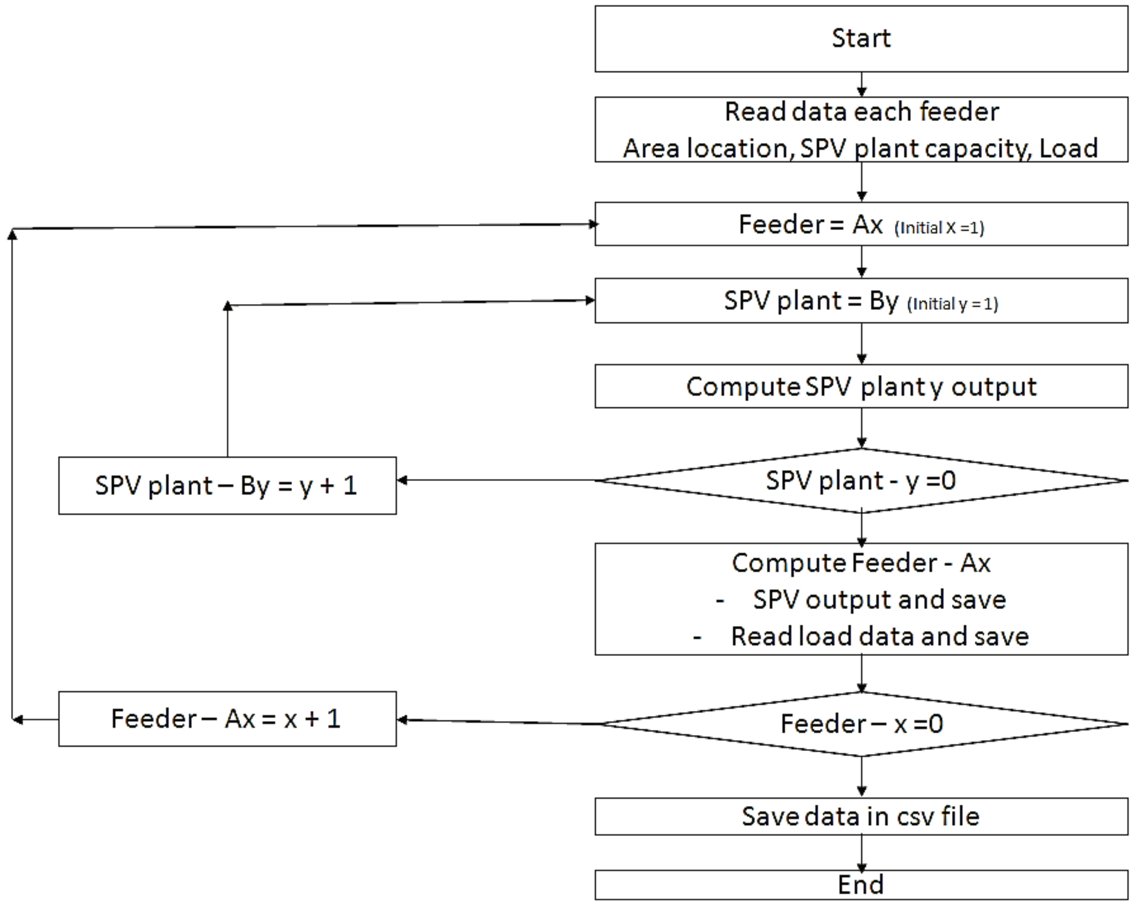

Figure 5. Proposed algorithm flowchart.

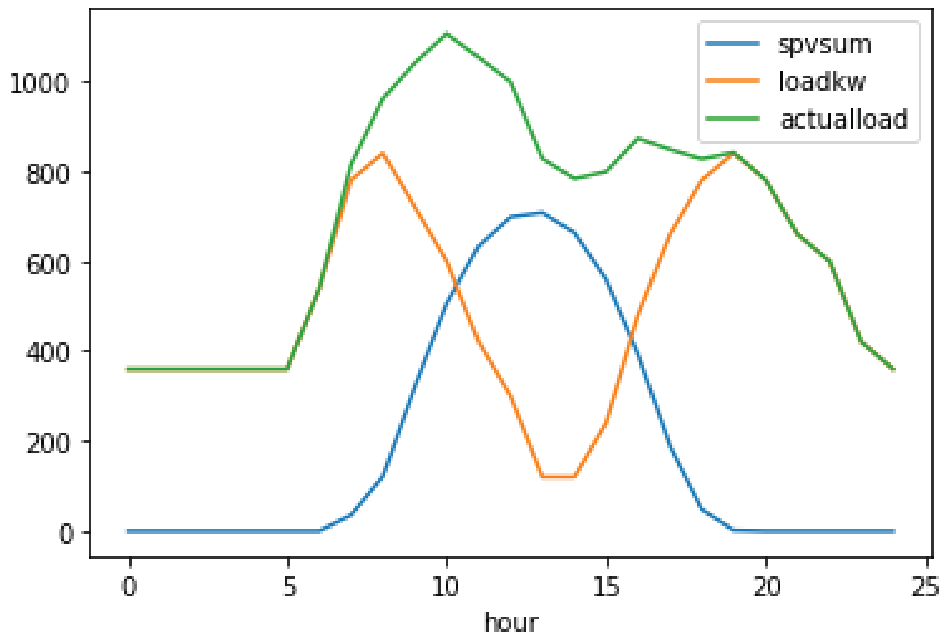

Figure 6. Load curve of feeder24 with actual and net load profile when SPV connected in system.

PV_{pen}, Total PV Penetration per day = 28.19 %

In this Study PV Penetration computed for Feeder24 the PV penetration is 28.19 % per day and result shows 28.19% of total electric energy is supplied by the connected Roof top Solar PV on that feeder 24. Also estimate penetration on feeder hourly or yearly this data can also useful for further study.

Above Figure 6 shows during mid-day time dip in load curve, this is due to presence of solar energy on feeder during day time. If we neglect the SPV generation then actual Load consumption by feeder for whole day is shown by green line.

The above Figure 7 presents a comparative analysis of PV penetration across different areas of city, illustrating the penetration levels for all feeders. This data can be utilized to develop systems aimed at improving grid stability, as discussed in the upcoming section.

Furthermore, this analysis helps for large system to address key research gaps, including:

- Potential integration of EV charging load for duck-curve mitigation.

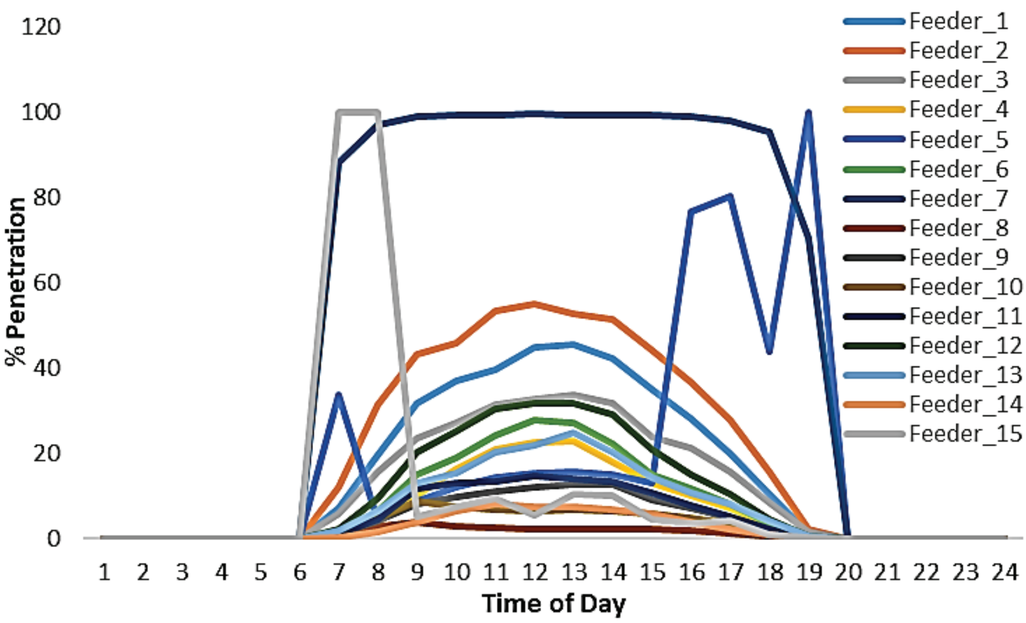

Figure 7. PV penetration in different areas of city.

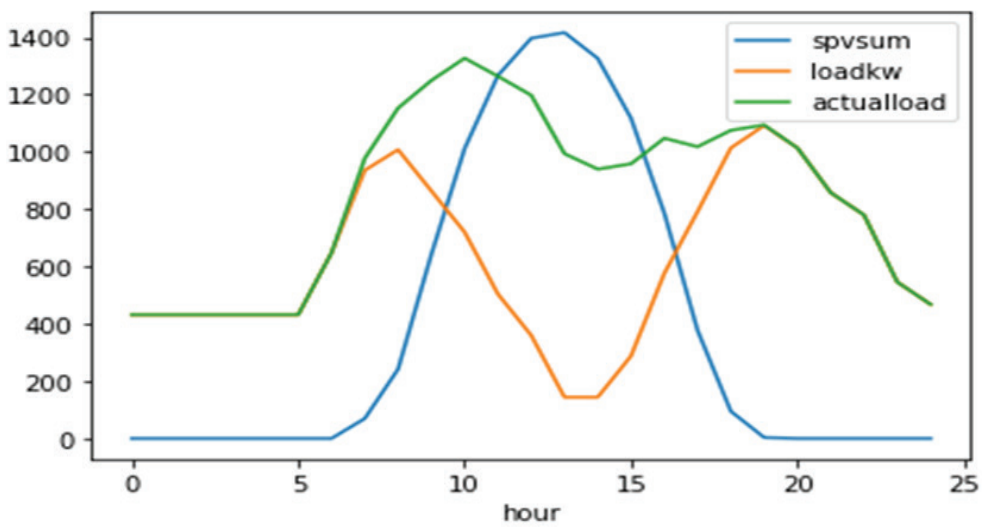

Figure 8. Load curve of feeder 10 with actual and net load profile when SPV connected in system.

- Estimating impacts with the incorporation of solar radiation variability modelling.
- Economic impact analysis of high PV penetration solution implementations.

PV penetration forecasting

To understand the scenario of large PV installation effect on feeder and export of PV energy, reverse power flow from customer end point to the power supply sending end specifically during time of low load, below figure shows PV penetration forecasting on feeder 24.

PL_a, Actual load on feeder per day = 21203.64 KWh

P_s, Solar PV power generation per day = 9751.25 KWh

PV_{pen},Total PV Penetration per day = 45.99 %

Above Figure 8 shows due to high penetration on feeder during day time from 1:00 pm to 3:30 pm feeder export power from feeder to grid and during such High PV penetration condition it will come up with grid issue as we discussed in Table 8.

Opportunities for Advancing Demand Response in Distribution Grids

This study "High penetration of rooftop Photovoltaic system in distribution grid – Feeder specific analysis" and its results and data analysis at bottom level of transmission and distribution grid system plays very important role for further future study and to develop new invention which can be a solutions of said issues due to high PV penetration on grid.

Following future work can be done

1. Energy trading strategy at distribution level
2. Integration of Energy Storage Systems
3. Demand Response Mechanisms
4. Real-time Forecasting and Grid Control
5. Optimization of Grid Infrastructure and Investments
6. Broader Case Studies in Different Geographies

Exploring the impact of electric vehicle load demand response on grid stability and energy management

The developed analytical model has been utilized to design a feeder-based electric vehicle (EV) charging infrastructure for urban areas, considering electrical power loading conditions and photovoltaic (PV) penetration levels of the feeder.

The proposed algorithm aims to:

- Maximize the utilization of renewable energy (RE) for EV charging.
- Shift EV charging load to off-peak periods.
- Minimize the impact of EV charging on the power grid.
- Minimize the high PV penetration impact on the grid.
- Promote large electrical vehicle adoption.

The feeder-aware EV charging load management system, as depicted in Figure 9, it estimate EV charging rates for different city areas feeders based on real-time loading conditions and solar PV power generation. Figure 9 presents a graphical simulation flow in Python, shows estimated EV charging rates value depending on feeder load and solar PV power generation capacity.

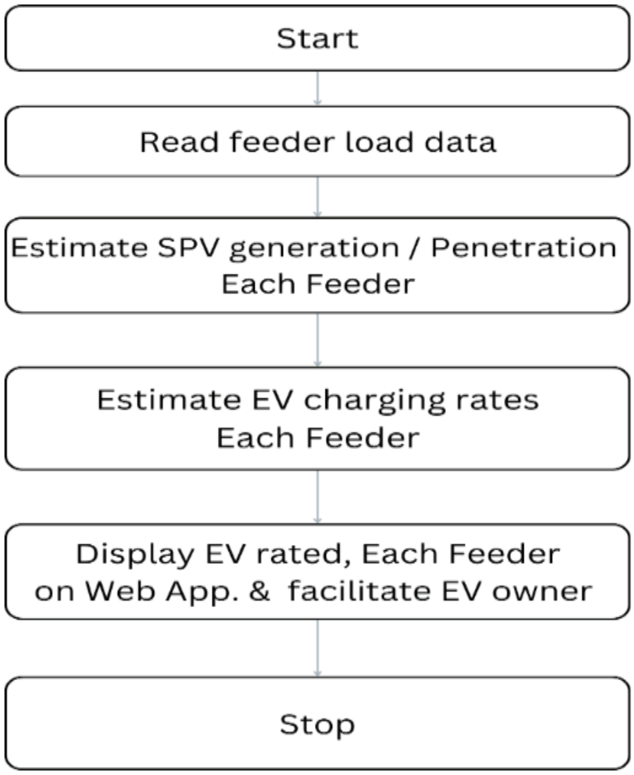

Figure 9. Feeder aware, PV penetration-based EV load management system.

By executing this proposed algorithm in actual field scenarios, EV owners encourage to charge their electric vehicles when solar PV power generation is high on feeder due to lower charging rates. This method improves grid stability and promotes efficient renewable energy utilization.

The above Figure 10 shows variable EV charging rates across different areas of the city, estimated based on feeder loading and solar PV power generation capability of that feeder, its gives a comparative analysis of EV charging rates, PV penetration levels, and feeder loading conditions. It encouraging EV owners to charge EV during solar hours when feeder load is minimal. Consequently, city areas with higher PV penetration and lower feeder load have the low EV charging rates.

In this study, according to PV penetration and power loading of different feeders in different areas of cities EV charging rates vary between ₹12 and ₹20. The charging rate dynamically changes throughout the day according to these factors. In India, typical EV charging rates is in range from ₹13 to ₹21, as per type of charger, with fast chargers having higher rates compared to slow chargers [46].

This result shows the potential integration of PV power generation with EV load for minimize duck-curve effect, increasing grid stability and optimizing the load factor near to 1 (Fig. 11).

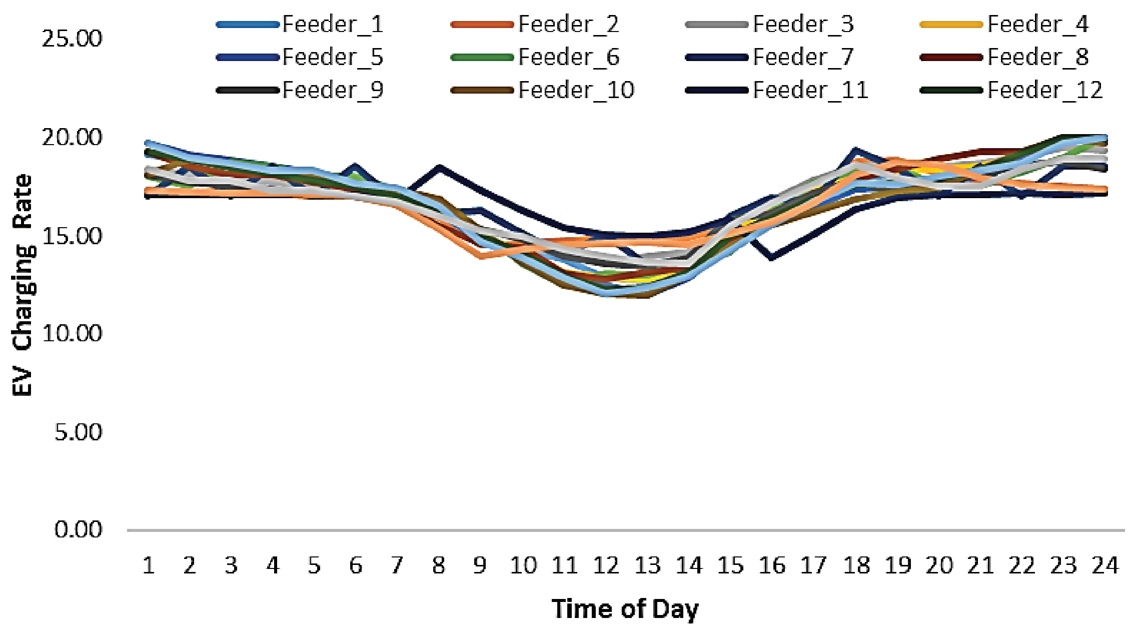

Figure 10. EV charging rate in different areas of city [46] [adopted by author].

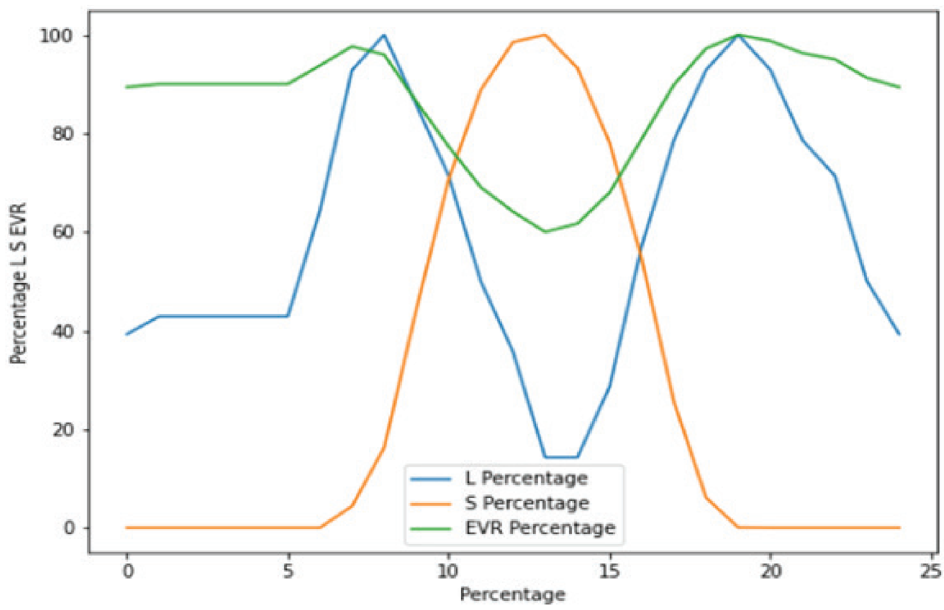

Figure 11. Estimated EV charging rates on feeder 24.

$L_{percentage}$: Electric power load of feeder KWH in percentage

$S_{percentage}$: SPV power generation of feeder KWH in percentage

$EVR_{percentage}$: Estimated EV charging rated of Feeder Rs in percentage

Additionally, the algorithm motivates EV owner to charge EV during peak solar power generation hours, results show it improving the feeder's load factor (LF). Without this algorithm, the feeder's LF was 0.73. While, by integrating this algorithm and utilizing solar PV power energy for EV charging, the LF improved to 0.81, These results show improvements in grid performance and renewable energy utilization.

Effectiveness in evaluating feeder-aware PV penetration, increase feeder load factor, by integrating EV charging rates, and analysing EV charging rate differences across different areas of the city according to loading on feeder and

PV penetration levels. By applying this algorithm across multiple cities at the state or national level and make easy and stable operation for distribution company, improve overall national grid stability.

- Maximize the utilization of renewable energy for EV charging.
- Shift EV charging demand to off-peak periods.
- Reduces EV charging load adverse effect on the grid.
- Promote adoptions of EV utilizations.
- Minimizes the challenges raises due to high PV penetration and improving overall grid stability.

The proposed system motivates EV owners to charge vehicles during solar hours at a low charging rate, make EV adoption more environment friendly and supporting the country's developments in the direction of sustainable green energy development. By increasing solar PV power utilization during the daytime and encouraging EV charging during peak solar hours, the system promotes zero emission transport system in country towards clean and green energy futures.

SCALABILITY AND ECONOMIC FEASIBILITY

Feeder aware, EV load management system according to PV penetration level of feeders, the proposed EV charging infrastructure algorithm can be implement to big cities by utilizing actual grid data, optimizing renewable energy uses, and implementing adaptive load management system. Proposed variable EV charging pricing model will enhance economic benefits by collaboration with distribution companies (DISCOMs) and will ensure seamless grid integration. Further smart IoT-based monitoring system and AI-based predictive integration can further maximize renewable energy power utilization, reducing grid stress. Additionally, coordination with municipal authorities and private stakeholders can help to implement widespread at high-demand locations. Regular incentive to consumers and regulatory support will drive adoption, ensuring that the algorithm remains adaptable thoughts the urban energy ecosystems, ultimately improving grid stability and increasing EV adoption at large scale.

As India rapidly, transition toward sustainable and green mobility, the incorporation of electric vehicles (EVs) charging load with renewable energy sources shows a important opportunity for economic, environmental, and energy security benefits.

Economic Benefit for EV Owners [12]

Annual savings for EV owners

- Fixed rate EV charging: Rs 36,000/year
  (Rs 20/KWh × 30 KWh × 500 charges)
- Dynamic rate EV charging: Rs 27,000/year
  (Rs 15/KWh × 30 KWh × 500 charges)

EV owners benefited ₹9,000 in annual savings around a 25% reduction in charging costs, making EV adoption more cost effective.

Annual Grid Cost Savings Per MW Electric Load Shift

Shifting EV charging load from peak hours to off peak hours or to periods of high renewable energy (RE) generation reduces strain on the grid, leading to significant cost savings.

- During peak hours, Distribution companies procure expensive power from thermal or peaking plants (Rs 6–Rs10/kWh) [47].
- Shifting 1 MW load for 5 hours daily (1,825 MWh annually) to RE-based charging at Rs3– Rs5/kWh instead of peak pricing results in savings Annual Grid Cost Savings per MW Load Shift around Rs. 3 – 5 crore.

National Economic Benefits

- India spends 100+ billion dollar annually on crude oil imports.
- India's EV30@30 target aims for 30% EV penetration by 2030, leading to 80-100 lakh EVs on the road. Large-scale, Feeder specific, PV penetration-based EV load management system, could save approx. Rs.5-7 lakh crore in fuel import costs by 2030 [12].
- Feeder aware, EV load management system as per PV penetration on feeder are in line with India's 500 GW renewable energy target by 2030. Encourages foreign investment in clean mobility & smart grids.

REGULATORY IMPLICATIONS AND RECOMMENDATIONS

Government of India implemented many policies for encouragement of solar energy to ensure sustainable and green energy transition. Key policies likes, the Jawaharlal Nehru National Solar Mission (JNNSM), 2010. Renewable Energy Certificates (REC), 2011, Clean Energy Cess, 2010, and Corporate Social Responsibility (CSR) funds have further incentivized solar energy adoption. The recent started the Time of Day (ToD) tariff and smart metering with the Electricity (Rights of Consumers) Rules, 2020, These all initiatives motivate consumers to improve energy use, promoting solar power integration. These collective efforts highlight the government's commitment to enhancing solar energy deployment, improving grid stability, and making renewable energy more accessible and affordable for all [25].

Indian government has also introduced policies in terms of initiatives to promote electric vehicle (EV) adoption and enhance charging infrastructure across the country. The Ministry, under the FAME-2 policy, offers financial support for community charging stations, while the Ministry of Power developed guidelines for charging infrastructure. Key initiatives include allowing EV owners to charge at home or offices, a revenue-sharing model for public charging stations, and timely electricity connections for new charging stations. To regulate EV charging tariffs, the government has set single-part EV tariffs with capping, slow AC EV charging rates at ₹2.50–₹3.50 per unit and fast DC charging at ₹10–₹12 per unit, with additional rebates and extra charges according to on solar and non-solar hours. In India cost of electricity for EV charging generally in range from ₹4 to ₹8 per kWh, and additional demand charges ranges from ₹50 to ₹120 per kVA. Additionally, initiatives like the green energy open access Rules, 2022, and the "GO ELECTRIC" drive further encourage sustainable and green energy adoption. However, the dynamic nature of charging infrastructure requirements, further suggests a continuous policies evolution to meet future demands efficiently [12,35,46,48].

Regulatory Implications recommendations for Feeder specific, PV penetration-based EV charging load management system to enabling a cost-effective, grid-friendly, and sustainable EV charging ecosystem in India.

- Electricity tariffs for EV charging are currently fixed, Real-time dynamic pricing based on PV generation and feeder load conditions is not yet regulated. CERC - The Central Electricity Regulatory Commission and SERC - State Electricity Regulatory Commission must need to approve dynamic EV charging tariffs linked to solar generation & grid demand.
- Lack of grid code to coordinate EV charging with renewable energy availability. Distribution company must identify high-PV penetration zones and mandate load-balancing algorithms.
- Distribution company do not provide financial incentives for consumers who charge EVs using solar PV Power. Introduce a "Green EV Charging Credit" system, where EV owners using 100% solar power get discounts on electricity bills. Define technical standards for bidirectional EV chargers (Vehicle-to-Grid or V2G) to support grid exports from EV batteries.

CONCLUSION

Feeder specific analysis at distribution level developed algorithm tested with real data and result demonstrating, significant advantages in grid performance and renewable energy integration. when distribution system dealing with Electric vehicle load and high PV penetration. Said algorithm will be useful to understand the issue on feeder with high SPV penetration and accordingly corrective or remedial action can be taken. It can also be used for supply side management and demand side management.

The findings of Feeder specific, PV penetration-based EV load management system, demonstrates a scalable and economically viable approach to integrating EV charging with renewable energy sources. helping to address the challenges of high PV penetration and the increasing demand from EVs. They could contribute to the development of more efficient, resilient, and cost-effective distribution systems, enabling the integration of renewable energy, enhances the eco-friendly advantages of EVs, supporting zero-emission transport and a sustainable energy future, while maintaining grid stability. With strategic collaboration among DISCOMs, policymakers, and private stakeholders, the model can be effectively deployed in larger urban centers, accelerating India's shift towards a cost-effective, grid-friendly, and environmentally sustainable EV charging ecosystem.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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