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# *Distributed Photovoltaic Systems and Electric Vehicle Clusters in Local Energy Networks: A Review*

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***Abstract.*** Distributed PV systems offer decentralized renewable generation, while EVs bring about flexible yet unpredictable demand profiles. By coordinating these technologies, we have the potential to decrease carbon emissions, improve grid reliability, and optimize energy usage on a local level. However, impediments such as the intermittent nature of PV generation, the uncertainty of EV charging behaviors, and the limitations of current grid infrastructures continue to pose significant challenges that must be addressed in order to fully realize the potential benefits of these technologies. In this paper, we undertake an in-depth examination of the existing research landscape pertaining to the integration of photovoltaic (PV) systems and electric vehicles (EVs) within local networks. Our analysis spans across technical, operational, environmental, and economic facets. We delve into the technological attributes of distributed PV systems and the distinctive load dynamics exhibited by EV clusters, emphasizing the potential for enhanced synergies through the implementation of smart grid solutions. Key areas of focus include advanced modeling techniques, coordinated scheduling strategies, and optimization frameworks, all aimed at bolstering system performance. Furthermore, we explore the substantial environmental advantages and cost-effectiveness associated with PV–EV integration, while simultaneously shedding light on the policy and market hurdles that impede widespread adoption. By amalgamating insights gleaned from recent scholarly endeavors, this paper offers a holistic perspective on PV–EV integration and serves as a valuable resource for researchers, policymakers, and stakeholders in the energy industry who aspire to design sustainable local energy systems.

***Keywords:*** Distributed Photovoltaics, Electric Vehicle Clusters, Local Energy Systems, Smart Grids, Energy Integration

## 1. Introduction

The global energy sector is in the midst of a significant shift, motivated by the dual mandates of decarbonization and electrification. In this transition, distributed photovoltaic (PV) systems and electric vehicles (EVs) have emerged as pivotal technologies. Distributed PV facilitates decentralized renewable energy generation, enabling electricity production near the consumption point. This approach minimizes transmission losses, bolsters energy self-sufficiency, and plays a crucial role in curbing greenhouse gas emissions [1]. Meanwhile, EVs mark a significant paradigm

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shift in the transportation industry, substituting fossil fuel usage with electricity demand. While their growing adoption holds promise, it also poses notable challenges for power system operation and planning, necessitating innovative solutions to address these emerging concerns [2,3].

The incorporation of distributed PV and EV clusters into local energy systems presents substantial prospects. By leveraging smart charging strategies, PV output, which peaks during daylight hours, can align well with EV charging demand [4]. Moreover, EV batteries can function as versatile energy storage devices, capturing excess PV generation and potentially feeding power back to the grid via vehicle-to-grid (V2G) technologies [5,6]. Such synergies have the potential to decrease peak energy demand, enhance renewable energy utilization, and fortify grid resilience. However, several obstacles impede the full capitalization of these benefits. PV generation is inherently intermittent and susceptible to weather conditions [7], while EV charging demand is highly unpredictable, swayed by user practices, mobility trends, and infrastructure accessibility [8]. In the absence of effective coordination, the concurrent variability of these technologies may actually augment grid instability rather than alleviate it.

International research has explored diverse strategies to tackle these challenges. Studies in Europe and North America underscore the significance of V2G and demand-side management in mitigating variability [9,10]. Conversely, research in China and Japan focuses on the importance of synchronized scheduling and microgrid implementation for achieving high renewable energy integration [11,12]. However, there remains a gap in integrating technical solutions with economic incentives and policy frameworks [13].

This review aims to offer a comprehensive overview of the current research on integrating PV and EV systems within local networks. It seeks to achieve four main objectives: firstly, to examine the technical characteristics and challenges of distributed PV systems and EV clusters; secondly, to analyze the operational and control challenges associated with their integration; thirdly, to evaluate optimization strategies and smart grid technologies that enhance coordination; and fourthly, to assess the environmental and economic implications of PV–EV integration. By thoroughly addressing these objectives, this study intends to advance the theoretical understanding of integrated energy systems and provide actionable insights for sustainable urban energy planning.

## 2. Overview of distributed photovoltaics and electric vehicle clusters

### 2.1. Technical characteristics, uncertainties, and grid integration of distributed PV

Distributed photovoltaic (PV) systems are rapidly growing as a popular form of renewable energy generation globally. Unlike centralized solar farms, distributed PV is installed on rooftops, residential buildings, and commercial facilities, allowing for localized electricity production and decreasing dependence on centralized grids. A key benefit of distributed PV is its capacity to lower transmission losses and enhance energy self-sufficiency for households and businesses. This decentralized approach to solar power offers numerous advantages, making it a promising solution for achieving greater sustainability and energy independence in various settings [14,15].

Distributed PV systems face challenges due to their intermittent nature, influenced by weather conditions, seasonal changes, and geographical factors. This variability poses difficulties in balancing supply and demand and affects voltage stability and power quality in distribution networks. The increasing penetration of PV systems can result in reverse power flows, necessitating additional ancillary services such as voltage regulation and frequency support. Consequently, managing the impact of distributed PV systems on the grid becomes crucial, requiring careful planning and investment in technologies to ensure system reliability and availability [16].

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The successful integration of distributed PV systems into the grid hinges on the use of advanced forecasting methods, real-time monitoring, and smart inverters to maintain stability. However, the lack of consistent regulatory frameworks and financial incentives across different regions presents a barrier to widespread adoption. Economic viability is also influenced by factors like installation expenses, electricity market setups, and policy backing. These obstacles underscore the need for synchronized approaches when combining PV with other adaptable resources like electric vehicles. It is imperative that solutions be developed to address these challenges and facilitate the seamless integration of PV systems into the grid.

### 2.2. Challenges and opportunities of EV–PV integration

As electric vehicles (EVs) become more prevalent, they are no longer just transportation tools but also vital elements of contemporary energy systems. When deployed in large numbers, EVs form clusters that serve as substantial and adaptable loads within local networks. The demand for EV charging is unpredictable, varying due to driving habits, user tendencies, and the availability of charging stations. Often, peak charging times coincide with evening spikes in energy consumption, placing further strain on local grids. This dynamic nature of EV charging behavior highlights the importance of effectively managing and integrating EVs into existing energy infrastructure.

Electric vehicle (EV) clusters present a promising strategy to enhance the efficiency of photovoltaic (PV) generation. By utilizing EV batteries as distributed storage resources, surplus PV energy can be stored during sunny periods and discharged to meet peak demand in the evenings. This integrated approach helps minimize renewable energy wastage, while also strengthening the flexibility of the grid. Furthermore, the implementation of vehicle-to-grid (V2G) technologies allows EVs to not only draw power but also feed excess electricity back into the grid. This capability enables EVs to support grid operations by providing essential services like frequency regulation and voltage stabilization [17].

The widespread implementation of integrated photovoltaic (PV) and electric vehicle (EV) systems faces a number of obstacles. Uncoordinated EV charging practices might lead to peak demand issues, necessitating costly upgrades to the grid. Concerns about battery degradation and economic uncertainties could dissuade EV owners from participating in vehicle-to-grid (V2G) programs. Additionally, existing regulatory frameworks often do not offer adequate incentives for consumers or grid operators to invest in PV–EV technologies. Despite these challenges, research indicates that coordinated charging strategies, demand response mechanisms, and supportive policies have the potential to fully unlock the benefits of PV–EV integration. With the right approach, the integration of PV and EV systems can be successfully implemented on a large scale [18].

### 2.3. Interactions between distributed PV and EV clusters in local networks

The relationship between PV systems and EV clusters varies greatly depending on factors like charging infrastructure, regulations, and consumer habits. Research suggests that linking workplace or public EV charging stations with rooftop PV installations can boost renewable energy use. In addition, EV clusters can help reduce the fluctuations in PV generation by serving as controllable energy loads, ultimately improving grid reliability. Furthermore, the integration of PV systems and EV clusters has the potential to enhance renewable energy utilization and grid stability in various contexts.

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The interplay of variable photovoltaic (PV) output and electric vehicle (EV) demand poses intricate operational challenges for electricity grids. The lack of coordinated scheduling can lead to mismatches between power generation and consumption, resulting in voltage fluctuations and posing potential threats to grid reliability. To tackle these issues, efficient optimization frameworks, timely communication systems, and smart grid technologies that incorporate PV and EV data are essential. Collaboration among stakeholders is crucial in ensuring a stable and resilient grid system [19].

International pilot projects have shown great potential for integrating photovoltaic (PV) and electric vehicle (EV) technologies, despite facing various challenges. In Germany, PV–EV microgrids have successfully increased the penetration of renewable energy sources through advanced demand response (DR) programs. In Japan, large-scale vehicle-to-grid (V2G) trials have proven that EV fleets can effectively support PV-rich microgrids during peak demand periods. Likewise, in China, coordinated scheduling models for PV and EV clusters have significantly reduced curtailment and enhanced overall system efficiency. These examples highlight the promising benefits of integrating PV–EV technologies on a global scale.

Effectively integrating distributed PV and EV clusters is essential for creating sustainable energy systems at the local level. However, this process is hindered by significant technical, economic, and institutional barriers. The upcoming chapter will explore in detail the specific challenges related to integrating PV and EV technologies, providing insights on how to overcome these barriers for a more sustainable future.

## 3. Technical and operational challenges

### 3.1. Intermittency of solar power and its impact on grid stability

Integrating distributed photovoltaic (PV) systems with local networks faces a critical challenge due to the intermittency of solar power generation. The output of PV systems can vary significantly depending on factors such as solar irradiance, cloud cover, and seasonal changes. This variability introduces uncertainty into local energy systems, making load balancing and forecasting more complex. For instance, sudden fluctuations in PV generation can lead to voltage instability, frequency deviations, and reverse power flows in distribution networks. Overcoming these challenges is essential for ensuring the reliable and efficient integration of PV systems with local networks.

The rapid increase in photovoltaic (PV) penetration poses challenges in maintaining power quality. Effective mitigation measures, such as advanced forecasting techniques, energy storage systems, and flexible demand-side resources like electric vehicles (EVs), are essential for managing PV variability. Despite their importance, coordinating PV output and EV charging demand in real-time is a significant technical hurdle due to the unpredictable nature of both resources. It is crucial to address this challenge to ensure a reliable and stable power system in the face of growing PV integration.

### 3.2. EV charging patterns and their impact on grid demand

The behavior of electric vehicle (EV) users has a substantial impact on local grid operations. The demand for EV charging is not only substantial but also concentrated both temporally and spatially. Research shows that many EV owners choose to charge their vehicles in the evening, coinciding with peak residential electricity usage. This synchronization exacerbates peak load issues and puts

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added strain on local distribution transformers. Managing EV charging patterns to avoid these peaks is crucial for ensuring grid stability and meeting the needs of both EV users and the wider community.

The unpredictability of electric vehicle (EV) user behavior adds complexity to demand forecasting. Unlike traditional electric loads, EV charging demand is influenced by factors such as travel patterns and user preferences. Without proper coordination, haphazard charging of EV clusters can lead to sudden spikes in demand, voltage drops, and potential reliability issues in distribution systems. Effective management and coordination are necessary to minimize these challenges and ensure a smooth transition to a more sustainable transportation system.

Implementing smart charging strategies, like time-of-use pricing, demand response, and V2G technologies, can help alleviate the negative impacts of electric vehicle charging on the grid. However, widespread adoption of these strategies is hindered by the lack of advanced communication infrastructure, low user participation rates, and inadequate regulatory frameworks. Overcoming these barriers is crucial for optimal integration of EV charging systems.

### 3.3. Combined variability and operational challenges

The interplay between fluctuating solar power generation and electric vehicle charging poses complex issues for grid management. When solar panel output decreases due to cloudy weather, it often aligns with peak demand for electric vehicle charging, exacerbating the imbalance between energy supply and consumption. Likewise, spikes in electric vehicle charging needs when solar power is reduced can strain the grid, leading to increased reliance on backup power sources and costly upgrades to the grid infrastructure. Mitigating these challenges requires careful planning and coordination between renewable energy sources and electric vehicle usage.

Advanced optimization and control frameworks are crucial for managing the combined variability and uncertainties associated with real-time data in PV-EV integrated systems. Stochastic optimization, robust scheduling, and model predictive control are proposed methods to enhance system reliability. However, implementing these approaches is challenging due to the complexity of real-time implementation, the requirement for high-resolution data, and the limited computational capacity of current grid management systems. Overcoming these obstacles will be essential for the widespread adoption of efficient and reliable PV-EV integrated systems.

### 3.4. Infrastructure and communication requirements

The integration of PV–EV clusters relies on both technical enhancements and infrastructure development. Upgrades to distribution networks, such as reinforced transformers, advanced metering systems, and bidirectional charging stations, are crucial. Additionally, real-time communication infrastructure is necessary for smart charging and coordinated scheduling. Successful coordination of PV and EV resources is impossible without reliable communication and data-sharing platforms. These improvements are essential to maximize the efficiency and effectiveness of PV–EV clusters.

The rising digitalization of grid operations highlights the importance of cybersecurity in protecting systems from potential cyberattacks. When designing resilient PV-EV integration frameworks, priority must be given to safeguarding user privacy and maintaining data integrity to ensure the security and reliability of the system.

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# 4. Optimization strategies

## 4.1. Optimal deployment of PV–EV systems in local clusters

Strategic placement of distributed PV and EV clusters is crucial for achieving a sustainable balance between technical efficiency, cost-effectiveness, and environmental advantages. Research has shown that carefully locating PV installations and EV charging stations can alleviate grid pressure and boost the use of renewable energy sources. For instance, situating charging points near business hubs or offices allows EVs to charge during the day, syncing with peak PV generation times. Additionally, incorporating PV systems into community microgrids enables local clusters to maximize self-sufficiency and reduce dependence on central power grids. By optimizing the deployment of these clusters, we can create a more efficient and environmentally friendly energy ecosystem.

Optimization models for deploying PV-EV systems take into account various objectives, such as minimizing power losses, decreasing peak demand, and maximizing renewable energy usage. Multi-objective optimization frameworks, like Pareto-front approaches, have been developed to assess the balance between technical, economic, and environmental targets. These models emphasize that strategic coordination in planning PV-EV systems not only improves efficiency but also supports sustainable energy development in the long run.

## 4.2. Smart grid solutions for coordinated scheduling

Smart grids are essential for successful integration of photovoltaic (PV) systems with electric vehicles (EVs). These grids enable real-time monitoring, bidirectional power flow, and advanced control mechanisms that facilitate effective scheduling. In addition, demand response features and dynamic pricing offer incentives for EV owners to charge during optimal times, such as when there is surplus PV energy available. This flexibility in charging helps alleviate excessive strain on the grid, enhancing its overall stability. Smart grids play a crucial role in balancing energy demands and improving the efficiency of PV–EV integration.

The significance of vehicle-to-grid (V2G) technologies in smart grid solutions cannot be overstated. These technologies enable electric vehicles (EVs) to offer essential services like frequency regulation, spinning reserves, and voltage support. By aggregating EV fleets, they can essentially function as virtual power plants (VPPs), helping to stabilize grids with high renewable energy penetration. However, for V2G to be economically feasible, it relies heavily on user engagement, considerations for battery wear and tear, and market structures that incentivize the provision of ancillary services. These factors are crucial in determining the success and sustainability of V2G implementations.

Energy storage systems, like stationary batteries, are utilized alongside vehicle-to-grid (V2G) technology to boost flexibility in electric vehicle (EV) clusters. By integrating photovoltaic (PV) systems, EVs, and ESS resources, a hybrid optimization approach has been proven to enhance system reliability and lower expenses. Advanced forecasting tools and robust optimization algorithms play a crucial role in managing uncertainties that arise from fluctuations in PV output and EV demand. By combining these technologies, the energy system becomes more reliable, cost-effective, and efficient overall [20].

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### 4.3. Advanced optimization techniques

Recent studies have delved into cutting-edge optimization strategies for integrating photovoltaic (PV) systems and electric vehicles (EVs). Stochastic optimization approaches account for uncertainties in PV power generation and EV charging demands, yielding more robust scheduling results. In contrast, robust optimization frameworks prioritize worst-case scenarios to enhance system reliability during adverse conditions. Model predictive control (MPC) stands out as a promising technique, allowing for real-time adjustments to charging and discharging schedules based on current data. These advanced methods highlight the potential for more efficient and reliable PV-EV integration solutions.

As the demand for efficient energy systems continues to rise, the integration of machine learning and artificial intelligence (AI) in the optimization of photovoltaic (PV) and electric vehicle (EV) systems is gaining momentum. Deep learning algorithms are proving to be instrumental in enhancing short-term PV forecasting and EV load prediction, both crucial components in scheduling models. Additionally, reinforcement learning is being explored for adaptive control of EV charging, enabling systems to continuously learn and improve their strategies over time. While these AI-based approaches hold great potential for increasing system flexibility and reducing computational complexity, several challenges still hinder their widespread practical implementation [21].

### 4.4. Policy and market mechanisms supporting optimization

Supportive policy and market mechanisms are essential for the success of optimization strategies. Implementing time-of-use tariffs, feed-in tariffs for solar PV systems, and financial incentives for vehicle-to-grid (V2G) participation are crucial in ensuring that user behavior aligns with system optimization goals. Additionally, allowing electric vehicles (EVs) to participate in providing ancillary services can improve the economic viability of integrating PV systems with EVs. Policymakers have a significant role in designing regulatory frameworks that promote investment in charging infrastructure, grid upgrades, and smart grid technologies. Ultimately, without the right policies and market structures in place, optimization strategies will struggle to achieve their full potential [22].

Countries like Denmark and states like California showcase the significance of policy backing in the adoption of electric vehicles. Denmark's regulatory frameworks allow EVs to provide frequency regulation services, while California offers incentives for workplace charging that aligns with solar power generation patterns. These cases emphasize that the shift towards EVs requires not only technological advancements but also coordinated institutional support. Collaboration among stakeholders is crucial to overcoming the challenges in transitioning to electric transportation on a global scale.

## 5. Environmental and economic impacts

### 5.1. Carbon emission reductions and environmental benefits

Integrating distributed photovoltaic (PV) systems with electric vehicle (EV) clusters offers a major advantage in decreasing greenhouse gas emissions. By using PV generation to replace fossil-fuel-based electricity with renewable energy and utilizing EVs to lessen reliance on internal combustion engines, the combined impact is a significant reduction in emissions. Charging EVs with PV-generated electricity can potentially decrease lifecycle carbon emissions by as much as 70%

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compared to traditional gasoline-powered vehicles. This synergy between PV systems and EV clusters not only promotes sustainability but also demonstrates the effectiveness of renewable energy in combating climate change.

Integrating solar photovoltaic systems with electric vehicles not only reduces carbon emissions but also enhances urban air quality by decreasing nitrogen oxides and particulate matter from transportation. This is crucial in heavily populated cities where transport significantly contributes to air pollution. Moreover, local solar power generation lessens dependence on centralized power plants, thereby minimizing environmental impacts such as water consumption and land use. Ultimately, integrating PV with EVs presents a sustainable solution for cleaner air and reduced environmental impact in urban areas.

While the environmental benefits of PV systems and EVs are significant, there are important considerations to keep in mind. The production and disposal of PV panels and EV batteries can have negative impacts, such as material extraction issues and challenges with recycling and electronic waste management. To address these concerns, experts recommend the implementation of circular economy practices, like battery recycling and PV panel reuse, to maximize the environmental sustainability of PV–EV systems.

### 5.2. Economic feasibility and cost–benefit analysis

Integrating solar energy and electric vehicles has various economic implications. Initial investments in distributed solar panels and charging infrastructure are substantial. Additional costs arise from grid upgrades, bidirectional chargers, and smart grid technologies. Moreover, participating in vehicle-to-grid programs can lead to costs associated with battery degradation, potentially diminishing the financial appeal for EV owners. Overall, while PV–EV integration has numerous benefits, it also involves significant financial considerations and potential drawbacks.

Despite the initial investment, the advantages of distributed PV systems far outweigh the costs. These systems decrease electricity expenses for both households and businesses by allowing them to use solar energy they generate themselves. Smart charging techniques have the potential to lower peak demand charges and enhance system efficiency. Furthermore, integrating PV with electric vehicles can mitigate external costs associated with air pollution and climate change, resulting in widespread economic advantages for society as a whole.

Various cost-benefit analyses from different regions have shown that the integration of photovoltaic (PV) and electric vehicle (EV) systems is economically viable. Studies in Europe and North America have indicated that implementing coordinated charging strategies can lead to a reduction in system operating costs by 10-20%, as well as an increase in renewable energy penetration. In China, optimization models have demonstrated that integrating PV and EV clusters can decrease curtailment and overall system costs by improving local energy self-sufficiency. These findings suggest that, with the right policy and market support, PV-EV integration can be a competitive alternative to traditional energy systems.

## 6. Conclusion

The combination of distributed photovoltaic (PV) systems and electric vehicle (EV) clusters in local energy networks has the potential to revolutionize sustainable energy systems worldwide. This integration offers various advantages, such as reducing carbon emissions, improving air quality, optimizing renewable energy utilization, and cutting long-term costs. However, significant obstacles remain in addressing technical and operational challenges. Issues like the intermittent nature of PV

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power generation, unpredictable EV charging demands, and limitations in infrastructure continue to pose challenges. Resolving these challenges will be key to maximizing the benefits of PV-EV integration and advancing the transition towards a more sustainable energy future.

Recent research has delved into the intricate interactions between photovoltaic (PV) and electric vehicle (EV) clusters, exploring their technical characteristics, operational challenges, and potential benefits. Various international studies and pilots have shown promise in integrating PV and EV systems, showcasing the feasibility of this integration. However, widespread adoption necessitates a cohesive strategy, encompassing technology advancements, regulatory frameworks, and market incentives to ensure successful deployment on a large scale.

Future research should focus on developing sophisticated models and scalable optimization frameworks to link photovoltaic and electric vehicle systems with broader energy infrastructures. Policymakers need to prioritize creating supportive regulations, incentives, and circular economy frameworks for environmental sustainability. By effectively integrating distributed photovoltaic and electric vehicle clusters, these technologies can become vital components of smart cities and carbon-neutral futures, advancing the global energy transition.

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