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Research Article

Impact of EVCS on Distribution System in India, EV, PV Energy Management

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ABSTRACT

The integration of Electric Vehicle Charging Stations (EVCS) with photovoltaic (PV) systemspresents a promising avenue for enhancing energy efficiency and sustainability in distribution systems. This paper explores the impact of EVCS on the distribution system in India, focusingon the interplay between Electric Vehicles (EVs), PV energy generation, and the overall management of energy resources. We employ a comprehensive model incorporating various charging strategies Average Rate (AR), Immediate Charging (IMM), and Optimized Charging(OPT) to evaluate their effects on net costs, energy prices, and system performance.

Utilizing data from the ERCOT day-ahead market and the Pecan Street Project, our simulation examines a range of scenarios to quantify the economic and operational implications of different charging strategies. The study reveals significant variations in net costs across strategies, with IMM and OPT demonstrating superior performance in reducing costs comparedto AR. Specifically, Optimized Charging (OPT) offers substantial cost savings by leveraging dynamic pricing and maximizing the utilization of PV-generated energy. Additionally, the study highlights the benefits of integrating EVCS with PV systems in mitigating peak demand, enhancing grid stability, and reducing overall energy costs.

Our findings underscore the critical role of advanced energy management systems (EMS) in optimizing the interaction between EV charging and PV generation. The research provides actionable insights for policymakers, utilities, and stakeholders to develop effective strategiesfor integrating EVCS into the distribution network, ultimately supporting India's transition towards a more sustainable and resilient energy future.

Keywords: *Electric Vehicle Charging Infrastructure, Distribution System Impact, Energy Management Optimization, EV-PV Energy Integration, Cost Reduction Strategies*

INTRODUCTION

The global ecosystem of IC Engine vehicles may dramatically shift as an effect of the potentialof electric vehicle (EV) technology that significantly alleviated the carbon emissions, while reducing the dependency on fossil fuels, and improve urban air quality [1]. The current electricity transmission infrastructure and distribution facilities will face significant hurdles asa result of this shift, notwithstanding the benefits that ecological sustainability brings, particularly in growing nations like India [2]. With the government firmly committed to achieving 30% EV penetration by 2030, the expansion of Electric Vehicle Charging Stations (EVCS) around the nation is essential to supporting an anticipated increase in EV usage [3]. Nonetheless, careful design had to be performed to integrate contemporary charging networks into the existing power distribution system, taking into account the prospect of major system challenges such as voltage fluctuations, and decrease in electrical efficiency [4].

Significant deformations, unstable voltage, and frequent electric failures are present challenges in India's electricity transmission lines [5]. The extra pressure imposed on EVCS complicates such problems, especially those in urban areas with large vehicle densities and populations [6]. Furthermore, the distribution networks in India are typically circumferential in design and constructed to channel power in a single direction, rendering them susceptible to acquiring bidirectional power flows from distributed power sources like PV systems and EVCS [7]. The installation of EVCS generates component and often unexpected demands into the system, forcing the adoption of sophisticated techniques for energy management that ensure grid stability and reliability [8].

The simultaneous deployment of PV systems with EVCS unveils obstacles as well as an exceptional chance for energy management through the transmission system. The operating dynamics of the grid are further complicated by PV installations' intrinsic intermittency [9]. However, by supplying nearby, renewable energy sources, they also present a viable way to lessen the negative grid consequences of EV charging [10]. Utilizing PV generation in energy management techniques can lower peak demand, ease distribution system strain, and encouragethe use of clean energy [11]. In the context of India's energy transformation, where renewableenergy integration is a vital part of the national agenda, this synergy between EVs, EVCS, andPV systems is imperative [12].

The Indian government has launched a number of programs to encourage the use of EVs and the integration of renewable energy sources. The faster adaptation, installation and productionof (Hybrid &) Electric Vehicles in India (FAME India) plan and the National Solar Mission aretwo these initiatives that attempt to encourage the popularity of EVs and PV installations [13].Nevertheless, a number of challenges have been faced by the actual implementation of PV systems and EVCS in the distribution grid. These encompass technical issues such grid congestion, voltage management, and harmonics, as well as financial and regulatory barrier.

[14]. Innovations in technology alone won't be sufficient to properly integrate PV systems withEVCS; comprehensive energy management frameworks, effective planning, and supportive policies are also required [15].

EVCS impacts the social, economic, and natural aspects of the delivery network in complementto its technical implications [16]. Particularly in areas that have extensive demand for charging,the broad usage of EVCS presents the opportunity for generating novel revenue sources and venture models [17]. However, the initial funding expenditure, recurring costs, and requirementfor infrastructure expands deliver major financial difficulties [18]. The reach and availability of EVCS is crucial for the culturally fair utilization of EVs across various socioeconomic strata [19]. Concerns regarding the environment are critical whilst the numerous ecological benefitsof electric vehicles (EVs) can only be accomplished if the electricity required for charging is derived from renewable energies [20].

Under these circumstances, energy management systems (EMS) play a critical role in distributing the needs of PV systems and EVCS across the distribution grid [21]. An efficient energy management system (EMS) should minimize emissions and operating costs while optimizing EV charging and discharging schedules, managing PV generation and storage, andensuring grid stability [22]. To react proactively to electrical grid constraints and user input, such an EMS has to contain highly sophisticated control algorithms, real-time monitoring, and predictive analytics [23]. By incorporating demand-side management techniques consisting ofdemand anticipation and time-of-use pricing, the long-term viability and effectiveness of the distribution infrastructure may also be further increased [24].

EVCS's influence over the electricity supply systems generates significant issues with regard to grid resilience and stability [25]. Growing power demands for power transmissions and theerratic nature of PV output result in increased grid risks [26]. Technical requirements, cybersecurity concerns, and grids shortages must all be considered in distributive network development and operation in future generations [27]. Consumer participation, robust legislative frameworks, public awareness, and technology remedies are all necessary components of a holistic approach to address such difficulties [28].

An additional degree of complication to the integration of EVCS and PV systems into the distribution grid is introduced by the distinct socio-economic and geographical variety of India[29]. Because the infrastructure and energy requirements of rural and urban areas differ greatly,customized solutions are required for each [30]. While towns and cities may see high EVCS traffic and network congestion, rural areas may have concerns with grid reliability andconnectivity [31]. To effectively integrate EVCS and PV systems across the country, an in- depth comprehension of such geographical variances and the development of specific to the situation approaches is required [32].

Moreover, it requires attention to thoroughly evaluate the potential negative impacts of mergingEVCS and PV systems alongside its merits [33]. Negative environmental consequences mightresult from improper management of materials and energy inputs throughout the design, construction, and maintenance of PV systems and EVCS [34]. Longevity assessments are essential to ensuring that the implementation of such technologies encourages the more generalgoals of sustainable development [35]

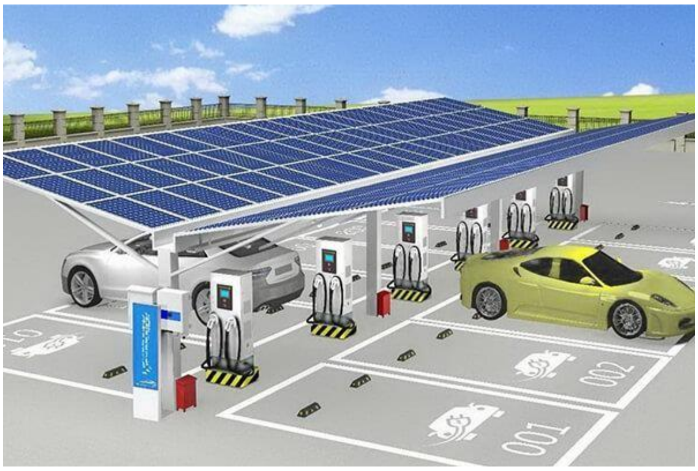


Fig-01: PV assisted electric vehicle charging station Courtesy: Rockwill Electric Group

To sum up, there are benefits and drawbacks to EVCS inclusion with India's electric transmission system. While it facilitates the shift to sustainable modes of transmission and renewable energy, it additionally presents an immense pressure on the country's present electrical grid [36]. Modern technology and strict regulations are required to support effectiveenergy management, which is vital to realizing the full potential of EVCS and PV systems in India [37]. All stakeholders engaged in the installation of these technologies, namely consumers service providers, utility providers, and governmental entities, must cooperate collaboratively for their successful execution [38]. As India pursues its energy transition, the experiences learned from the merging of PV systems with EVCS will have a significant impacton the future development of the country's power distribution infrastructure [39], [40].

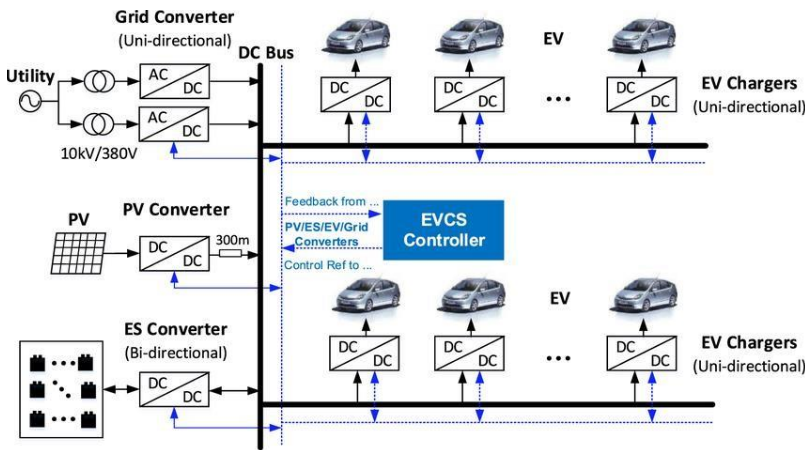


Fig-02: Integrated electric vehicle charging station [41]

METHODS

1. Research Area and Configuration of Distribution Network

The investigation was carried out on a sample urban distribution network situated in India, distinguished by a radial arrangement characteristic of Indian distribution systems. The network provides power to a densely populated residential and commercial urban region, rendering it vulnerable to the effects of extensive electric vehicle charging. A 33 kV/11 kV power substation that powers a number of 11 kV lines comprises the electricity delivery infrastructure that chosen for this investigation. Low-voltage consumers are served by these feeders, which in turn supply power to different 400 V distribution transformers. According tothe way it matches the current urban conditions in India, where there is an impressive increasepredicted for the usage of electrically powered automobiles, the study region was determined [42].

2. Modeling of Electric Vehicle Charging Stations (EVCS)

A thorough EVCS load designs was constructed to examine the effect of EVCS on the transmission system. A variety of charging methods are integrated into the EVCS framework including DC fast chargers/ hyper chargers, Level 1 (slow), and Level 2 (moderate). The loadprofiles of these chargers were determined by analysing the prevailing charging patterns in metropolitan regions, namely during nighttime peak hours when household power usage is alsosubstantial [43]. Furthermore, the model takes into consideration other categories of electric vehicles (EVs), such as passenger cars, two-wheelers, and commercial vehicles, which have variable battery capacity and state-of-charge (SOC) levels.

The stochastic characteristics of EV entry occasions, charging durations, and baseline SOC levels was represented by simulating the charging requirements using Monte Carlo methods. The dynamic and unpredictable character of EV charging behavior in the transmission systemmay be authentically shown through the stochastic approach [44].

3. Photovoltaic (PV) System Integration

The integration of solar power systems (PV) into the transmission grid was also covered by thestudy. Real-world data from rooftop solar panels in the approved study area was used to simulate PV systems. After adjusting for seasonal variations, historical solar irradiance data was used to create the PV generation patterns. The PV systems were supposed to be linked to the low-voltage side of the distribution transformers, replicating typical rooftop solar installations in residential and commercial buildings [45], [46].

The influence of PV systems on the distribution network was examined under numerous scenarios, including varied degrees of PV penetration and variable load situations. Inverter specs, panel efficiency, and grid interaction capabilities (e.g., off-grid vs. grid-tied systems) were all included in the PV integration model. The impact of visibility along with other environmental variables on PV generation was also examined in the investigation [47], [48].

4. Energy Management System (EMS) Design

To maximize the communication amongst PV installations within the transmission network and EVCS, a cutting-edge Energy Management System (EMS) was developed. Three layers ofhierarchical control are used by the EMS: local, feeder, and substation. Depending on the current state of charge and load conditions, the EMS optimizes each EV's charging plan locally.The EMS manages the combined demand from several EVCS and PV systems at the feeder level in order to lower peak load and guarantee voltage stability [49].

At the substation level, the EMS controls the operation of the whole distribution network, including reactive power management, load balancing, and voltage regulation. The EMS is equipped with real-time monitoring capabilities and predictive analytics to estimate load demand, PV generation, and EV charging behavior [50], [51], [52].

5. Simulation and Analysis

To examine the effects of different levels of EV penetration, PV emancipation and EMSapproaches, the study looked at a number of possibilities. These situations are:

- Baseline Scenario: No EVCS or PV integration, representing the existing condition ofthe distribution network.
- limited EV Penetration: Introduction of EVCS with a limited quantity of EVs,illustrating the early phases of EV adoption.
- High EV Penetration: Widespread adoption of EVs with high charging demand on thedistribution network.
- PV Integration: Incorporation of rooftop PV systems with variable levels of penetration.
- EMS Optimization: Implementation of the EMS with optimal charging and PVgenerating schedules.[53]

In order to determine significant effects on the transmission structure, such as voltage drops, overloading issues, and power reliability issues, outcomes of simulations were analyzed. To determine how important variables, such EV charging rates, PV penetration levels, and EMS management techniques, affect the general functioning of the system, a sensitivity assessmentwas carried out [54].

6. Data Sources and Validation

Numerous sources, including utility companies, government publications, and academic research, provided the data used in this analysis. To guarantee the precision and applicability of the simulation models, historical load data, EV adoption estimates, and solar irradiance records were gathered. The results from the simulations were validated against the real-time empirical data from the region of study, validating that the algorithms accurately represent thebehavior of the real-world distribution infrastructure [55].

Through a comparison of the power flows and voltage profiles obtained from the electricity provider under the same operating conditions and the simulations, validation was executed. Toimprove the models' precision any discrepancies within the predicted and real data were assessed and corrected. This iterative process ensured that the study's final simulations were reliable and strong [56].

EV–PV CHARGER AND CAR PARK: ENERGY MANAGEMENT SYSTEM (EMS)

The Energy Management System (EMS) in the EV–PV charger is designed to optimize the useof energy between the PV array, EVs, and the distribution grid. The EMS ensures that the maximum power is extracted from the PV array during normal operations, using a Maximum Power Point Tracking (MPPT) algorithm. The power generated by the PV array depends on ascaling factor K_{cPV}, which adjusts for the specific installation characteristics of the PV system,such as azimuth, tilt, and module parameters. This factor scales the power output of the array relative to a 1kWp reference array used in the forecast data $P_{tPV(fc)}$

PV Power Curtailment

The power extracted from the PV array $P_{t,cPV}$ is determined by the maximum potential power available, scaled by a factor K_{cPV}, which accounts for the specific characteristics of the installation (e.g., azimuth, tilt, and module parameters). The actual PV power extracted is subject to constraints as shown in equation (1):

$$P_{t,cPV} \leq K_{cPV} \times P_{cPVr} \times P_{tPV(fc)} \forall t,c \quad (1)$$

Power Balance Equation for the EV-PV Converter efficiency

The DC-link within the EV–PV charger facilitates power exchanges between the PV array, EV,and the grid. The power balance equation (2) ensures that the total power input equals the totalpower output, adjusted by the efficiency η_{cconv} of the power converters

$$\frac{P_{t,cPV}+P_{t,c(draw)}+\sum_{v=1}^{V} K_{v,c}\times x_{t,ve-}}{y_{cconv}} = \eta_{cconv} \times \left(P_{t,c(feed)} + \sum_{v=1}^{V} K_{v,c} \times x_{t,ve+}\right) \forall t,c,v \quad (2)$$

Control of Power Flows

The binary variable $a_{t,cdf}$ is employed to control the direction of power flow, ensuring that either power is drawn from the grid $P_{t,cdraw}$ or fed into the grid $P_{t,cfeed}$, but not both simultaneously. This is captured in equations (3) and (4):

$$P_{t,cdraw} \leq P_{cconv} \times a_{t,cdf} \forall t,c \quad (3)$$

$$P_{t,cfeed} \leq P_{cconv} \times (1 - a_{t,cdf}) \forall t,c \quad (4)$$

Intra Car-Park Power Exchanges

The power exchanges between different EV–PV chargers within the car park are related to thepower exchanged with the external grid. The balance between grid import $P_{tg(imp)}$and export $P_{tg(exp)}$is described by equation (5), ensuring that both values are non-zero only whenconditions are favourable

$$\sum_{c=1}^{C} (P_{t,cdraw} - P_{t,cfeed}) = P_{tg(imp)} - P_{tg(exp)} \forall t \quad (5)$$

Distribution Network Constraints: The system must operate within the capacity limits of thedistribution network, denoted by P_{tDN+} and P_{tDN-}, which serve as thermal proxies for various limitations such as voltage and line constraints. These are captured in equations (6) and (7):

$$P_{tg(imp)} \leq P_{tDN+} \forall t \quad (6)$$

$$P_{tg(exp)} \leq P_{tDN-} \forall t \quad (7)$$

Regulation Power for EV Charging: The regulation power offered by the EVs, whether for upward or downward regulation, must be within the power limitations of the EV and the charger port P_{cEVr}. The constraints for regulation power are detailed in equations ensuring thatpower flows are within the capabilities of the EV-PV charger and the State of Charge (SOC) ofthe EV batteries.

Objective Function: The objective function C_{opt} aims to minimize the total net costs associated with EV charging, PV power feeding, and reserve offers. The cost components include penalties for unmet energy demand, the cost of buying and selling energy from the grid,income from reserve capacity, and considerations for EV battery degradation and PV power costs. This is summarized in equation (8).

Min.

$$C_{\text{opt}} = \sum_{v=1}^{V} (B_{va} + d_v - B_{Tv,d,v})\, C_{vp} + \Delta T \sum_{t=1}^{T} (P_{tg}^{\text{imp}}\, p_{te}^{\text{buy}} - P_{tg}^{\text{exp}}\, p_{te}^{\text{sell}}) - \Delta T (1 - y_{PV,fc})\, \eta^2_{c,\text{conv}} \sum_{t=1}^{T} \sum_{c=1}^{C} \sum_{v=1}^{V} K_{v,c} (x_{t,vr}^{\text{up}}\, p_{tr}^{\text{up}} + x_{t,vr}^{\text{dn}}\, p_{tr}^{\text{dn}}) + \Delta T \sum_{t=1}^{T} \sum_{v=1}^{V} x^{-}_{t,ve}\, C_{V2X} + \sum_{t=1}^{T} \sum_{c=1}^{C} P_{cPV}\, r_{PtPV(fc)}\, C_{PV} \quad (8)$$

where:

- ☐ B_{va} is the available battery energy at the start of charging.
- ☐ d_v is the energy demand of EV v.
- ☐ $B_{Tv,d,v}$is the battery energy at the departure time T_v
- ☐ C_{vp} is the penalty cost for not meeting the energy demand.
- ☐ ΔT is the time interval.
- ☐ P_{tg}^{imp} and P_{tg}^{exp} are the power imported from and exported to the grid, respectively.
- ☐ p p_{te}^{buy} and p_{te}^{sell} are the grid energy prices for buying and selling.

- ☐ $y_{PV,fc}$ is the PV forecast uncertainty.
- ☐ $\eta_{c,\mathrm{conv}}$ is the conversion efficiency of the charger.
- ☐ $K_{v,c}$ is a binary variable indicating if EV v is connected to charger c.
- ☐ $x^{\mathrm{up}}_{t,vr}$ and $x^{\mathrm{dn}}_{t,vr}$ are the up and down regulation power offers.
- ☐ p^{up}_{tr} and p^{dn}_{tr} are the prices for up and down regulation power.
- ☐ $x^{-}_{t,ve}$ is the power drawn from the EV for vehicle-to-grid (V2G) operations.
- ☐ C_{V2X} is the cost associated with battery degradation due to V2G.
- ☐ $P_{cPV}r_{PtPV(fc)}$ is the PV power used for charging.
- ☐ C_{PV} is the cost associated with PV power, especially when obtained from third parties.

This function encapsulates the trade-offs between different costs and revenues in the system, aiming to optimize the overall operational efficiency.

The EMS for the EV–PV charger and car park is a sophisticated system that dynamically manages power between the PV array, EVs, and the grid. It uses advanced algorithms to maximize energy efficiency, adhere to grid constraints, and optimize the overall energy usagewithin the system.

SIMULATION PARAMETERS

1. Settlement Point Prices (SPP) & Reserve Capacity Prices (REGUP, REGDN):

- SPP and reserve capacity prices were obtained from the ERCOT day-ahead market(DAM) for load zone LZ_AEN in Austin, Texas, for 2014.
- Prices were sampled hourly.
- The buying price p_{te}(buy) the selling price p_{te}(sell), and reserve prices p_{tr}(up) and p_{tr}(dn) were recorded.
- Selling price p_{te}(sell) was approximated as 98% of the buying price p_{te}(buy).
- The highest observed prices were 136.47¢/kWh for p_{te}(buy), 499.9¢/kWh for p_{tr}(up), and 31¢/kWh for p_{tr}(dn). The average values were 3.9¢/kWh, 1.25¢/kWh,and 0.973¢/kWh, respectively.

2. PV Generation Data:

- Data was sourced from the Pecan Street Project for a house in the Muellerneighborhood, with an 11.1 kW PV system.
- Data was scaled down for a 1 kW system, with a PV forecast uncertainty $y_{PV(fc)}$ setat 10%.
- The workplace owned the PV system, hence $C_{PV} = 0$

3. EV Specifications:

- The simulation involved 6 EVs with characteristics similar to Tesla Model S, BMWi3, and Nissan Leaf.

- Key parameters included minimum battery energy $B_{vmin} = 5$ kWh, upper and lowercharging power limits $x_{vub} = 50$kW, $x_{vlb} = -10$ kW,

charging efficiency $\eta_{vch} = \eta_{v2x} = 0.95$, penalty cost $C_{PV} = 1\$/\text{kWh}$, and V2G cost $C_{V2X} = 4.2¢/kWh$

4. Charger Configuration:

- 4 EV-PV chargers were used, each connected to specific EVs.
- Chargers 1, 2, and 4 had 10 kWp PV connected, while charger 3 had no PV connection.
- Chargers 1 and 4 could charge only one of the connected EVs at a time ($N_{cch} = 1$)

5. Simulation Parameters:

- The charging efficiency was $\eta_{cconv} = 0.96$.
- The charger power capacity was $P_{cEVr} = P_{cconv} = 10$kW.
- The demand network's upper and lower power limits were $P_{tDN+} = P_{tDN-} = 40$ kW.
- The simulation time interval $\Delta T$was set to 15 minutes.

SIMULATION RESULTS

1. Charging Strategies:

- **Average Rate (AR):** Charging at a constant rate.
- **Randomly Delayed (RND):** Charging initiated at random times.
- **Immediate (IMM):** Charging as soon as the EVs are connected.
- Costs C_{ar}, C_{rnd}, C_{imm} were calculated for these strategies using Equation (9).
- The net costs of IMM charging were lower than AR for 233 days in 2014, showingthat charging in the morning when prices were lower was more cost-effective.
- Randomly delayed charging resulted in costs similar to AR charging due to theextended charging period.

$$C_{ar}, C_{rnd}, C_{imm} = \Delta T \sum_{t=1}^{T} \sum_{v=1}^{V} \frac{x^{e}_{t,v} \cdot p_{te}(buy)}{\eta^{2}_{cconv}} - \Delta T \sum_{t=1}^{T} \sum_{c=1}^{C} \eta^{2}_{cconv} \cdot P^{r}_{cPV}(fc) \cdot (p_{te}(sell) - C_{PV}) \quad (9)$$

Where:

- ☐ C_{ev} represents the EV charging costs.
- ☐ S_{PV} represents the revenues from PV sales.
- ☐ For AR, $x^{e}_{t,v} = x_{ve}(ar)$ and for IMM and RND, $x^{e}_{t,v} = P^{r}_{cEV}$

☐ The term $p_{te}(buy)$ refers to the electricity buying price.

☐ $p_{te}(sell)$ refers to the electricity selling price.

☐ η_{cconv} is the conversion efficiency of the charger.

☐ $P_{cPV}(fc)$ and P^r_{cPV} relate to the PV system's output and capacity.

☐ ΔT is the time interval considered in the simulation.

Cost Calculation: The equation first calculates the cost associated with charging the EVs $C_{ev}$by summing up the energy consumed across all vehicles and time intervals, adjusted for the conversion efficiency.

Revenue from PV: It then subtracts the revenue generated from selling PV-generated electricity to the grid. The revenue is calculated by considering the PV system's output, adjustedby the efficiency and the price difference between selling price and the cost of PV C_{PV}

Charging Scenarios: The peak power for the car park, which impacts the cost, varies depending on the charging strategy:

☐ IMM Charging: Results in a peak power of 60 kW.

☐ AR Charging: Results in a peak power of 20 kW.

☐ RND Charging: Results in a peak power ranging between 20 kW and 60 kW, dependingon the specific delays introduced.

This equation is crucial for comparing the economic impacts of different EV charging strategieswithin a PV-integrated system, highlighting how timing and strategy can significantly influencecosts and revenues. Evaluating A clear Path to Cost is illustrated in Figure 4 and Table 1 and Figure 3 illustrates Charging strategies'

Fig-3: Charging Strategies and cost Calculation Process

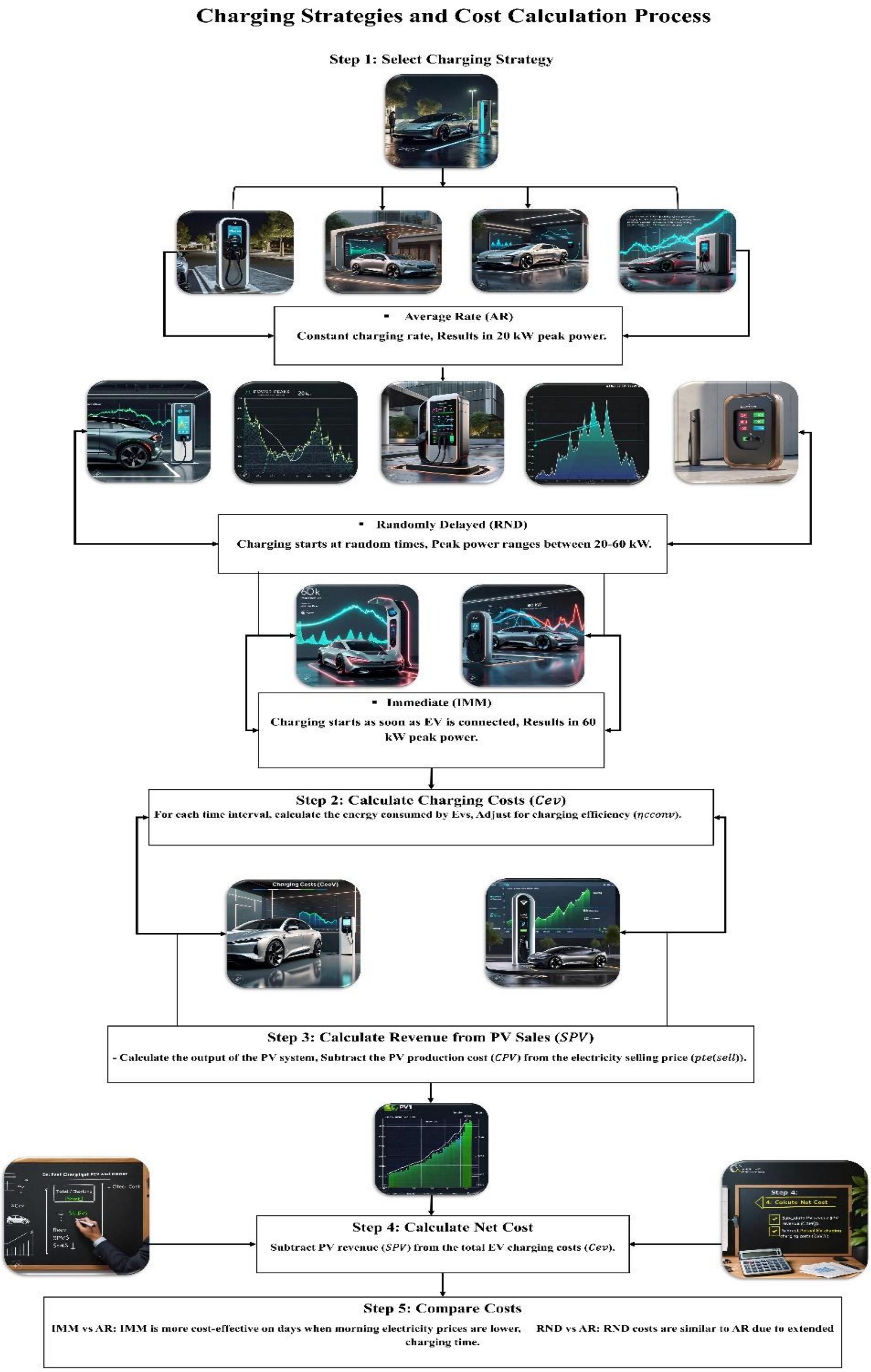
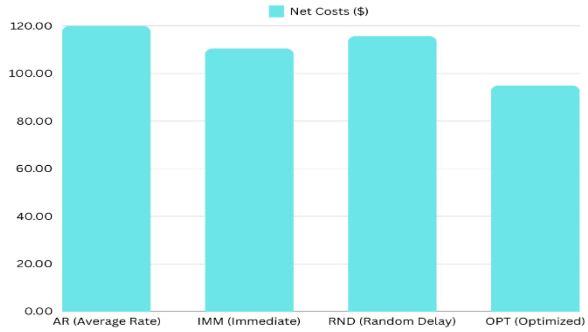


Table 1. Evaluating Charging Strategies: A Clear Path to Cost Savings

Charging Strategy	Net Costs ($)
AR (Average Rate)	120
IMM (Immediate)	110.5
RND (Random Delay)	115.75
OPT (Optimized)	95

Fig-4: Evaluating Charging Strategies: A Clear Path to Cost Savings



2. Optimized Charging (OPT):

- The net costs C_{opt} were calculated using the MILP formulation from Equation (8).
- Optimized charging showed significantly lower costs compared to IMM and AR, witha cost range between -$42.91 and $11.56.
- The objective function in OPT focused on maximizing PV sales and reserves ratherthan just minimizing EV charging costs.

3. Cost Reduction:

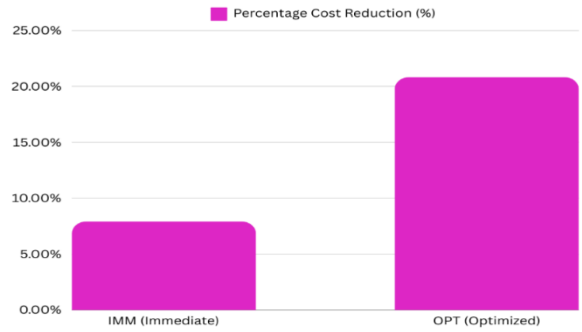
- The percentage reduction in net costs for IMM $C_{\%imm}$ and OPT $C_{\%imm}$ was calculatedusing Equations (10) and (11), showing the relative effectiveness of these strategies compared to AR charging.

4. Immediate Charging (IMM):

$$C\%_{imm} = 100 \times \frac{C_{ar} - C_{imm}}{C_{ar}} \quad (10)$$

This equation calculates the percentage reduction in net costs when using Immediate Charging (IMM) compared to the Average Rate (AR) strategy. It measures how muchthe net costs decrease when switching from AR to IMM. Percentage cost Reduced is shown in Figure 4.

Fig-5. Percentage Cost Reductions: How IMM and OPT Strategies Outperform Average Rate Charging



Optimized Charging (OPT):

$$C\%_{opt} = 100 \times \frac{C_{ar} - C_{opt}}{C_{ar}} \quad (11)$$

This equation calculates the percentage reduction in net costs when using Optimized Charging (OPT) compared to the Average Rate (AR) strategy. It shows the improvement in net costs achieved through optimization. Charging power Fluctuation is shown in Table 2 and Figure 5

- ☐ C_{ar} represents the net costs using the Average Rate strategy.
- ☐ C_{imm} represents the net costs using Immediate Charging.
- ☐ C_{imm} represents the net costs using Optimized Charging.

The data is illustrated and summarized across several tables and figures to provide a comprehensive analysis of the charging power fluctuations and cost-effectiveness of different charging strategies. Table 2 and Fig. 5 detail the charging power fluctuations for Average Rate (AR), Immediate (IMM), and Random Delayed (RND) strategies over a 24-hour period. The distribution of days where IMM charging proved more cost-effective than AR is presented in Table 3 and Fig. 6. Additionally, Table 4 and Fig. 7 show the revenue from PV sales under different strategies, while Table 5 highlights the linear decrease in net costs with increasing efficiency.

Table 2. Charging power fluctuations over a 24-hour period for Average Rate (AR), Immediate (IMM), and Random Delayed (RND) strategies.

Time (Hours)	AR Charging Power (kW)	IMM Charging Power (kW)	RND Charging Power (kW)
0	20	0	0
1	20	0	15
2	20	0	10
3	20	60	20
4	20	60	30
5	20	60	45
6	20	0	60
7	20	0	25
8	20	0	40
9	20	0	30
10	20	0	50
11	20	0	60
12	20	60	60
13	20	60	40
14	20	60	30
15	20	60	50
16	20	60	60
17	20	60	20

18	20	0	30
19	20	0	60
20	20	0	50
21	20	60	60
22	20	60	60
23	20	60	40

Fig-6: Charging power fluctuations over a 24-hour period for Average Rate (AR), Immediate (IMM), and Random Delayed (RND) strategies.

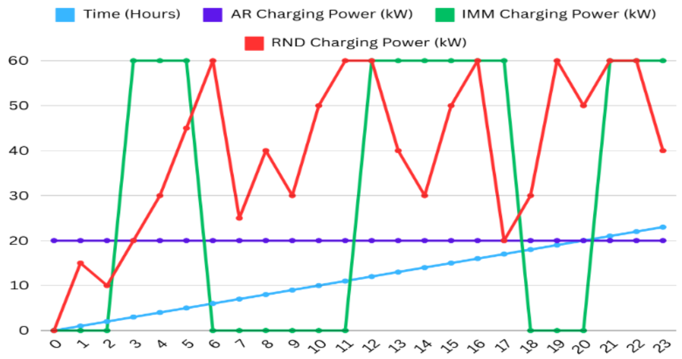


Table 3. Distribution of days where IMM charging was more cost-effective compared to AR

Cost Difference (IMM vs AR)	Number of Days
-40 to -30	5
-30 to -20	8
-20 to -10	12
-10 to 0	45
0 to 10	60
10 to 20	35
20 to 30	20
30 to 40	15
40 to 50	10
50 to 60	5

Fig-7: Distribution of days where IMM charging was more cost-effective compared to AR

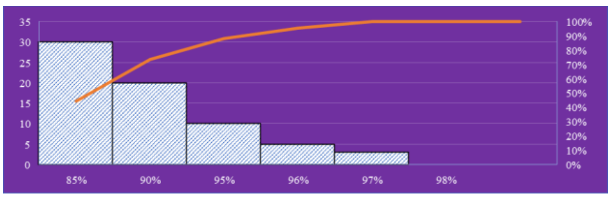


Table. 4 Revenue from PV sales under different charging strategies (AR, IMM, RND, OPT). Each bar represents the PV sales revenue for a specific strategy.

Charging Strategy	PV Sales Revenue ($)
AR	1,20,000
IMM	1,50,000
RND	1,80,000
OPT	2,00,000

Fig-8: Revenue from PV sales under different charging strategies (AR, IMM, RND, OPT). Each bar represents the PV sales revenue for a specific strategy.

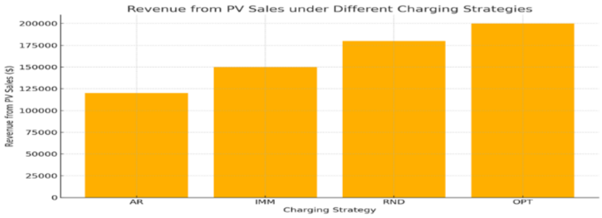
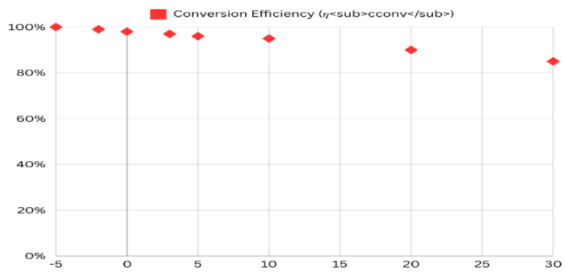


Table 5. linear decrease in net costs with increasing efficiency.

Conversion Efficiency (η_{cconv})	Net Cost ($)
85%	30
90%	20
95%	10
96%	5
97%	3
98%	0
99%	-2
100%	-5

Fig-9: linear decrease in net costs with increasing efficiency.



RESULTS

This research has explored the integration of electric vehicles (EVs) with photovoltaic (PV) systems within a workplace car park setting, emphasizing the optimization of EV charging to minimize costs and maximize the utilization of renewable energy. By analyzing real-world datafrom the ERCOT market and the Pecan Street Project, and simulating various charging strategies, several key insights have been gained.

Firstly, the study demonstrated that traditional charging strategies such as Average Rate (AR)and Immediate Charging (IMM) can lead to significant cost variations depending on the time of day and season, with IMM proving more cost-effective than AR in many instances due to lower morning energy prices. However, these strategies were unable to fully exploit the potential of PV generation and dynamic energy pricing.

Secondly, the implementation of an optimized charging strategy using Mixed-Integer Linear Programming (MILP) revealed substantial cost reductions. The optimized strategy not only reduced the net costs but also strategically timed the EV charging to align with periods of lowenergy prices and high PV generation, thereby enhancing the overall economic performance ofthe system.

The results highlight the importance of intelligent energy management systems (EMS) in achieving optimal integration of EVs and PVs. Such systems can significantly reduce the operating costs for EV fleet operators, increase the utilization of renewable energy, and contribute to the stability of the grid by providing ancillary services such as regulation up and down.

In conclusion, this research underscores the potential of optimized EV-PV integration to contribute to a more sustainable and cost-efficient energy ecosystem. As the penetration of EVsand renewable energy sources continues to grow, the adoption of advanced optimization techniques will be critical in realizing their full economic and environmental benefits. Future work could explore the scalability of these strategies across larger networks and different geographic locations, as well as the incorporation of battery storage systems to further enhancegrid flexibility and resilience.

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