



**Escola Tècnica Superior  
d'Enginyeria Química**



**UNIVERSITAT ROVIRA i VIRGILI  
Departament d'Enginyeria Mecànica**

# **FINAL MASTER PROJECT**

**MASTER IN ENVIRONMENTAL ENGINEERING  
AND SUSTAINABLE ENERGY**



**Design of Electrical Vehicle charger system with renewable energies**

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**Tarragona, January 2024**

## Acknowledgments

I would first like to express my gratitude to Almighty ALLAH for the courage and strength he has given me to complete this thesis successfully. I firmly believe that without his help and blessings, I would never be able to accomplish this task. I am heartily grateful to my supervisor, **Marc Marín Genescà**, and my coordinator, **Sandra Contreras Iglesias** for their continuous support, excellent guidance, motivation, and immense knowledge from the beginning. I feel it is a great privilege to express my deepest and most sincere gratitude to them for their inspiration, for giving me the confidence to complete difficult tasks, and for providing a friendly atmosphere for all the research activities and concept-building discussions.

## Abbreviations

EVs	Electric Vehicles
RESs	Renewable Energy Sources
BESS	Battery Energy Storage Systems
DC	Direct Current
GHG	Greenhouse Gas
CO <sub>2</sub>	Carbon Dioxide
V2G	Vehicle-to-Grid
IoT	Internet of Things
AI	Artificial Intelligence
EV	Electric Vehicle
V2V	Vehicle-to-Vehicle
MCSs	Mobile Charging Stations
PCSs	Permanent Charging Stations
SO	System Operators
ToU	Time of Use
SAC	Soft Actor-Critic
LPSP	Loss of Power Supply Probability
PV	Photovoltaic
BESS	Battery Energy Storage System
CS	Charging Station
CLPs	Charging Load Profiles
CLARA	Clustering LARge Applications
GIS	Geographic Information System
M/G/K	Markovian/General/Queue with K servers
EV	Electric Vehicle
gha	Global Hectare
kWh	Kilowatt-hour
CSLP	Charging Station Location Problem
PV	Photovoltaic
BESS	Battery Energy Storage System

## **Abstract**

This study addresses the critical need for sustainable and economically viable electric vehicle (EV) charging infrastructure. With a growing emphasis on renewable energy and the rising adoption of electric mobility, understanding the energy dynamics, environmental impact, and financial feasibility of various charging scenarios is paramount. The research employs an analytical approach, scrutinizing four distinct charging infrastructure scenarios. These scenarios encompass different combinations of renewable energy sources, energy storage systems, and grid dependence. A pivotal tool in this analysis is the HOMER Grid<sup>®</sup> software, which facilitates the simulation and optimization of these proposed scenarios, offering a robust platform for assessing their performance and viability. A thorough operational analysis of EV charging units, accounting for both fast and slow charging preferences, is conducted. Financial evaluations include net present cost, return on investment, internal rate of return, and payback periods. Findings reveal a clear environmental and economic advantage in scenarios incorporating renewable energy. Integration of photovoltaic systems and a battery energy storage system significantly reduces carbon emissions, contrasting with the higher emissions observed in grid-dependent scenarios. Financially, scenarios with renewable integration demonstrate higher efficiency and cost savings compared to grid-dependent counterparts. In conclusion, this study underscores the profound benefits of incorporating renewable energy into EV charging infrastructures. Significant reductions in carbon emissions and impressive economic outcomes advocate for a sustainable and financially viable approach to EV charging infrastructure development. As electric mobility continues to evolve, these insights provide essential guidance for policymakers, urban planners, and energy sector stakeholders, shaping future investments and strategies for sustainable EV infrastructure.

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# **1. Introduction**

## **1.1 Background and Context**

The global transportation sector which is a pivotal component of the modern industrial landscape plays a substantial role in contributing to worldwide carbon emissions. As concerns regarding environmental sustainability and the urgent need for climate change mitigation intensify, the transportation industry is taken into consideration [1]. The sector's undeniable impact on the environment necessitates a comprehensive understanding of its role in the broader context of global challenges. Against the backdrop of escalating environmental issues, discussions on sustainable transportation have gained unprecedented momentum. The imperative to address climate change has become a driving force. This compels stakeholder to explore transformative measures within the transportation sector [2]. The inherent link between transportation activities and the escalating levels of greenhouse gas emissions is explored. The international community has set ambitious climate goals that underscore the critical importance of transitioning towards sustainable transportation practices [3]. This contextual framework highlights the multifaceted nature of the challenges faced by the global transportation sector. It is not merely a matter of addressing carbon emissions but involves rethinking and reshaping the entire landscape to meet the pressing demands of environmental sustainability [4]. The urgency of this transition cannot be overstated, as the transportation sector stands as both a significant contributor to climate change and essential in the global effort to reduce reliance on fossil fuels. In essence, the expanded background and context underscore the intricate interplay between the transportation sector and the broader environmental concerns of our time. The discourse transcends mere acknowledgment of the problem and delves into the complexities inherent in crafting effective solutions. As the proposed study delve into subsequent sections, a brief understanding of the challenges and opportunities within the global transportation sector will pave the way for informed discussions on sustainable practices and policy interventions [5].

## **1.2 The Rise of Electric Vehicles**

Electric Vehicles (EVs) have undergone a remarkable ascent and transforming into a pivotal force driving the transition toward sustainable transportation. This surge represents a dramatic shift in automotive technology, with far-reaching consequences for energy consumption trends and environmental sustainability. The evolution and escalating market integration of EVs underscore a departure from traditional internal combustion engine vehicles. This highlights a new era in the automotive landscape [6]. The emergence of EVs is marked by a paradigm shift that extends beyond mere technological advancement. It encompasses a broader societal and environmental transformation, positioning EVs as catalysts for change. Notably, their adoption stands as a testament to the collective commitment to mitigating the environmental impact of transportation [7]. Unlike their conventional counterparts reliant on internal combustion engines, EVs distinguish themselves through a commitment to a cleaner mode of transportation. The elimination of tailpipe emissions becomes a defining feature. It

underscores their contribution to the reduction of air pollution in urban settings. This characteristic positions EVs as instrumental tools in the ongoing battle against the detrimental effects of urban air pollution [8]. Furthermore, the environmental advantages of EVs extend to their pivotal role in restricting greenhouse gas emissions. By relying on electric power sources, these vehicles play a crucial part in diminishing the carbon footprint associated with traditional transportation methods. The ripple effect of this reduction contributes significantly to global efforts aimed at combating climate change [9]. In essence, the rise of electric vehicles transcends a mere shift in propulsion technology. It embodies a conscientious choice towards sustainable and eco-friendly transportation. As EVs continue to gain momentum in the market, their impact reverberates through various facets of society. This is reshaping not only the automotive industry but also the broader narrative of responsible and forward-thinking mobility solutions [10].

### **1.3 Challenges in EVs**

The transition from traditional internal combustion engine vehicles to EVs is a crucial step towards a more sustainable future. However, several challenges hinder the widespread adoption of EVs. Understanding and addressing these challenges is essential for policymakers, manufacturers, and consumers alike.

#### **1.3.1 Development of Charging Infrastructure**

- 1 ***Insufficient Number of Charging Stations:*** One of the most pressing issues is the inadequacy of charging infrastructure. Many regions, especially rural and underserved urban areas, lack sufficient public charging stations. This leads to 'range anxiety' among potential EV users, who fear they may run out of charge without access to a charging point. The distribution of charging stations also tends to be uneven, with a high concentration in some urban areas while completely absent in others [11].
- 2 ***Variability in Charging Speeds:*** Charging speed varies significantly across different EV models and charging station types. There are three primary types of EV chargers - Level 1, Level 2, and DC Fast Chargers. Level 1 chargers are the slowest, often taking overnight to fully charge a vehicle, while DC Fast Chargers can charge a vehicle to 80% in about 30 minutes. However, the latter are more expensive and less common. The inconsistency in charging speeds can be inconvenient for users, particularly for those needing a quick charge.
- 3 ***Grid Reliability and Capacity Issues:*** The existing electrical grid in many areas is not equipped to handle the increased demand that a widespread shift to EVs would entail. Charging multiple EVs simultaneously, especially during peak hours, could lead to significant strain on the electrical grid. This necessitates substantial upgrades to the current grid infrastructure, which can be costly and time-consuming [12].
- 4 ***Dependency on Non-Renewable Energy:*** The environmental benefits of EVs are somewhat diminished if the electricity used to charge them comes from non-renewable sources like coal or natural gas. For EVs to be truly sustainable, the electricity used must come from renewable sources. However, integrating renewable

energy sources (RESs) into the grid remains a challenge due to their intermittent nature and the need for energy storage solutions.

### **1.3.2 Other Related Challenges**

1. **High Initial Cost and Economic Considerations:** EVs generally have a higher upfront cost compared to traditional vehicles, though they are cheaper in the long run due to lower operating costs. This high initial cost can be a barrier for many potential buyers. Additionally, the economic impact on industries related to traditional vehicles, such as oil and gas, and automotive parts, can be significant, leading to resistance in some sectors [13].
2. **Battery Life and Performance Issues:** Battery performance can degrade over time, reducing the range and efficiency of EVs. Concerns about battery life, replacement costs, and the environmental impact of battery production and disposal are also significant considerations.
3. **Lack of Consumer Awareness and Confidence:** Many consumers are not fully aware of the benefits and functionalities of EVs. Misconceptions about range, the availability of charging stations, and vehicle performance can deter potential buyers. Building consumer confidence through education and experience is crucial for wider EV adoption.
4. **Policy and Regulatory Hurdles:** Inconsistent policies and regulations regarding EVs and EV charging infrastructure across different regions can impede the growth of the EV market. Government incentives, subsidies, and coherent policies play a critical role in accelerating EV adoption [14].

## **1.4 Integrating Renewable Energy and BESS in EV Charging Infrastructure**

The integration of RESs, like solar and wind power, with Battery Energy Storage Systems (BESS) is used in the context of EV charging infrastructure. This integration is pivotal in steering EV charging towards sustainability while addressing the inherent challenges posed by the use of renewable energy.

### **1.4.1 Renewable Energy Sources in EV Charging**

The adoption of RESs in EV charging infrastructure is a significant stride towards reducing the carbon footprint associated with EVs. By harnessing solar and wind energy, EV charging stations can operate on cleaner energy, thus amplifying the overall environmental benefits of electric vehicles.

1. **Solar Power Integration:** Solar panels can be installed in EV charging stations to capture solar energy. This not only includes large-scale solar farms but also rooftop installations in urban environments. The photovoltaic cells in these panels convert sunlight directly into electricity, which can then be used to charge EVs.
2. **Wind Power Utilization:** Wind turbines can also be integrated into the power supply chain for EV charging stations. These turbines convert kinetic energy from wind into electrical energy, which, like solar power, can be used for EV charging [14].

### 1.4.2 Challenges with Renewable Energy

Despite their benefits, RESs face significant challenges, primarily due to their intermittent nature. Solar power generation is subject to daily and seasonal variations, while wind energy depends on wind speed and consistency. This intermittency can lead to periods where the renewable energy supply is insufficient to meet the demand for EV charging stations.

### 1.5 Role of BESS

BESS is critical in mitigating the challenges posed by the intermittency of RESs. They offer a robust solution by storing excess energy generated during periods of high renewable energy output (like sunny or windy periods) [15].

1. ***Energy Storage and Balancing:*** BESS stores excess energy when production from renewable sources exceeds demand. This stored energy can then be released back into the power grid or directly used for EV charging during periods of low renewable energy generation or high charging demand.
2. ***Enhancing Grid Stability:*** By providing a buffer for the energy generated from renewable sources, BESS contributes to the overall stability of the electrical grid. They can quickly release energy to balance supply and demand. This aids in grid management and reducing reliance on traditional fossil-fuel-based peaker plants.
3. ***Technology and Capacity Considerations:*** The efficiency of BESS is heavily influenced by the advancements in battery technology. This includes improvements in energy density, charging speed, lifespan, and safety. The capacity of these systems is also a critical factor, as it determines how much excess energy can be stored and how long it can sustain the EV charging demand during periods without sufficient renewable energy generation.

### 1.6 Key Elements for Renewable Energy and BESS Integration

The integration of RESs with BESS in EV charging infrastructure involves a complex interplay of technology, energy management, and grid interaction. This integration must be optimized to ensure that the charging infrastructure is sustainable, reliable, and efficient. Key considerations include:

1. ***System Design and Optimization:*** Designing an integrated system that maximizes the use of renewable energy and effectively utilizes BESS for energy storage and supply.
2. ***Smart Charging and Energy Management:*** Implementing smart charging systems that can adjust the charging rates based on the availability of renewable energy and stored energy in BESS.
3. ***Grid Interaction and Regulations:*** Navigating the regulatory landscape and ensuring that the integrated system complies with grid standards and contributes positively to the overall energy network [16].

### **1.7 Importance of Sustainable Charging Solutions**

The advancement of sustainable charging solutions for EVs represents a critical juncture in the evolution of the global transportation sector. This endeavor transcends mere technical innovation; it is fundamentally intertwined with the broader objective of achieving a sustainable future. The emphasis on developing such solutions is driven by several key factors [17]:

1. ***Environmental Impact Reduction:*** Traditional fossil fuel-powered vehicles contribute significantly to greenhouse gas (GHG) emissions. Primarily carbon dioxide (CO<sub>2</sub>), which is pivotal in driving climate change. EVs offer a promising alternative, yet their environmental benefits are contingent on the sustainability of their charging infrastructure. By focusing on RESs, such as solar or wind power, for EV charging, we can drastically reduce the carbon footprint associated with transportation. This shift is imperative for meeting the targets set by international climate accords, such as the Paris Agreement.
2. ***Energy Efficiency:*** Sustainable charging solutions emphasize not only the source of electricity but also the efficiency of the charging process. Advanced technologies like smart chargers and high-efficiency power electronics can minimize energy loss during charging. This efficiency is crucial for reducing overall energy consumption, thereby lessening the strain on the electrical grid and diminishing the environmental impact [18].
3. ***Grid Stability and Demand Response:*** As EV adoption escalates, the electricity demand will inevitably surge. Sustainable charging solutions incorporate smart grid technologies that enable demand response. This means that charging can be dynamically adjusted based on grid load, thereby preventing overloads and promoting grid stability. Such systems can also support vehicle-to-grid (V2G) technologies, where EVs can supply energy back to the grid during peak demand periods, further enhancing grid resilience.
4. ***Economic Viability:*** For EVs to be a feasible option for the majority, the charging infrastructure must be economically sustainable. This includes the cost of installation, maintenance, and electricity. By employing renewable energy and implementing efficient technologies, long-term operational costs can be reduced. Moreover, a sustainable charging infrastructure can stimulate job creation in both the renewable energy sector and the EV industry, bolstering economic growth [19].
5. ***Accessibility and Convenience:*** A sustainable charging network must be widely accessible to encourage EV adoption. This means installing chargers in various locations – residential areas, workplaces, and public spaces – and ensuring they are compatible with different vehicle models. The convenience of charging is a critical factor in consumer decisions to switch to EVs, and thus, a comprehensive, user-friendly network is essential.
6. ***Technological Integration and Innovation:*** Sustainable charging solutions are at the forefront of integrating emerging technologies like IoT (Internet of Things), AI (Artificial Intelligence), and blockchain. These technologies can enhance user experience, improve system efficiencies, and ensure secure transactions. For instance, blockchain can facilitate

transparent and efficient energy transactions in V2G systems, while AI can optimize charging schedules based on user patterns and grid demands [20].

### **1.8 Motivation of Research**

This research is fundamentally motivated by the global shift towards electric mobility. This is necessitated by the urgent need to mitigate climate change through reduced GHG emissions. With transportation being a significant contributor to carbon emissions, the availability and optimization of EV charging infrastructure are pivotal. The integration of RESs and advanced technologies like smart grids into these infrastructures presents both opportunities and challenges, particularly in enhancing energy efficiency and reducing environmental impact. Furthermore, economic considerations, policy implications, and consumer adoption patterns play crucial roles in shaping the EV landscape. This study aims to bridge gaps in current knowledge, providing comprehensive insights into the long-term performance, environmental sustainability, and economic viability of various charging infrastructures. Ultimately, the research is driven by the overarching goal of advancing sustainable transportation, aligning with global efforts to promote renewable energy use and foster a more sustainable future.

### **1.9 Problem Statement and Focus of the Research**

The research is intricately designed to delve into multifaceted aspects of EV charging infrastructure. The research aims to provide insights into its operational efficiency, environmental impact, economic viability, and integration of RESs. The following detailed focus areas encapsulate the comprehensive scope of this study:

1. ***Operational Efficiency of Charging Stations:*** The study rigorously examines the operational metrics of both fast and slow EV charging stations over an entire year. It meticulously analyzes the number of charging sessions, the quantum of energy delivered, utilization factors, and peak power requirements. The goal is not only to understand the intricate dynamics of these charging stations but also to identify optimization opportunities that enhance their operational efficiency.
2. ***Environmental Impact Assessment:*** A critical facet of this research is the in-depth analysis of carbon emissions across various EV charging scenarios. By scrutinizing scenarios powered by renewable energy, conventional grid-only systems, and hybrid models, the study aims to provide a nuanced understanding of the environmental implications associated with different charging infrastructure configurations. It aspires to contribute valuable insights into sustainable practices within the burgeoning field of electric mobility.
3. ***Integration of RESs:*** With a specific focus on sustainability, the research investigates the integration of RESs, particularly PV systems, into the EV charging infrastructure. This involves assessing the feasibility, efficiency, and impact of incorporating solar energy into the charging process. The ultimate goal of reducing reliance on non-renewable energy and minimize the overall carbon footprint of EVs.

4. ***Economic Analysis:*** The study conducts a comprehensive economic analysis, evaluating the financial aspects of diverse EV charging models. This includes an assessment of cost efficiency, return on investment (ROI), and the overall economic viability of different scenarios. By providing detailed insights into the economic considerations associated with each model, the research aims to guide decision-makers toward sustainable and economically sound choices in EV infrastructure development.
5. ***Policy and Consumer Behavior Insights:*** Recognizing the pivotal role of policy frameworks and consumer behavior in shaping the landscape of EV adoption, the research explores the interconnected influence of these factors on the efficiency and acceptance of EV charging infrastructures. Understanding how policies and consumer preferences align or diverge is crucial for developing strategies that support the widespread and effective deployment of sustainable EV charging solutions.

This intricate and detailed focus of the research underscores its commitment to unraveling the complexities of EV charging infrastructure. It offers a perspective that combines operational, environmental, economic, and sociopolitical considerations. By addressing these multifaceted aspects, the research aspires to contribute actionable insights that foster sustainable and economically viable electric mobility solutions for the future.

## 2. Literature Review

The literature [21] concerning the ecological footprint of EV charging stations extensively examines three key parameters: direct/indirect emissions, manpower, and physical land requirements. The environmental impact of EV charging stations is intricately tied to the source of electricity used for battery charging. The estimated ecological footprint of EV charging stations stands at 40.69 gha, prompting a comprehensive exploration of potential mitigation strategies. A proposed hybrid power system emerges as a promising solution, showcasing a potential 89.9% reduction in ecological footprint. The specific Ecological Footprint per unit of energy consumed in EV battery charging is calculated at  $3.1 \times 10^{-4}$  gha/kWh. The introduction of the suggested hybrid system significantly reduces this impact to  $3.15 \times 10^{-5}$  gha/kWh, indicating a substantial environmental benefit. The literature also delves into the lifecycle cost analysis, revealing an estimated 0.168 \$/kWh for traditional battery charging, substantially reduced to 0.107 \$/kWh with the integration of the proposed hybrid system. In conclusion, the literature strongly advocates for the widespread promotion of renewable energy sources to power EV charging stations as a fundamental strategy to minimize environmental impact and enhance overall sustainability.

The presented research [22] introduces a novel learning-based approach to address the charging station location problem (CSLP) with a focus on integrating EV charging demand management into the planning of charging infrastructures. The two-stage model commences with the development of a gradient boosting-based learning model in the first stage, predicting charging demand for a station based on 15 defined features. Subsequently, in the second stage, a demand-supply-coupled CSLP model is formulated to optimize total charging usage rates for both existing and newly selected charging stations. The optimization problem is addressed using a gradient-based stochastic spatial search algorithm. The efficacy of the proposed method is evaluated through a case study utilizing 6-year charging event data from Kansas City, Missouri. Results indicate that the model generates accurate charging demand predictions and achieves a 14% increase in charging usage rates, surpassing the performance of two benchmark approaches. This research contributes valuable insights for agencies involved in identifying optimal locations for new charging stations. It demonstrates the potential of learning-based strategies in enhancing the efficiency of EV charging infrastructure planning.

The research [4] explores the techno-economic viability and environmental impact of grid-connected PV-based EV charging stations in Kentucky. It considers various PV system sizes, locations, orientations, and the influence of net metering policies and electricity tariffs. The research evaluates the potential of combining green hydrogen fuel energy with solar energy to create sustainable alternatives for carbon-free transportation. Lithium-ion batteries are charged using excess PV energy, and the study investigates different scenarios. It includes on-

grid PV-based EV charging stations, low-tariff period charging and integrating green hydrogen production. Despite similar techno-economic feasibility for EV stations in Kentucky, the study suggests that the second scenario (charging during low-tariff periods) is environmentally favorable. It factors in hydrogen production costs and carbon footprint considerations. The findings contribute valuable insights for the transition to sustainable transportation with a focus on renewable energy integration.

The study [23] emphasizes the significant role of EV charging stations in the daily regulation and operation of power distribution systems. The strategic placement and appropriate capacity configuration of these stations directly impact the operation strategy and conditions of the distribution system. Subsequently influencing the economic and environmental benefits of distributed power supply and EV load integration with the power grid. The analysis considers the travel characteristics of EVs, coupled with electrical geography. It derives a more accurate EV charging load by fitting charging data with travel patterns. An optimal allocation model for EV charging stations is formulated to minimize grid losses. This addresses the nonconvex problem using a combination of second-order cone relaxation and the Dist flow power flow model. Through simulation, the study validates the effectiveness of the proposed configuration scheme by optimizing the placement of two types of charging stations: conventional and fast charging. The research offers a theoretical foundation for the planning and capacity expansion of EV charging stations.

The ref. [6] addresses the importance of optimal power scheduling for the design of integrated EV charging stations with PV and BESS. It critiques traditional design methods for neglecting accurate PV power modeling and adopting simplistic EV charging strategies, which can lead to suboptimal designs. The study proposes a novel simultaneous optimization model for capacity configuration and scheduling. It integrates hybrid PV power prediction modeling and optimal charging strategies. Using the Big-M method, the original model is transformed into a more computationally efficient mixed-integer linear programming problem. Results from a commercial scenario demonstrate a 15.67% improvement in economic benefits and a 37.14% reduction in carbon emissions compared to the entire grid-based mode. The integration of PV hybrid modeling and optimal charging scheduling proves effective in enhancing capacity configurations and overall system performance. It offers a promising solution for the optimal design and scheduling of PV/BESS-integrated EV charging stations.

The study [24] addresses the challenges posed by the increasing market penetration of EVs and the resultant surge in charging load demand at charging stations. A key challenge is the uncertainty in EV schedules, which complicates the optimal operation of charging stations and can lead to computational difficulties. To mitigate this, the study proposes a two-stage operational strategy that balances computational efficiency with the maintenance of individual EV schedules in high penetration scenarios. In the first stage, EVs are clustered based on similar attributes and behaviors, significantly simplifying the computational process and optimization modeling by reducing the number of individual schedules and operational

constraints to consider. This clustering allows for treating groups of EVs with similar patterns as single entities. The second stage focuses on optimizing the operation of each EV cluster rather than each vehicle. This stage introduces a cooperative operation strategy among EV clusters, utilizing vehicle-to-vehicle (V2V) services. This cooperative approach aims to reduce the need for imported power from the utility grid during peak price periods and decrease the amount of energy storage required at the charging stations, leading to minimized investment and operational costs. The proposed method's effectiveness is demonstrated in a case study involving an EV charging station serving over 180 EVs. The study concludes that this approach is a viable solution for managing the increased charging demand and operational complexity in high EV penetration scenarios, efficiently reducing both cost and computational burden.

The paper [25] presents a strategic planning approach for distribution systems integrated with EV charging stations, addressing the need for efficient charging load management. Employing fuzzy Pareto optimality, the study introduces a heuristic network reconfiguration to minimize real power loss and enhance voltage profiles. Additionally, Time of Use (ToU) pricing-based EV charging load scheduling is developed to minimize annual energy costs. Simulations on 33 and 69-bus distribution systems, considering integrated EV charging stations, distributed generations, and shunt capacitors, demonstrate the effectiveness of the proposed approach in improving system performance. The study also compares ToU pricing-based EV charging with customer comfort-based charging, showing the former's advantage in reducing emissions through real power loss reduction. Overall, the strategic planning approach offers economic benefits while minimizing carbon emissions, providing a comprehensive solution for the efficient integration of EVs into distribution systems.

The literature [26] proposes a methodology for optimizing the layout of EV charging stations in China, considering both EV charging behavior and its broader impact on the power system. The study addresses the need for system flexibility arising from renewable energy fluctuations and increasing EV charging demand. Unlike previous work focusing solely on maximizing profits for station owners and vehicle users, the suggested research integrates an optimized station layout and charging schedule with a comprehensive power system model. Applied to Jiangxi in 2025, the methodology recommends cumulative charging station capacities for workplaces, residences, and shopping centers. The results indicate increased renewable energy integration, decreased thermal power generation, and a substantial reduction in carbon emissions (800 kilotons), aligning with China's carbon neutrality goals by 2060. This work provides an effective approach for EV charging station layout optimization within the context of an integrated power system.

The research [12] introduces a framework integrating a mobility and traffic simulator with evolutionary algorithms to address the location problem of EV charging infrastructure. Utilizing a real-life scenario with a specified number of charging stations and EVs, the study formulates the problem as a multi-objective optimization task. Two evolutionary algorithms,

NSGA-II and MOEA/D-gen, are employed to search for optimal station locations and capacities, considering the travel time and the number of charging stations. Results highlight a trade-off between the two objectives, where improvements in one lead to deterioration in the other. NSGA-II outperforms MOEA/D-gen in approximating optimal solutions. These results provide insights into algorithm efficiency and effectiveness for solving the multi-objective EV charging stations problem. The research sets the groundwork for further exploration of scenarios and meta-heuristics to address this evolving problem.

The article [27] addresses the challenges posed by the extensive integration of EVs into energy systems. Particularly in terms of operational and technological difficulties during bulk charging. The research proposes an optimization algorithm using mixed integer linear programming to dispatch mobile charging stations (MCSs) as a solution to complement and supplement permanent charging stations (PCSs). The goal is to reduce the number of EVs unable to charge at PCSs due to limited capacity and long waiting times. Five scenarios involving different operating and pricing mechanisms are analyzed. The findings show that MCSs offer significant economic and operational advantages. In the most effective scenario, the use of MCSs results in a 64.3% operational improvement compared to not using MCSs. Out of 1074 EVs requesting service, 986 are successfully served in this best-case scenario. Moreover, dynamic pricing leads to a profit increase of 46%. Notably, the application of incentive mechanisms in Case 5 significantly boosts profit, serving 967 EVs, while Case 4 without incentives serves 968 EVs. The study highlights the effectiveness of MCSs in enhancing the efficiency and profitability of EV charging infrastructure.

The study [14] presents an intelligent reinforcement learning-based approach for optimizing the operation of photovoltaic-storage charging stations. It focuses on the entire lifecycle of the energy storage system. Traditional model-driven stochastic optimization methods often fall short in addressing the complexities of energy storage operations and the uncertainties in photovoltaic power generation and EV charging loads. The proposed method fine-tunes the energy storage operation efficiency and capacity attenuation models. It establishes an optimization strategy for energy storage operations using reinforcement learning, aiming to maximize the revenue of photovoltaic charging stations. This approach considers the uncertainties of EV charging demand, PV output, and electricity prices, ensuring efficient charging and PV energy consumption. A dual delay depth deterministic strategy gradient algorithm is employed for solving the continuous decision-making actions for energy storage charging and discharging. The model is trained using actual historical data and optimizes the charging and discharging strategy in real time based on current status. Comparative analysis with traditional methods demonstrates the effectiveness of the proposed approach. It shows improved revenue for photovoltaic storage charging stations throughout their energy storage lifecycle.

The study [28] addresses the anticipated surge in charging stations due to the rising number of electric vehicles, posing grid concerns. To address this, a novel solar-powered charging

station is developed, integrating liquid CO<sub>2</sub> for off-grid conditions. Solar energy is stored by converting CO<sub>2</sub> into liquid, ensuring operation without grid power. Liquid CO<sub>2</sub> is expanded via a turbine for power generation when solar power is insufficient. The study evaluates the impact of using yearly dynamic vs. average solar data on off-grid conditions and system performance. Results reveal a 37% error in estimating solar PV area using yearly averages. The developed system has a total PV panel area of 100,723 m<sup>2</sup>, with a discrepancy of 63,938 m<sup>2</sup> between dynamic and average data. Overall energy and exergy efficiencies are calculated at 0.062 and 0.066, respectively, highlighting the potential of this innovative off-grid charging station.

The ref. [29] focuses on electric vehicle charging station (EVCS) location strategies in response to the growing demand for EV charging in China, with a specific emphasis on the perspective of private investors. Considering the competitive landscape of existing EVCSs, a three-level location model incorporating dynamic pricing is developed, encompassing user decisions, EVCS pricing, and EVCS location decisions. The soft actor-critic (SAC) reinforcement learning algorithm is employed to optimize the pricing strategy, ensuring maximum cumulative revenue. Case studies conducted in an industrial park in China validate the proposed methodology. It demonstrates its superiority in making more economical and scientifically sound location decisions compared to traditional methods. The dynamic pricing approach based on reinforcement learning provides valuable insights for the effective location and operation of additional EVCSs in the future.

China's EV industry has experienced significant growth, yet the demand for charging stations remains a critical gap. As EV subsidies shift away, charging facility subsidies are on the rise to sustain EV growth. Using a multi-factor combination prediction model integrating grey correlation and long and short-term memory, the paper [30] forecasts that China's EV count will reach 1.02 billion by 2030. Through qualitative analysis of EV electricity consumption and power supply scenarios, varying growth patterns for charging stations in China from 2021 to 2030 are identified. The study concludes with strategic suggestions for charging stations, encompassing subsidy initiatives, technology R&D innovation policies, and licensing quotas.

The literature review [31] addresses the rising interest in EVs and the challenges stemming from the lag in fixed charging station (FXCS) investments. These challenges affect both system operators (SO), impacting power system reliability and stability, and EV users, causing long charging times and range anxiety. The study introduces mobile charging stations (MCSs) as a solution to alleviate the burden of FXCSs. A novel energy management strategy is proposed for the optimal operation of MCSs, focusing on the needs of both the SO and EV users. The optimization algorithm aims to minimize the total operational cost of MCSs serving EVs city-wide, while also considering the battery degradation cost of MCSs. Additionally, the strategy promotes fairness between MCS and FXCS operations by incorporating TOU tariff prices. The review discusses the outcomes of this approach, examining operational costs, waiting times, and the impact on the power system.

In the context of smart cities, the rapid increase in EVs necessitates optimized deployment of charging stations to minimize power loss and voltage imbalance. Existing strategies for EV charging station deployment often lead to high power utilization, increased power loss, harmonic distortion, and voltage imbalance. To address these challenges, a novel Dove-based Recursive Deep Network (DbRDN) approach is proposed [32]. This approach involves integrating hybrid renewable energy sources (wind, solar, and hydropower) into a Distributed Generation (DG) grid system. The DbRDN then identifies optimal locations for EV charging stations by analyzing load and line data. The system's efficiency is evaluated under both balanced and unbalanced conditions, with metrics including power loss, harmonic distortion, voltage imbalance, error, and accuracy. The performance of this new approach is compared with existing techniques, demonstrating significant improvements in the deployment of EV charging stations in smart cities.

In the context of the UK's plan to ban fuel vehicle sales by 2035, this study [33] focuses on the reliability of a 2 MW standalone photovoltaic electric vehicle charging station (PVEVCS) to meet the anticipated increase in EV charging demand. The PVEVCS, comprising a PV system, a BESS, and a CS, is analyzed using the loss of power supply probability (LPSP) metric, with climate data from Camborne, UK segmented into high and low irradiation periods. Four charging demand profiles are examined to assess the model's LPSP, and these profiles are optimized through various combinations of PV systems, BESS, and CS. The study finds that solar irradiation significantly affects LPSP, with higher PV capacity improving daytime LPSP, increased BESS capacity benefiting nighttime LPSP, and larger CS capacity reducing hourly LPSP. The research highlights the importance of component capacity in standalone charging stations to ensure reliable power supply for EVs.

The study [34] addresses the challenge of managing grid load due to the unpredictable charging behaviors of EVs. It proposes a method to identify typical charging load profiles (CLPs) using large-scale data from EV charging sessions. The methodology involves computing daily CLPs from these sessions and employing a comprehensive similarity metric that combines Euclidean and Pearson correlation coefficients for more effective clustering. The Clustering LARge Applications (CLARA) algorithm is used to handle large data sets, followed by hierarchical clustering of charging stations based on potential CLPs. These CLPs are then estimated through Monte Carlo simulation. The method's effectiveness is validated with over 340,000 charging sessions from 109 CSs in Wuhan, Central China. The study identifies 17 typical CLPs, highlighting significant seasonal variations in power demand and demonstrating the method's accuracy in group-based load estimation. The research contributes valuable insights for grid load management in the context of increasing EV adoption. The rapid urbanization and growth of transport systems pose challenges, particularly pollution and noise from conventional internal combustion engine vehicles. The shift to greener solutions, such as EVs, aims to mitigate these issues. However, a major obstacle is the strategic placement of charging stations within urban areas.

The article [35] proposes a GIS-based method for siting charging stations, considering distances between them to optimize their location. The approach allows verification and adaptation of results based on different scenarios and charging station numbers, with a focus on pedestrian accessibility. The study applies this method to Katowice, Poland, demonstrating increased coverage area (up to 199%) by expanding the number of stations. The method proves effective in planning EV charging station distribution, offering flexibility to align with city budgets in an iterative process.

The literature review [36] highlights the importance of establishing a robust charging station network for EVs as a key factor in promoting their adoption. Emphasizing environmental protection and government incentives, the review discusses the necessity of early-stage, rational, and scientific planning of EV charging stations. This is vital not only for user convenience but also for effective resource utilization. The paper introduces a novel approach for the charging station service division based on the Voronoi diagram, coupled with an M/G/K queuing model to assess the station's charging capacity. Furthermore, it proposes a location and volume model to determine the most cost-effective construction plan for EV charging stations, minimizing societal costs. Experimental results demonstrate that this planning method is economical and significantly enhances the convenience of EV users. Moreover, it supports the sustainable development of the power grid in the planned area, underlining its practical significance.

### **3. Methodology**

#### **3.1 Optimal System Configuration Analysis Using HOMER Grid Software**

##### **3.1.1 Charging Unit Configurations**

This intricate section embarks on an exhaustive exploration of optimal charging unit configurations, employing the advanced capabilities of the HOMER Grid® Software. The objective is to decipher the intricate dynamics of EV charging infrastructure, with a meticulous examination of two distinct charging units.

##### **3.1.2 Fast Charging Unit (FCU)**

In this proposed study, the focus lies on a detailed examination of the Fast Charging Unit (FCU). The FCU boasts a high-capacity charger with an impressive power output of 150 kW. The primary emphasis of this investigation is on assessing the operational aspects of the FCU, with a keen eye on evaluating its efficiency and effectiveness across various practical scenarios.

$$P_{FCU} = 150 \text{ kW}$$

The above formula signifies the formidable power capacity of the FCU, a central aspect for the analysis of its dynamic performance characteristics.

##### **3.1.3 Slow Charging Unit (SCU)**

In contrast, attention will be directed towards the Slow Charging Unit (SCU), adopting a more collective strategy. The SCU comprises a network of 13 chargers, each contributing 18 kW, resulting in a total power output of 234 kW. The objective is to conduct an in-depth investigation into this collective approach, seeking to understand its impact on overall system dynamics, particularly in terms of efficiency and operational considerations.

$$P_{SCU} = 13 \text{ chargers} \times 18 \text{ kW/charger} = 234 \text{ kW}$$

This equation is crucial for the study as it represents the complex power structure of the SCU. Understanding this configuration is essential for analyzing collective charging dynamics and its influence on the broader energy system, providing insights into potential optimization strategies for maximum efficiency and effectiveness.

#### **3.2 Cost Analysis of Energy System Configurations**

This pivotal section endeavors to undertake a thorough exploration of the financial intricacies of different energy system configurations, employing key financial metrics to unravel their economic implications.

##### **3.2.1 Net Present Cost (NPC)**

The NPC is a sum-total evaluation of all costs associated with the energy system throughout its lifetime. This cumulative cost is strategically discounted to its present value, and the formal expression is elucidated below:

$$NPC = \sum_{t=0}^N \frac{C_t}{(1+r)^t} \quad (1)$$

In this equation,  $C_t$  represents the cost incurred in the t-th year, and  $r$  signifies the discount rate which is a fundamental factor in assessing the time-value of costs over the system's operational lifespan.

### 3.2.2 Levelized Cost of Electricity (LCOE)

The LCOE is a normalized metric providing a comprehensive measure of the cost of electricity production over the entire lifetime of the system. The formula integrates the NPC and the annual operation and maintenance cost and is expressed as:

$$LCOE = \frac{NPC + O \& M}{\sum_{t=0}^N \frac{E_t}{(1+r)^t}} \quad (2)$$

In this equation, O&M represents the annual operation and maintenance cost, and  $E_t$  signifies the annual energy production. It is an integral component in delineating the normalized cost of electricity production.

### 3.2.3 Annual Operating Cost (AOC)

The AOC encapsulates the continual operational expenses linked to the energy system over its lifespan. The comprehensive formulation is depicted as follows:

$$AOC = \sum_{t=0}^N \frac{O \& M_t}{(1+r)^t} \quad (3)$$

This equation meticulously accounts for the annual operation and maintenance costs (O&M<sub>t</sub>) over each year of the system's operational existence.

### 3.2.4 Capital Expenditure (CAPEX)

The CAPEX is a foundational metric encapsulating the initial investment imperative for setting up the energy system. Understanding CAPEX is fundamental in gauging the economic implications of the energy configuration:

$$\text{CAPEX} = \text{Initial Investment} \quad (4)$$

This equation underscores the criticality of the initial investment in shaping the financial landscape of the energy system under consideration.

## 3.3 Electric Bills and Energy Consumption of Each Scenario

This section of the research delves deeply into the complex relationship between electric bills and energy consumption across different EV charging scenarios. The primary focus is on dissecting how various parameters, including energy consumption patterns, tariff structures, and the configurations of charging units, interact and influence overall electricity costs and consumption metrics.

### 3.3.1 Energy Consumption Formulation

The total energy consumption ( $E_{\text{total}}$ ) in a given scenario is a function of several key variables:

1. **Charging Unit Power ( $P_{charging}$ ):** This represents the power rating of each charging unit. It varies depending on whether the unit is a fast or slow charger.
2. **Charging Duration ( $t_{charging}$ ):** The time for which a vehicle is charged. This can depend on the battery capacity of the EV and the charger type.
3. **Number of EVs ( $N_{EV}$ ):** The number of EVs being charged in a specific scenario.

The formulation can be represented as:

$$E_{total} = \sum_{i=1}^{N_{EV}} P_{charging,i} \times t_{charging,i} \quad (5)$$

Where  $P_{charging,i}$  and  $t_{charging,i}$  are the power and charging duration for the  $i$ -th EV, respectively.

### 3.3.2 Electric Bills Formulation

The electric bill ( $B$ ) is calculated by considering both the energy cost and additional charges or discounts that may apply.

1. **Energy Cost ( $C_{energy}$ ):** This is the direct cost of electricity consumed, calculated by multiplying the total energy consumption by the tariff rate.

$$C_{energy} = E_{total} \times \text{Tariff} \quad (6)$$

Where "Tariff" is the cost of electricity per unit of energy (e.g., per kWh).

2. **Additional Charges or Discounts ( $C_{additional}$ ):** This includes any extra fees or reductions in the bill due to factors like demand charges, time-of-use rates, or seasonal adjustments.

$$C_{additional} = F_{demand}(E_{total}, \text{Time}) + F_{seasonal}(E_{total}, \text{Season}) - \text{Discounts}(E_{total}, \text{Usage Pattern}) \quad (7)$$

Where  $F_{demand}$  and  $F_{seasonal}$  represent functions calculating demand and seasonal charges, respectively, and  $\text{Discounts}$  represent any reductions based on usage patterns.

Combining these elements, the total electric bill is given by:

$$B = C_{energy} + C_{additional} \quad (8)$$

This comprehensive approach allows for a detailed analysis of the electricity costs associated with different EV charging scenarios, considering the complexities of various influencing factors. By quantifying these relationships, the research aims to provide a nuanced understanding of the cost implications of EV charging and guide stakeholders in making informed decisions about infrastructure development and energy management.

### 3.4 Seasonal Variations in EV Load on Fast and Slow Chargers

This section aims to meticulously divide the influence of seasonal variations on EV load, with a specific focus on differentiating between fast and slow chargers. The problem formulation involves an intricate analysis, considering various factors contributing to seasonal fluctuations in EV charging demand.

### 3.4.1 Seasonal Load Formulation

The seasonal variation in EV load ( $L_{seasonal}$ ) is modeled as a function of diverse factors, incorporating climate parameters ( $C_{climate}$ ), user behavior ( $B_{user}$ ), and external factors ( $F_{external}$ ):

$$L_{seasonal} = C_{climate} \times B_{user} \times F_{external} \quad (9)$$

1. **Climate Parameters ( $C_{climate}$ ):** This encompasses variables such as temperature, humidity, and sunlight intensity. The formulation accounts for how these parameters influence the overall seasonal load.
2. **User Behavior ( $B_{user}$ ):** Daily commuting patterns, charging preferences, and lifestyle choices are encapsulated within this variable, acknowledging the significant role of user behavior in shaping EV charging demand.
3. **External Factors ( $F_{external}$ ):** External influences, including regulatory policies, public events, and societal trends, are factored in. These external factors can exert a considerable impact on seasonal variations in EV load.

### 3.4.2 Fast and Slow Charger Load Distribution

The distribution of seasonal load between fast ( $L_{fast}$ ) and slow ( $L_{slow}$ ) chargers is a critical aspect of this analysis. The allocation is influenced by factors such as charging speed, availability, and user preferences:

$$L_{fast} = \alpha \times L_{seasonal} \quad (10)$$

$$L_{slow} = (1 - \alpha) \times L_{seasonal} \quad (11)$$

**Charging Speed Factor ( $\alpha$ ):** This represents the proportion of the total load allocated to fast charging. The value of  $\alpha$  is determined by considering the efficiency and charging speed characteristics of fast chargers. This formulation ensures a detailed understanding of how seasonal variations impact the distribution of load between fast and slow chargers. By incorporating climate parameters, user behavior, and external influences, the research aims to provide a comprehensive insight into the dynamic nature of EV charging demand throughout the seasons.

## 3.5 Energy Dynamics and Power Source Interactions

This section delves into the intricate dynamics of energy flow within the system, emphasizing the interactions between different power sources. The problem formulation involves the development of mathematical models that comprehensively describe energy dynamics and the intricate relationships between renewable sources, the grid, and energy storage.

### 3.5.1 Energy Flow Formulation

The energy flow ( $E_{flow}$ ) within the system, comprising renewable sources (R), the grid (G), and storage (S), is described by the summation of these components:

$$E_{flow} = R + G + S \quad (12)$$

1. **Renewable Sources (R):** This term represents the energy contribution from renewable sources such as solar, wind, or hydroelectric power.

2. **Grid Contribution (G):** This is the energy drawn from the electrical grid to meet demand.
3. **Storage (S):** Energy stored or discharged from storage facilities.

### 3.5.2 Power Source Interactions

The interaction between power sources ( $P_{interaction}$ ) is modeled based on a priority function (*Priority*) that considers factors such as cost, environmental impact, and system efficiency:

$$P_{interaction} = \text{Priority}(R, G, S) \quad (13)$$

This function defines the order of preference in utilizing power sources. It considers factors such as the availability of renewable energy, cost-effectiveness, and the environmental impact of each source.

This detailed formulation captures the intricate interplay between different power sources, providing a robust foundation for analyzing energy dynamics within the system. The priority function ensures a nuanced understanding of the factors influencing the utilization of renewable sources, the grid, and energy storage in different scenarios.

## 3.6 Performance Analysis of Fast and Slow EV Charging Units

This section is dedicated to the performance assessment of both fast and slow EV charging units. The objective is to analyze the efficiency, reliability, and overall effectiveness of these units under varying operational conditions.

### 3.6.1 Efficiency Formulation

Efficiency ( $\eta$ ) is a critical metric in assessing charging units. It is determined by comparing the energy input ( $E_{input}$ ) to the energy effectively utilized ( $E_{output}$ ). This measurement helps in understanding how much of the input energy is converted into useful charging power. For instance, a high-efficiency charger minimizes energy loss, leading to faster and more cost-effective charging sessions. Efficiency is particularly crucial in fast chargers where high power levels can lead to greater losses if not managed properly:

$$\eta = \frac{E_{output}}{E_{input}} \times 100\% \quad (14)$$

### 3.6.2 Reliability Assessment

Reliability ( $R$ ) of charging units is equally important, especially considering the growing dependence on EVs. This metric is modeled by considering the downtime ( $D$ ), maintenance frequency ( $M$ ), and lifespan ( $L$ ) of the units. Downtime and frequent maintenance can significantly disrupt the availability and consistent performance of charging stations. The aim is to minimize  $D$  and  $M$  relative to  $L$ , ensuring that the units are dependable over a long period. This aspect is vital in both fast and slow charging contexts but becomes more critical in fast charging due to the higher stresses involved:

$$R = 1 - \frac{D + M}{L} \quad (15)$$

### **3.7 Carbon Emission Analysis Across Scenarios**

In this section, the focus is on evaluating the carbon emission implications of different charging scenarios and system configurations. The goal is to establish a comprehensive understanding of the environmental impact of each scenario.

#### **3.7.1 Emission Calculation**

The total carbon emissions ( $C_{total}$ ) are calculated based on the mix of energy sources ( $E_{source}$ ) and their respective emission factors ( $EF_{source}$ ). This formula helps in quantifying the carbon footprint of different charging setups, factoring in whether the energy is derived from fossil fuels, renewables, or a mix. It is a key indicator of the environmental sustainability of EV charging systems.:

$$C_{total} = \sum E_{source} \times EF_{source} \quad (16)$$

#### **3.7.2 Scenario-based Emission Analysis**

Further, the emission profile for each specific charging scenario is examined by considering the energy consumption ( $E_{scenario}$ ) and the carbon intensity of the energy mix. This analysis aids in identifying which scenarios are more environmentally friendly, providing critical insights for policymakers and stakeholders in the EV industry.

$$C_{scenario} = E_{scenario} \times Carbon\ Intensity \quad (17)$$

### **3.8 Comparative Analysis**

#### **3.8.1 Cost Efficiency and Renewable Energy Penetration**

This subsection aims to compare the cost efficiency and the level of renewable energy integration in different system configurations.

- 1. Cost Efficiency Formulation:** Cost efficiency (CE) is a comparison between the cost (C) and the performance (P) of the system. This analysis is crucial for understanding the economic viability of different charging infrastructures, balancing initial setup and operational costs against the benefits gained in terms of charging speed and capacity:

$$CE = \frac{C}{P} \quad (18)$$

- 2. Renewable Penetration Level:** The level of renewable energy penetration (RP) is assessed as the ratio of renewable energy used (RE) to the total energy consumed (TE). This metric is significant in highlighting how 'green' a charging system is, pushing towards a more sustainable and eco-friendlier EV charging infrastructure:

$$RP = \frac{RE}{TE} \times 100\% \quad (19)$$

#### **3.8.2 Comparative Analysis of Energy Production, Storage, and Costs Across Different Scenarios**

This subsection involves a detailed comparative analysis of energy production, storage capabilities, and associated costs across different scenarios.

1. **Energy Production Comparison:** Here, the total energy produced ( $EP_{total}$ ) in various scenarios is analyzed. This comparison sheds light on the capacity and efficiency of different energy sources, including renewable and non-renewable options, in meeting the demands of EV charging.:

$$EP_{total} = \sum \text{Energy Sources Output} \quad (20)$$

2. **Storage and Cost Comparison:** Storage capabilities (SC) and cost implications (CC) of different scenarios are evaluated. This analysis helps in understanding how different storage technologies and strategies impact the overall efficiency and cost-effectiveness of EV charging systems:

$$SC = \text{Storage Capacity and Efficiency Metrics} \quad (21)$$

$$CC = \text{Cost Metrics} \quad (22)$$

### 3.8.3 Financial Outcomes of Energy Scenarios

This final subsection focuses on the financial outcomes associated with each energy scenario.

1. **Return on Investment (ROI):** ROI is calculated to determine the profitability of various charging infrastructure investments. It reflects the time it takes for the benefits (financial gains) to outweigh the costs, a crucial factor in investment decisions:

$$ROI = \frac{\text{Initial Investment}}{\text{Net Profit}} \times 100\% \quad (23)$$

2. **Payback Period:** The payback period measures the time required to recover the initial investment. It's a vital metric for investors and stakeholders to understand the financial feasibility and time frame for return on investment in different EV charging scenarios:

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Annual Savings}} \quad (24)$$

By applying these mathematical formulations across the respective sections, the research paper will deliver a comprehensive, quantitative analysis of the optimal system configuration, cost-efficiency, environmental impact, and financial outcomes of different EV charging scenarios.

## 3.9 HOMER Grid® Optimization Function

The HOMER Grid® optimization function lies at the heart of the software's capability to design and analyze energy systems, emphasizing hybrid and renewable energy configurations. This section provides a comprehensive and detailed exploration of how the HOMER optimization function operates, encompassing various intricacies involved in the optimization process.

### 3.9.1 Model Configuration

Before delving into optimization, users input a wide array of parameters that define the system. These include:

1. **Load Requirements:** Detailed information about the energy demand profile the system is intended to meet.
2. **Resource Availability:** Data on available resources such as solar irradiation, wind speed, and other relevant environmental factors.
3. **Component Specifications:** Details regarding potential system components like solar PV panels, wind turbines, batteries, and conventional generators, including their costs, performance characteristics, and operational constraints.
4. **Constraints and Preferences:** Users can input any constraints that the system must adhere to, such as emission limits, as well as express preferences, such as prioritizing the use of renewable sources.

### 3.9.2 Optimization Process

HOMER's optimization function employs a sophisticated and iterative process to find the optimal configuration for the specified energy system. Key steps in this process include:

1. **HOMER Grid<sup>®</sup> Feasibility Check:** HOMER Grid<sup>®</sup> assesses the feasibility of each potential system configuration to meet the load requirements under various conditions, considering the availability of resources and the characteristics of the components.
2. **Simulation:** For feasible configurations, HOMER Grid<sup>®</sup> conducts detailed simulations of the system's operation over a specified period, often using hourly time steps. This simulation considers dynamic factors such as varying energy resource availability and fluctuating demand patterns.
3. **Economic and Technical Analysis:** HOMER Grid<sup>®</sup> calculates a range of parameters for each configuration, including the total Net Present Cost (NPC), the Cost of Energy (COE), renewable fraction, emissions, and other relevant metrics. This analysis provides a comprehensive evaluation of the economic and technical viability of each configuration.

### 3.9.3 Optimization Criteria

The primary objective of the HOMER Grid<sup>®</sup> optimization function is to minimize the total Net Present Cost (NPC) of the system over its designated lifetime. The NPC is a comprehensive measure that considers all costs over time, discounted to their present value. By minimizing NPC, HOMER Grid<sup>®</sup> seeks to identify the most economically efficient configuration that fulfills the specified requirements and constraints.

### 3.9.4 Sensitivity Analysis

HOMER Grid<sup>®</sup> facilitates sensitivity analysis, allowing users to explore how changes in various input parameters impact the optimal system configuration. This feature is crucial for understanding the robustness of the system under different scenarios and external influences.

### 3.9.5 Output and Decision Support

The output of the optimization process is a set of feasible configurations ranked by their Net Present Cost. HOMER Grid<sup>®</sup> provides detailed reports and graphical representations

illustrating system performance, financial summaries, and environmental impacts. This wealth of information serves as a decision-support tool, enabling stakeholders to make well-informed decisions about the design and investment in the energy system.

### 3.9.6 Iterative Approach

The optimization process in HOMER Grid<sup>®</sup> is iterative, continually adjusting system configurations and rerunning simulations until the most optimal solution is found. This iterative nature allows HOMER Grid<sup>®</sup> to explore a vast solution space and consider a myriad of potential combinations and operational strategies. This comprehensive overview highlights how the HOMER Grid<sup>®</sup> optimization function combines sophisticated modeling, simulation, and economic analysis to deliver robust and cost-effective solutions for hybrid and renewable energy systems. Its iterative approach, sensitivity analysis, and detailed outputs make it a powerful tool for designing sustainable and resilient energy solutions across diverse contexts and applications.

### 3.10 Dynamic Pricing Model for Energy Purchase and Sale

In the proposed study, a dynamic pricing model for energy purchase and sale is a pivotal element. It reflects the varying market conditions and contributes to the optimization of the overall energy system. This dynamic pricing strategy introduces flexibility in responding to changing energy market dynamics (Fig.1). Specifically:

#### 3.10.1 Energy Purchase Rate Dynamics

The energy purchase rate ( $P_{\text{purchase}}$ ) is subject to fluctuations throughout the year, reflecting the dynamic nature of the energy market. The range of purchase rates spans from \$0.15/kWh to \$0.20/kWh. This variability is influenced by factors such as market demand, fuel prices, and regulatory changes. The model incorporates this dynamic pricing structure to ensure a realistic representation of the financial landscape and to optimize the system's operational strategies accordingly.

$$P_{\text{purchase}}(t) = 0.15 + 0.05 \times \sin(\omega t) \quad (25)$$

where  $t$  is the time in hours, and  $\omega$  is the angular frequency determining the periodicity of rate variations.

#### 3.10.2 Energy Sell Back Rate Dynamics

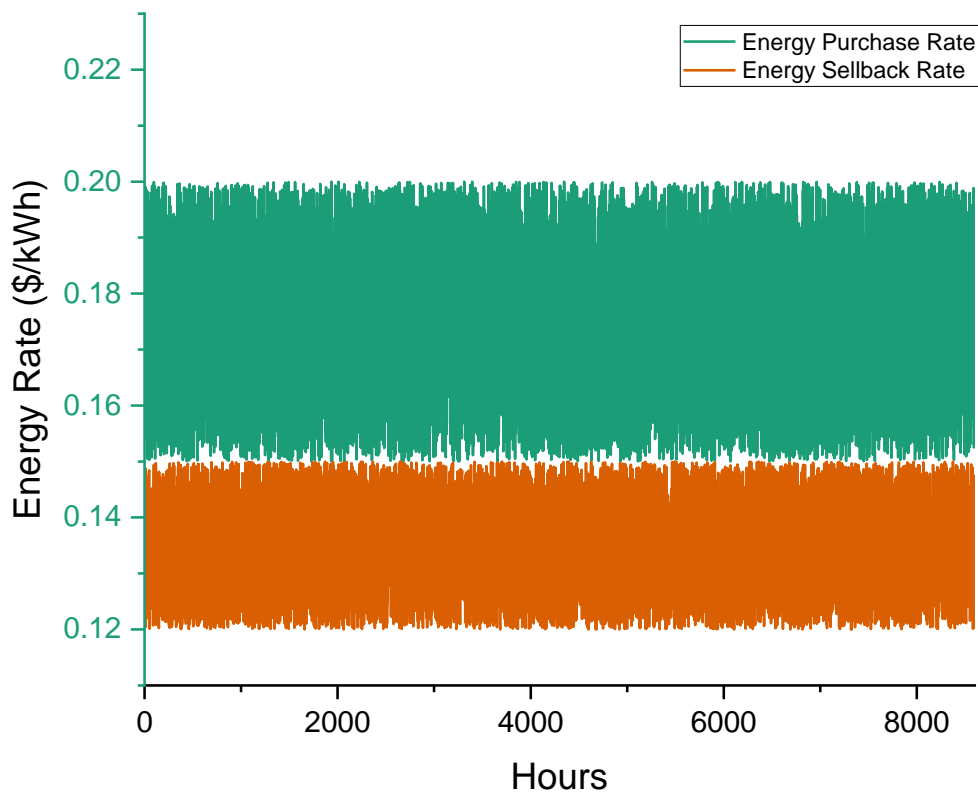
Similar to the energy purchase rate, the energy sell-back rate ( $P_{\text{sell back}}$ ) is characterized by a dynamic range, fluctuating from \$0.12/kWh to \$0.15/kWh throughout the year. This dynamic pricing for energy sold back to the grid reflects the changing landscape of renewable energy incentives, market demand, and regulatory frameworks. It introduces a responsive mechanism to capitalize on favorable selling conditions.

$$P_{\text{sell back}}(t) = 0.12 + 0.03 \times \cos(\omega t) \quad (26)$$

where  $t$  is the time in hours, and  $\omega$  is the angular frequency determining the periodicity of rate variations.

### 3.10.3 Implications for System Optimization

The integration of dynamic pricing for energy purchase and sale rates plays a crucial role in the optimization process. The optimization algorithm considers these varying rates when determining the optimal operation of the energy system. During periods of lower purchase rates, the system may prefer to draw more energy from the grid, while during high sell-back rates, excess energy generated locally can be fed back to the grid for maximum financial gain.



**Figure 1.** Energy Purchase and Sell Back Rate Dynamics

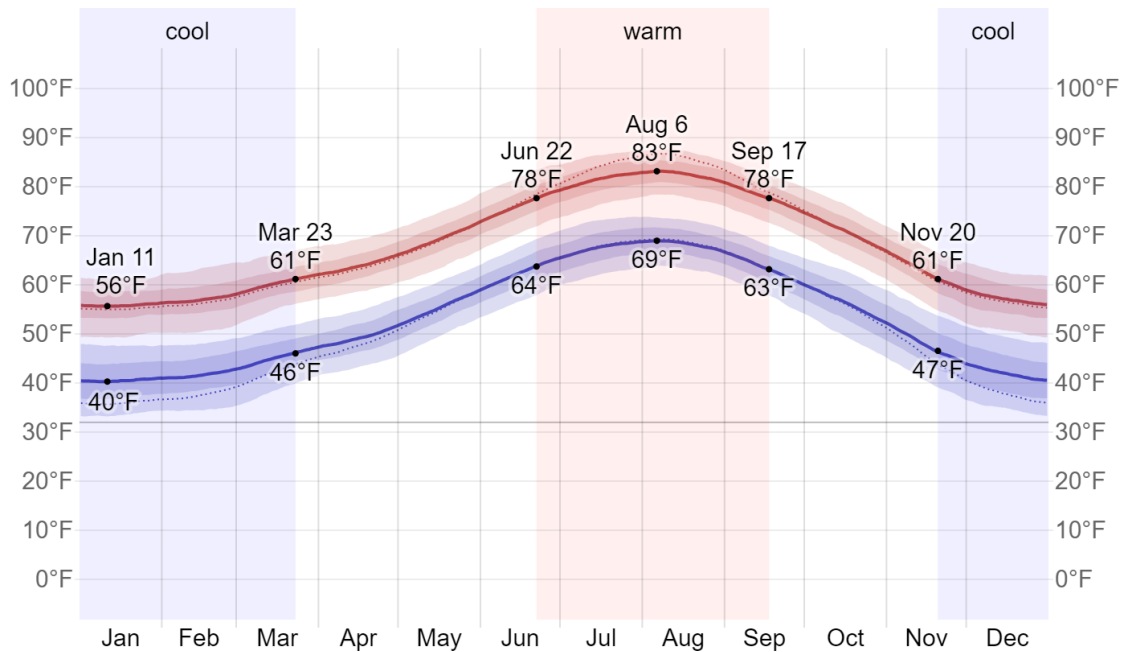
## 3.11 Overview of Climate Conditions

Barcelona, situated on the northeastern coast of the Iberian Peninsula, experiences a Mediterranean climate with distinct warm and cool seasons. Understanding the city's climate is crucial for planning various activities, from beach outings to cultural excursions.

### 3.11.1 Average Temperature Trends

The warm season, lasting approximately 2.9 months from June 22 to September 17, brings average daily high temperatures above 78°F. August stands out as the hottest month, with an average high of 82°F and a low of 68°F. In contrast, the cool season spans about 4.1 months,

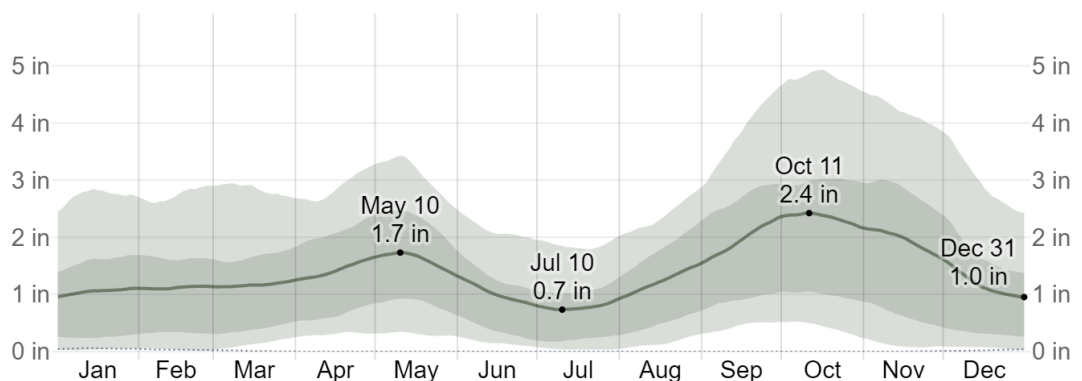
starting from November 20 to March 23, with average daily highs falling below 61°F. January, the coldest month, sees temperatures ranging from a low of 41°F to a high of 56°F, making it a time when locals and visitors alike opt for indoor activities (Fig.2).



**Figure 2.** Seasonal Temperature Variations and Their Duration

### 3.11.2 Rainfall Patterns

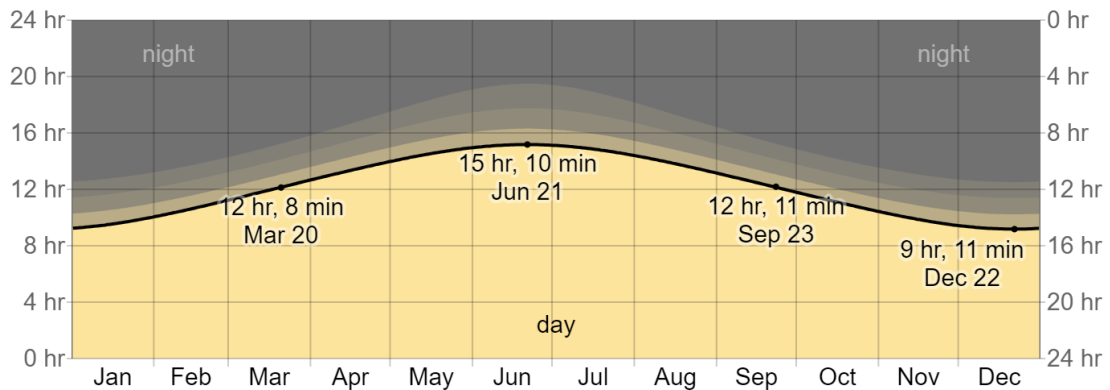
Rainfall in Barcelona showcases seasonal variations throughout the year (Fig.3). The month with the highest precipitation is October, recording an average rainfall of 2.4 inches. Travelers should be mindful of potential rain during this period. Conversely, July is the driest month, with an average rainfall of a mere 0.8 inches, aligning with the peak tourist season, and offering favorable conditions for outdoor exploration. To provide a nuanced view of rainfall, a 31-day sliding period centered around each day of the year is analyzed, emphasizing the variability within each month.



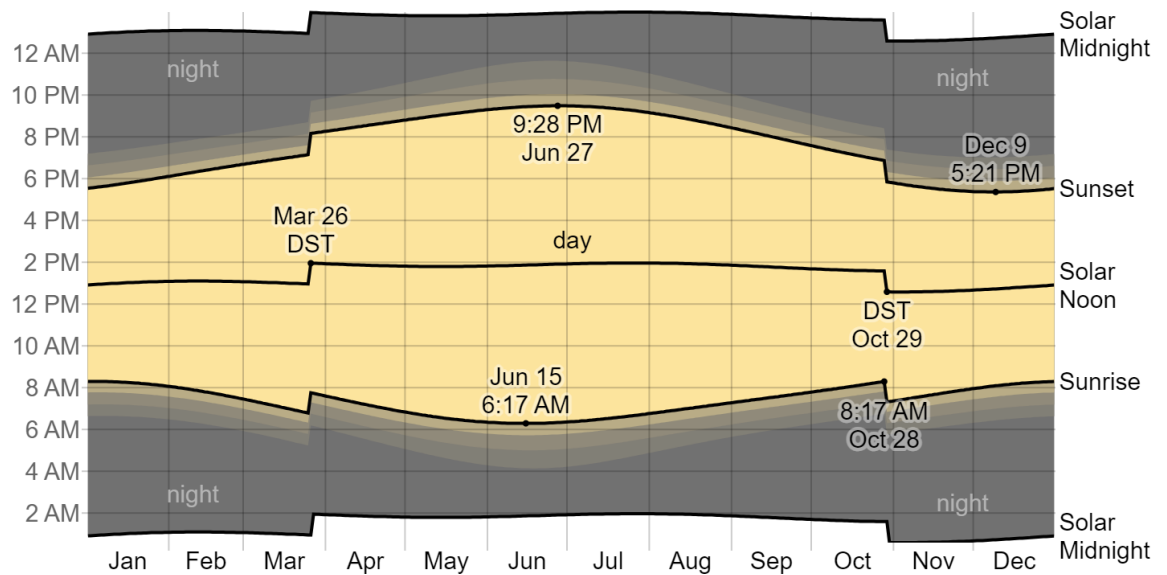
**Figure 3.** Seasonal Rainfall Patterns in Barcelona

### 3.11.3 Daylight Variability and Daylight-Saving Time

Barcelona experiences significant fluctuations in daylight hours over the year. The longest day occurs on June 21, with 15 hours and 10 minutes of daylight, epitomizing the height of summer. In contrast, December 22 marks the shortest day, with only 9 hours and 11 minutes of daylight, indicating the peak of winter (Fig.4). The implementation of Daylight Saving Time (DST) in Barcelona during 2023 adds another layer to daylight dynamics (Fig.5). DST begins on March 26, lasting 7.1 months until its conclusion on October 29, influencing the timing of sunrise and sunset.



**Figure 4.** Daylight Variations Throughout the Year in Barcelona with Daylight Saving Time Adjustment

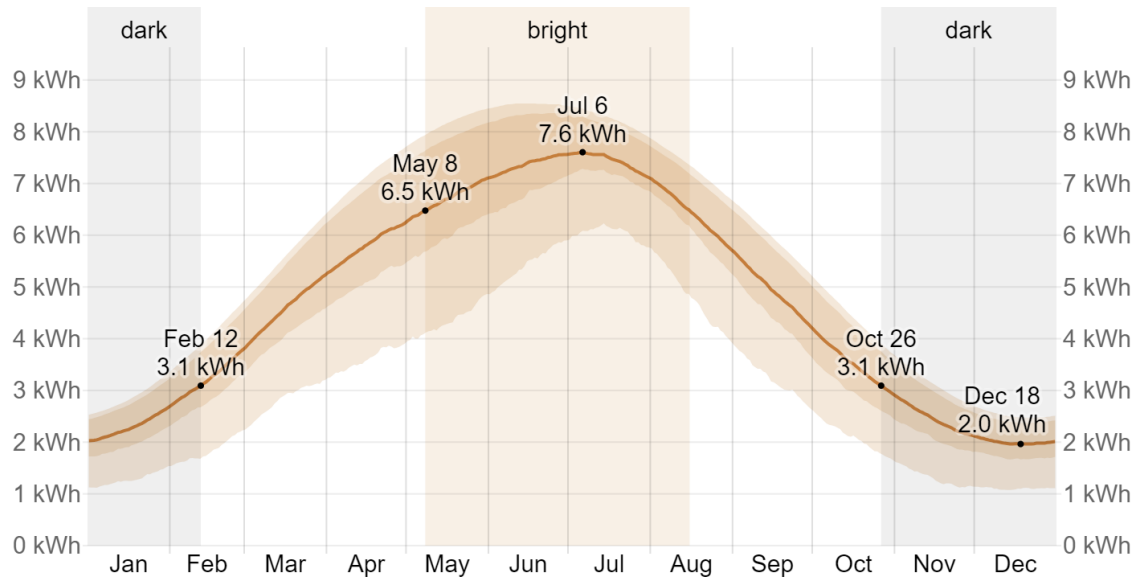


**Figure 5.** Daylight Saving Time Adjustment in Barcelona

### 3.11.4 Solar Energy Dynamics

The solar energy in Barcelona exhibits pronounced seasonal variation (Fig.6), impacting everything from tourism to energy consumption. The brighter period, lasting 3.2 months from May 8 to August 15, sees an average daily incident shortwave solar energy per square meter

above 6.5 kWh. July emerges as the brightest month, with an average of 7.4 kWh. Conversely, the darker period spans 3.5 months from October 26 to February 12, featuring an average daily incident shortwave solar energy per square meter below 3.1 kWh. December, with an average of 2.0 kWh, is the darkest month, emphasizing the city's reliance on alternative energy sources during this period.



**Figure 6.** Seasonal Variation in Solar Energy in Barcelona

Table 1 provides a quantitative overview of the monthly solar energy potential in Barcelona, offering insights into the clearness index and solar irradiance measured in kWh/m<sup>2</sup>/day. The clearness index, ranging from 0 to 1, indicates atmospheric clarity, with a higher value signifying clearer skies and greater solar radiation penetration. In January, the clearness index starts at 0.522, reflecting lower atmospheric clarity and subsequently yielding a solar irradiance of 2.090 kWh/m<sup>2</sup>/day. As the year progresses, both the clearness index and solar irradiance exhibit a notable upward trend, reaching their peaks in July at 0.603 and 6.800 kWh/m<sup>2</sup>/day, respectively. This signifies optimal conditions for solar energy generation during the summer months. Conversely, the values decrease in the latter part of the year, with December recording the lowest clearness index of 0.495 and the lowest solar irradiance at 1.770 kWh/m<sup>2</sup>/day. These figures underscore the seasonal variability in Barcelona's solar energy potential, with implications for sustainable energy planning and highlighting the need for alternative strategies during periods of reduced solar irradiance, particularly in the winter months.

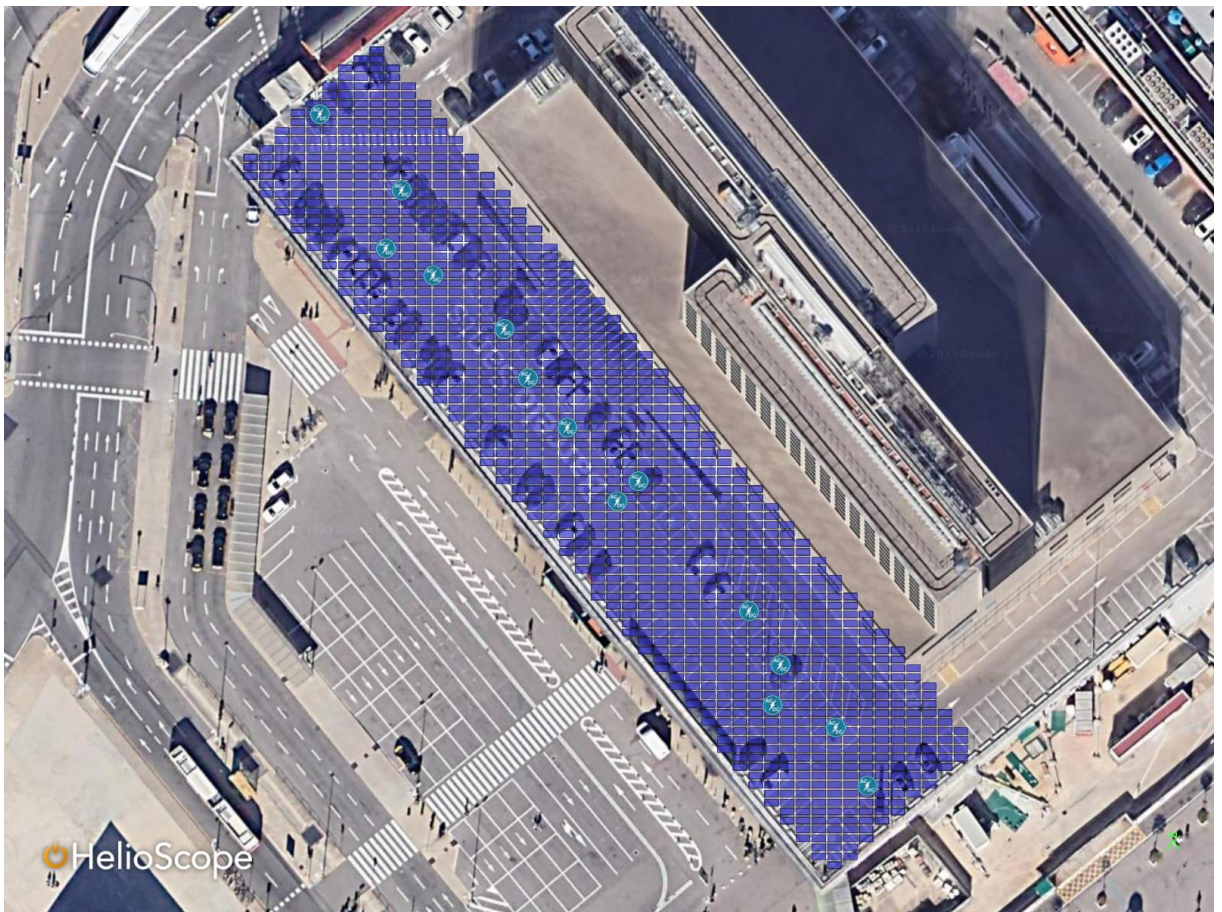
**Table 1.** Monthly Solar Energy Potential in Barcelona: Clearness Index and Solar Irradiance

Month	Clearness Index	Solar Irradiance (kWh/m <sup>2</sup> /day)
Jan	0.522	2.090
Feb	0.578	3.130
Mar	0.579	4.310
Apr	0.560	5.330
May	0.546	6.000
Jun	0.577	6.690
Jul	0.603	6.800
Aug	0.579	5.810
Sep	0.561	4.560
Oct	0.518	3.110
Nov	0.497	2.140
Dec	0.495	1.770

## 4. Result and Discussions

### 4.1 Solar Module Assessment and Installation Capacity

The preliminary step of this study involved the utilization of Helioscope, a sophisticated solar design software. The software evaluates the potential of the selected site for the installation of a RERs-based EV charging station. This assessment was crucial to determine the feasibility and capacity of the solar PV system that could be installed in the designated area. For installing a solar charging station at the coordinates 41.37°N, 2.14°E (Plaça dels Països Catalans, Barcelona, Spain), it's essential to assess solar potential, site constraints, and energy requirements. Designing an efficient solar system, navigating local regulations, conducting an economic analysis, and evaluating environmental impacts are key steps in the comprehensive planning process.



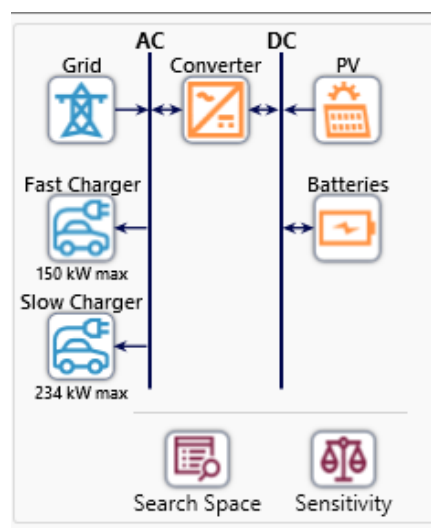
**Figure 7.** Layout of the Proposed RERs-Based EV Charging Station.

The Helioscope analysis revealed that the site could accommodate a total of 1,259 solar modules. These modules, when optimally arranged, would collectively provide a significant capacity of approximately 402.9 kW. This finding is instrumental in understanding the extent to which solar energy can be captured at the selected site. To efficiently convert the solar

energy captured by these modules into usable electrical power, the system necessitates the installation of PV converters. The study determined that a total of 14 PV converters would be required. These converters collectively offer a capacity of 336.8 kW. The selection of these converters was based on their compatibility with the solar modules and the overall system efficiency they offered, ensuring optimal energy conversion from the solar installations. Figure 7, as referenced in the study, illustrates the precise location of the proposed RERs-based EV charging station. This visual representation is vital for understanding the spatial arrangement and the feasibility of the installation in the selected environment. The configuration of the EV charging station is designed to cater to diverse user needs, comprising both slow and fast charging options. The station is planned to feature 13 slow chargers, each with a power output of 18 kW. These slow chargers are ideal for drivers who plan to park their vehicles for longer durations. Additionally, the station includes a more powerful fast charger, capable of delivering 150 kW. This fast charger is particularly beneficial for EV drivers requiring quick top-ups, significantly reducing charging time compared to the slow chargers.

#### **4.2 Optimal System Configuration Analysis Using HOMER Grid Software**

To determine the most effective and sustainable energy management solution for the proposed RESs based EV charging station, the HOMER Grid® Software was employed (Fig.8). This software is adept at simulating various energy scenarios to identify the most optimal system configuration in terms of efficiency, cost, and reliability. The analysis included four distinct scenarios, each representing a different combination of solar PV systems, BESS, grid connections, and converters. The scenarios were structured as follows, with the key components varied to assess their impact on the overall system performance:



**Figure 8.** Schematic Representation of Energy Management Scenarios

### **1. Scenario 1: PV and Grid Integration**

PV System: 400 kW

BESS: Not Included

Grid: Connected

Converter: 340 kW

### **2. Scenario 2: PV, BESS, and Grid Integration**

PV System: 400 kW

BESS: 50 (In Numbers)

Grid: Connected

Converter: 340 kW

### **3. Scenario 3: Grid-Only System**

PV System: Not included

BESS: Not included

Grid: Unlimited (sole energy source)

Converter: Not included

### **4. Scenario 4: BESS and Grid Integration**

PV System: Not included

BESS: 50 (In Numbers)

Grid: Unlimited

Converter: 340 kW

## **4.3 Charging Unit Configurations**

In addition to these scenarios, the study also considered two types of charging units for the EV charging station:

1. **Fast Charging Unit:** A single charger with a power output of 150 kW.
2. **Slow Charging Unit:** A set of 13 chargers with a collective output of 234 kW (18 kW each).

This comprehensive scenario analysis aimed to evaluate the most effective configuration for meeting the energy demands of the charging station while maximizing the use of RESs. The different combinations of PV systems, BESS, and grid connection, along with varying converter capacities, were analyzed to understand their impact on system performance, sustainability, and cost-effectiveness. The inclusion of fast and slow charging units in the analysis provided an interpretation of the station's operational capability, catering to different user needs and charging speeds.

## **4.4 Cost Analysis of Energy System Configurations**

A comprehensive cost analysis was conducted for each of the four scenarios explored using HOMER Grid<sup>®</sup> Software. The analysis focused on several financial metrics, including NPC,

LCOE, Annual Operating Cost, and CAPEX. These metrics provide a brief understanding of the economic viability of each scenario.

#### 4.4.1 Scenario 1: PV and Grid Integration

- NPC: \$-1,807,750
- LCOE: \$0.03392942/kWh
- Annual Operating Cost (AOC): \$-160,104.2
- CAPEX: \$262,000

This scenario, integrating a PV system with the grid, shows a negative NPC, suggesting a long-term cost benefit. The LCOE is the lowest among all scenarios, indicating high cost-efficiency. The negative annual operating cost reflects potential revenue or savings, and the CAPEX is moderate. The financial analysis of Scenario 1, integrating a 400 kW PV system with the grid for an EV charging station, reveals a compelling economic proposition. The initial capital investment of \$262,000 includes \$160,000 for the PV system and \$102,000 for the system converter. Replacement costs of \$43,275.93, allocated solely to the system converter, anticipate future maintenance needs. Operation and maintenance (O&M) costs demonstrate a net saving of -\$2,104,880.85, showcasing operational efficiency. Minimal O&M costs for the PV system (\$48,703.68) and significant savings in utility tariffs (-\$824,704.45) contribute to this efficiency. Remarkably, the fast and slow EV chargers result in substantial savings of -\$1,329,397.18. Fuel costs amount to \$0.00, emphasizing reliance on cost-free solar energy and grid electricity. The salvage value at the system's end is -\$8,144.97, indicating residual value for the system converter. The total NPC of -\$1,807,750 underscores the economic advantage of the system over its lifetime. This reflects significant operational savings, particularly from adjusted utility tariffs and efficient EV charger operation. In summary, Scenario 1 exemplifies the financial viability and sustainability of integrating renewable energy in EV charging infrastructure as depicted in Table 2 and Table 3. The upfront investment is effectively offset by operational savings, presenting a compelling case for renewable energy adoption in EV projects.

**Table 2.** Financial Analysis Summary (NPC) for Scenario 1

Cost Summary (Net Present)	Overall System	PV System	Utility Tariff	Fast Charger	Slow Charger	System Converter
Capital	\$262,000.00	\$160,000.00	\$0.00	\$0.00	\$0.00	\$102,000.00
Replacement	\$43,275.93	\$0.00	\$0.00	\$0.00	\$0.00	\$43,275.93
O&M	-\$2,104,880	\$517.10	\$48,703.68	-\$824,704.45	-\$1,329,397	\$0.00
Fuel	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Salvage	-\$8,144.97	\$0.00	\$0.00	\$0.00	\$0.00	-\$8,144.97
Total	-\$1,807,750	\$160,517.10	\$48,703.68	-\$824,704.45	-\$1,329,397	\$137,130.96

**Table 3.** Financial Analysis Summary (Annualized Cost) for Scenario 1

Cost Summary (Net Present)	Overall System	PV System	Utility Tariff	Fast Charger	Slow Charger	System Converter
Capital	\$20,266.85	\$12,376.70	\$0.00	\$0.00	\$0.00	\$7,890.15
Replacement	\$3,347.58	\$0.00	\$0.00	\$0.00	\$0.00	\$3,347.58
O&M	-\$162,821.75	\$40.00	\$3,767.44	-\$63,794.50	-\$102,834.69	\$0.00
Fuel	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Salvage	-\$630.05	\$0.00	\$0.00	\$0.00	\$0.00	-\$630.05
Total	-\$139,837.37	\$12,416.70	\$3,767.44	-\$63,794.50	-\$102,834.69	\$10,607.68

#### 4.4.2 Scenario 2: PV, BESS, and Grid Integration

- NPC: \$-1,250,850
- LCOE: \$0.09962394/kWh
- AOC: \$-142,165.8
- CAPEX: \$587,000

The addition of BESS increases the CAPEX significantly in this scenario. The LCOE is higher compared to Scenario 1, reflecting the added costs of battery storage. However, the NPC remains negative, and the annual operating cost is also negative, suggesting economic viability over the long term. In Scenario 2 of the electric vehicle charging station project, integrating a PV system, BESS, and grid connection, the NPC analysis reveals a detailed financial breakdown. The capital investment totals \$587,000, with \$160,000 allocated for the PV system and a significant \$325,000 for the BESS, underlining the importance of energy storage in this setup. Replacement costs, amounting to \$330,393.16, are predominantly for the BESS system converter, suggesting future maintenance or replacement needs for this key component. The O&M costs indicate a net saving of -\$2,121,170.12, reflecting the system's operational efficiency, with minimal maintenance required for the solar panels (\$517.10) and substantial savings on utility tariffs (-\$824,704.45) and EV chargers (-\$1,329,397.18). The salvage value, at -\$47,073.12, suggests a residual value for the system components, particularly the BESS, at the end of their lifecycle. Overall, the total NPC of -\$1,250,850.08 indicates that despite higher initial investments, especially in the PV system and BESS, the project is economically viable over time, benefiting from operational savings and the long-term value of its components Table (4 and Table 5).

**Table 4. Financial Analysis Summary (NPC) for Scenario 2**

Cost Summary (Net Present)	Overall System	PV System	Utility Tariff	Fast Charger	Slow Charger	BESS	System Converter
Capital	\$587,000.00	\$160,000.00	\$0.00	\$0.00	\$0.00	\$325,000.00	\$102,000.00
Replacement	\$330,393.16	\$0.00	\$0.00	\$0.00	\$0.00	\$287,117.23	\$43,275.93
O&M	-\$2,121,170.12	\$517.10	\$29,182.54	-\$824,704.45	-\$1,329,397.18	\$3,231.88	\$0.00
Fuel	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Salvage	-\$47,073.12	\$0.00	\$0.00	\$0.00	\$0.00	-\$38,928.15	-\$8,144.97
Total	-\$1,250,850.08	\$160,517.10	\$29,182.54	-\$824,704.45	-\$1,329,397.18	\$576,420.96	\$137,130.96

**Table 5. Financial Analysis Summary (Annualized Cost) for Scenario 2**

Cost Summary (Net Present)	Overall System	PV System	Utility Tariff	Fast Charger	Slow Charger	BESS	System Converter
Capital	\$45,407.02	\$12,376.70	\$0.00	\$0.00	\$0.00	\$25,140.17	\$7,890.15
Replacement	\$25,557.36	\$0.00	\$0.00	\$0.00	\$0.00	\$22,209.77	\$3,347.58
O&M	-\$164,081.79	\$40.00	\$2,257.40	\$63,794.50	\$102,834.69	\$250.00	\$0.00
Fuel	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Salvage	-\$3,641.31	\$0.00	\$0.00	\$0.00	\$0.00	\$3,011.26	\$630.05
Total	-\$96,758.73	\$12,416.70	\$2,257.40	-\$63,794.50	\$102,834.69	\$44,588.68	\$10,607.68

#### 4.4.3 Scenario 3: Grid-Only System

- NPC: \$-984,671.9
- LCOE: \$0.1722886/kWh
- AOC: \$-76,168.68
- CAPEX: \$0

This scenario relies entirely on the grid and involves no CAPEX, as there are no solar or storage installations. The LCOE is higher due to the sole reliance on grid electricity. The negative NPC and annual operating cost indicate potential savings, but the sustainability aspect is lower compared to the other scenarios. Scenario 3 outlines a Grid-Only system for an EV charging station, focusing solely on utility tariffs and charging units. The NPC summary indicates no capital or replacement costs (both \$0.00), as the scenario relies exclusively on grid power without additional energy-generating or storage systems. The overall system's negative O&M cost of -\$984,671.91 suggests that operational savings or revenue generated surpass associated costs. The utility tariff, representing grid power expenses, is \$1,169,429.73, constituting the primary operational cost. Both the fast and slow chargers exhibit negative O&M costs of -\$824,704.45 and -\$1,329,397.18, respectively, indicating substantial operational savings or revenue. Fuel costs and salvage values are both \$0.00, aligning with the grid-only nature of the scenario. The total NPC of -\$984,671.91 emphasizes the financial viability of a grid-only system, demonstrating that despite higher operational costs tied to grid reliance, revenue or savings from the efficient EV charging services substantially offset these expenses (Table 6 and Table 7). This underscores the economic effectiveness of a simplified, grid-centric approach in EV charging infrastructure.

**Table 6.** Financial Analysis Summary (NPC) for Scenario 3

Cost Summary (Net Present)	Overall System	Utility Tariff	Fast Charger	Slow Charger
Capital	\$0.00	\$0.00	\$0.00	\$0.00
Replacement	\$0.00	\$0.00	\$0.00	\$0.00
O&M	-\$984,671.91	\$1,169,429.73	-\$824,704.45	-\$1,329,397.18
Total	-\$984,671.91	\$1,169,429.73	-\$824,704.45	-\$1,329,397.18

**Table 7.** Financial Analysis Summary (Annualized Cost) for Scenario 3

Cost Summary (Net Present)	Overall System	Utility Tariff	Fast Charger	Slow Charger
Capital	\$0.00	\$0.00	\$0.00	\$0.00
Replacement	\$0.00	\$0.00	\$0.00	\$0.00
O&M	-\$76,168.68	\$90,460.51	-\$63,794.50	-\$102,834.69
Total	-\$76,168.68	\$90,460.51	-\$63,794.50	-\$102,834.69

#### 4.4.4 Scenario 4: BESS and Grid Integration

- NPC: \$-266,239.1
- LCOE: \$0.2781331/kWh
- AOC: \$-53,625.08
- CAPEX: \$427,000

This scenario, integrating BESS with the grid, shows the highest LCOE, reflecting the cost impact of battery storage without the offsetting benefits of solar generation. While the CAPEX is substantial, the scenario still offers a negative NPC and annual operating cost, indicating potential financial benefits in the long run. In Scenario 4 of the EV charging station project, which integrates 50 (In Numbers) BESS with grid connectivity, the NPC breakdown reveals key financial insights. The total capital investment is \$427,000.00, with the BESS accounting for the majority at \$325,000.00, emphasizing the critical role of energy storage. Replacement costs amount to \$330,393.16, primarily for the BESS system converter, indicating anticipated maintenance or replacement needs for energy storage components. The O&M costs demonstrate a net saving of -\$976,559.17, with the utility tariff constituting the primary operational cost at \$1,174,310.58. Negative contributions from the fast and slow EV chargers (-\$824,704.45 and -\$1,329,397.18, respectively) suggest substantial operational savings or revenue generation. Minimal O&M costs for the BESS system (\$3,231.88) indicate low maintenance requirements. Both fuel costs and salvage values are \$0.00, aligning with the grid-dependent and non-combustion nature of the scenario. The negative total NPC of -\$266,239.13 underscores the economic viability of integrating BESS into the charging infrastructure, demonstrating financial benefits over the system's lifetime (Table 8 and Table 9).

**Table 8.** Financial Analysis Summary (NPC) for Scenario 4

Cost Summary (Net Present)	Overall System	Utility Tariff	Fast Charger	Slow Charger	BESS	System Converter
Capital	\$427,000.00	\$0.00	\$0.00	\$0.00	\$325,000.00	\$102,000.00
Replacement	\$330,393.16	\$0.00	\$0.00	\$0.00	\$287,117.23	\$43,275.93
O&M	-\$976,559.17	\$1,174,310.58	-\$824,704.45	-\$1,329,397.18	\$3,231.88	\$0.00
Fuel	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Salvage	-\$47,073.12	\$0.00	\$0.00	\$0.00	-\$38,928.15	-\$8,144.97
Total	-\$266,239.13	\$1,174,310.58	-\$824,704.45	-\$1,329,397.18	\$576,420.96	\$137,130.96

**Table 9.** Financial Analysis Summary (Annualized Cost) for Scenario 4

Cost Summary (Net Present)	Overall System	Utility Tariff	Fast Charger	Slow Charger	BESS	System Converter
Capital	\$33,030.32	\$0.00	\$0.00	\$0.00	\$25,140.17	\$7,890.15
Replacement	\$25,557.36	\$0.00	\$0.00	\$0.00	\$22,209.77	\$3,347.58
O&M	-\$75,541.13	\$90,838.06	-\$63,794.50	-\$102,834.69	\$250.00	\$0.00
Fuel	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Salvage	-\$3,641.31	\$0.00	\$0.00	\$0.00	-\$3,011.26	-\$630.05
Total	-\$20,594.76	\$90,838.06	-\$63,794.50	-\$102,834.69	\$44,588.68	\$10,607.68

The cost analysis reveals that integrating PV systems with the grid (Scenario 1) presents the most economically viable option, offering the lowest LCOE and a favorable balance of CAPEX and operating costs. The addition of BESS (Scenario 2) increases financial viability, though at a higher LCOE due to additional CAPEX. The grid-only approach (Scenario 3), while lacking upfront investment, results in a higher LCOE, indicating greater long-term costs compared to scenarios involving renewable energy sources. Scenario 4, focusing solely on BESS and grid integration, shows the highest LCOE, suggesting that battery storage without solar PV may not be as cost-effective. These findings underscore the economic advantages of integrating renewable energy sources, particularly solar PV, into the EV charging station's energy mix, both in terms of long-term savings and sustainability.

## **4.5 Electric Bills and Energy Consumption**

### **4.5.1 Scenario 1: PV and Grid Integration**

In Scenario 1, which integrates a PV system with the grid for an EV charging station, the Electric Bills and Energy Consumption data reveal a significant interplay between energy generation, consumption, and grid interaction over a year. During January, February, October, November, and December, the station incurs energy charges (ranging from \$301 to \$2,720), indicating higher consumption (18,366 kWh to 26,985 kWh) than energy generation. Conversely, from March to September, the system generates excess energy, leading to negative energy charges (from -\$293 to -\$1,337), signifying revenue generation or credits from the grid for the surplus energy. The highest consumption occurs in January and December (26,317 kWh and 26,985 kWh, respectively), while the maximum sales to the grid

are in June and July (24,818 kWh and 27,390 kWh, respectively), highlighting seasonal variations in solar generation and energy demand. Peak demand varies moderately across the year (161 kW to 203 kW), reflecting consistent operational requirements of the station. The monthly totals align with these trends, showcasing a beneficial balance between generating renewable energy and drawing power from the grid, especially during sunnier months.

**Table 10.** Monthly Electric Bills and Energy Consumption Analysis for Scenario 1

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Energy Charges (\$)	1,967	301	-490	-527	-525	-866	-1,337	-547	-293	1,170	2,195	2,720
Consumption (kWh)	26,317	18,366	18,209	15,537	16,425	14,351	13,829	16,553	17,392	21,051	25,236	26,985
Sales (kWh)	18,761	21,133	26,632	23,765	24,582	24,818	27,390	24,942	24,291	17,892	15,910	14,465
Peak Demand (kW)	203	172	176	199	168	181	168	161	161	188	199	195
Monthly Total	1,967	301	-490	-527	-525	-866	-1,337	-547	-293	1,170	2,195	2,720

#### 4.5.2 Scenario 2: PV, BESS, and Grid Integration

In Scenario 2, involving PV, BESS, and Grid Integration for an EV charging station, the Electric Bills and Energy Consumption data for each month provide valuable insights. The negative values in the Energy Charges section (-\$611 to -\$1,434) highlight significant savings, indicating that the system is generating surplus energy, contributing to revenue or cost reduction. The Consumption values ranging from 7,853 kWh to 19,930 kWh represent the station's energy usage, demonstrating fluctuations throughout the year. Notably, the negative values in the Sales column (-\$611 to -\$1,434) signify that the station is exporting excess energy to the grid, leading to potential revenue generation. The Monthly Total, ranging from -\$966 to \$2,554, summarizes the overall financial impact, with negative values suggesting periods of surplus energy generation and positive values indicating potential electricity expenses. The Peak Demand values, ranging from 168 kW to 484 kW, depict the maximum power demand during each month, offering insights into the station's peak load requirements. Overall, the data highlights the financial benefits of the integrated PV and BESS system, showcasing potential revenue from energy sales and significant savings in energy charges.

**Table 11.** Monthly Electric Bills and Energy Consumption Analysis for Scenario 2

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Energy Charges (\$)	1,825	194	-611	-662	-619	-966	-1,434	-653	-445	1,047	2,028	2,554
Consumption (kWh)	19,083	12,358	10,450	8,734	10,785	9,105	7,853	10,697	11,216	13,787	18,689	19,930
Sales (kWh)	10,416	14,304	17,922	16,090	18,315	18,842	20,672	18,338	17,323	9,595	8,268	6,203
Peak Demand (kW)	341	484	176	340	168	206	168	194	233	320	314	444
Monthly Total	1,825	194	-611	-662	-619	-966	-1,434	-653	-445	1,047	2,028	2,554

### 4.5.3 Scenario 3: Grid Only

In Scenario 3, where the EV charging station relies solely on grid power, the Electric Bills and Energy Consumption section provides a concise overview of monthly energy charges, consumption, and related metrics. Monthly energy charges fluctuate between \$6,868 and \$7,965, reflecting variations in electricity rates throughout the year. The monthly consumption ranges from 39,923 kWh to 46,141 kWh, indicating seasonal energy demand patterns. Notably, sales of electricity are absent, as the system operates solely as a consumer, and the grid is the sole energy source. Peak demand, reaching up to 231 kW, showcases the maximum power required in a given month. Overall, the section highlights the varying energy consumption and associated costs, offering insights into the operational dynamics of the grid-based charging station throughout the year.

**Table 12.** Monthly Electric Bills and Energy Consumption Analysis for Scenario 3

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Energy Charges (\$)	7,788	6,868	7,695	7,470	7,613	7,406	7,612	7,965	7,325	7,537	7,359	7,822
Consumption (kWh)	45,344	39,923	44,737	43,203	44,323	42,850	44,010	46,141	42,559	43,965	42,693	45,304
Sales (kWh)	0	0	0	0	0	0	0	0	0	0	0	0
Peak Demand (kW)	230	215	205	218	224	201	217	231	206	218	215	201
Monthly Total	7,788	6,868	7,695	7,470	7,613	7,406	7,612	7,965	7,325	7,537	7,359	7,822

### 4.5.4 Scenario 4: BESS and Grid Integration

In Scenario 4, which integrates a BESS and grid connectivity for an EV charging station, the Electric Bills and Energy Consumption section for each month provides a compact overview. The energy charges fluctuate between 6,892 kWh and 8,001 kWh across the months, with corresponding consumption ranging from 41,850 kWh to 48,482 kWh. Notably, there are no sales recorded, indicating that the system operates as a consumer rather than a generator during these periods. The peak demand, representing the maximum power required in a given month, varies from 472 kW to 589 kW. The total monthly values consistently align with the energy charges, reflecting the monthly consumption patterns. This section serves as a vital reference for understanding the electricity consumption dynamics and associated costs, crucial for assessing the operational and financial performance of the integrated BESS and grid system throughout the year.

**Table 13.** Monthly Electric Bills and Energy Consumption Analysis for Scenario 4

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Energy Charges (\$)	7,834	6,892	7,726	7,494	7,636	7,437	7,630	8,001	7,362	7,562	7,401	7,863
Consumption (kWh)	47,636	41,850	47,021	45,525	46,122	45,043	46,313	48,482	44,900	46,264	45,294	47,626
Sales (kWh)	0	0	0	0	0	0	0	0	0	0	0	0
Peak Demand (kW)	500	484	492	556	500	528	498	589	523	472	565	464
Monthly Total	7,834	6,892	7,726	7,494	7,636	7,437	7,630	8,001	7,362	7,562	7,401	7,863

#### 4.6 Seasonal Variations in EV Load on Fast and Slow Chargers

In January, the slow charger experiences minimal load during the night, with sporadic usage, peaking at 114.12 kW around 9 AM and 112.77 kW at 10 AM. The fast charger kicks in around 10 AM, reaching its peak of 63.33 kW at the 21st hour, indicating a preference for fast charging during daylight hours, especially in the afternoon and early evening. Come April, the slow charger sees early morning usage, peaking at 71.19 kW around 9 AM, while the fast charger's peak demand is 44.17 kW at the 14th hour. The fast charger usage is more evenly distributed throughout the day, starting around 10 AM, and experiences a decline late at night. Moving to July, the slow charger peaks in the morning and evening, reaching 116.82 kW at 10 AM. The fast charger shows a more consistent usage pattern throughout the day, starting from 10 AM, with a peak of 109.98 kW at the 16th hour. In October, the slow charger is heavily utilized in the early morning and evening, peaking at 135.29 kW around 9 AM. The fast charger exhibits variable usage, peaking at 73.33 kW at the 14th hour and showcasing significant activity in the midday and evening.

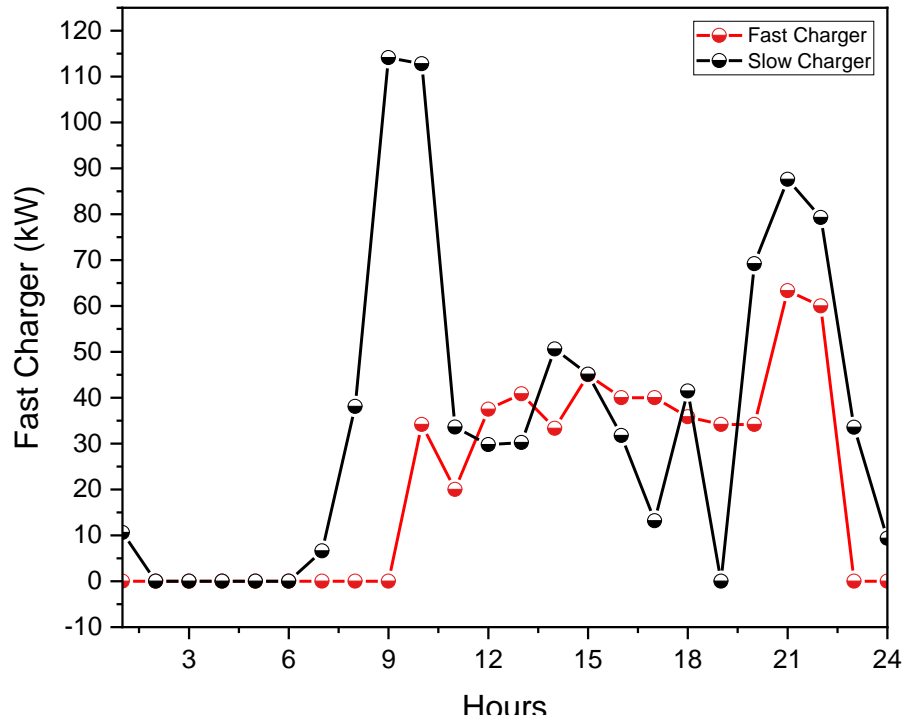
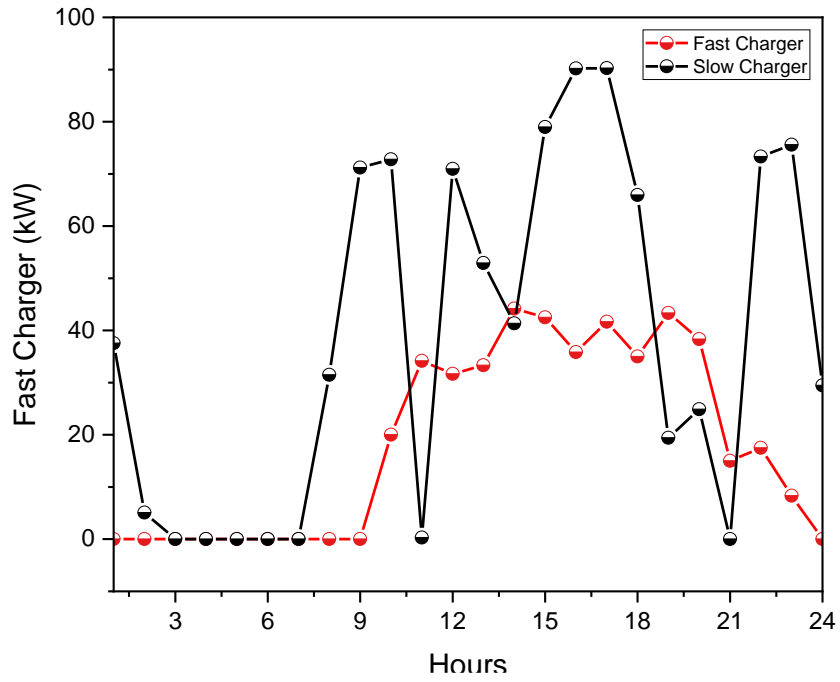
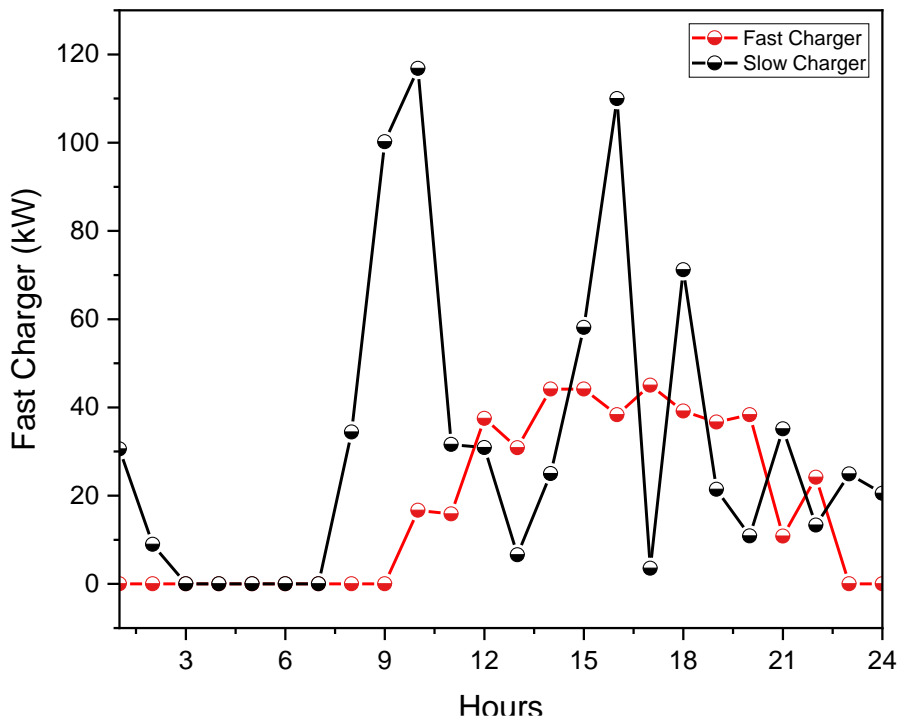


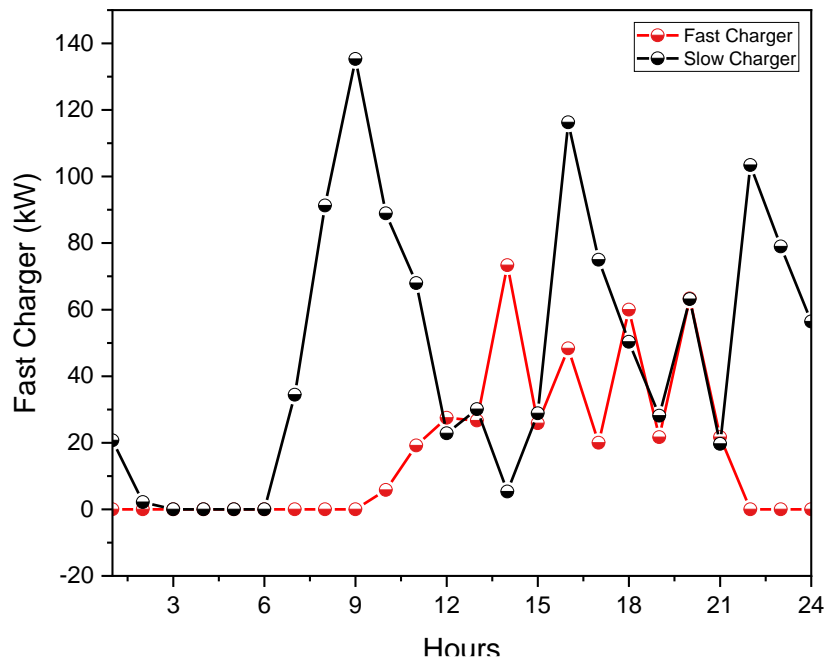
Figure 9. Hourly Load Profiles for Slow and Fast Chargers in Jan



**Figure 10.** Hourly Load Profiles for Slow and Fast Chargers in Apr



**Figure 11.** Hourly Load Profiles for Slow and Fast Chargers in Jul



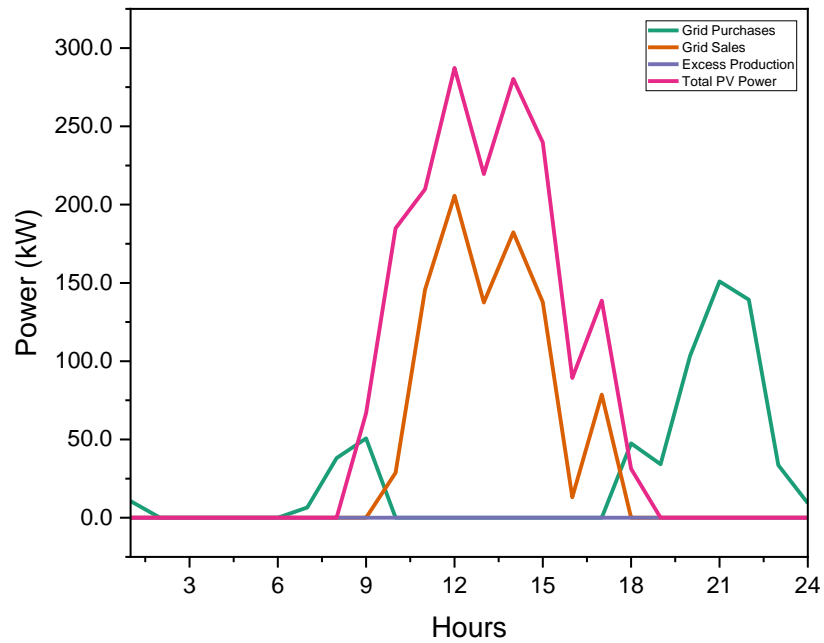
**Figure 12.** Hourly Load Profiles for Slow and Fast Chargers in Oct

## **4.7 Energy Dynamics and Power Source Interactions**

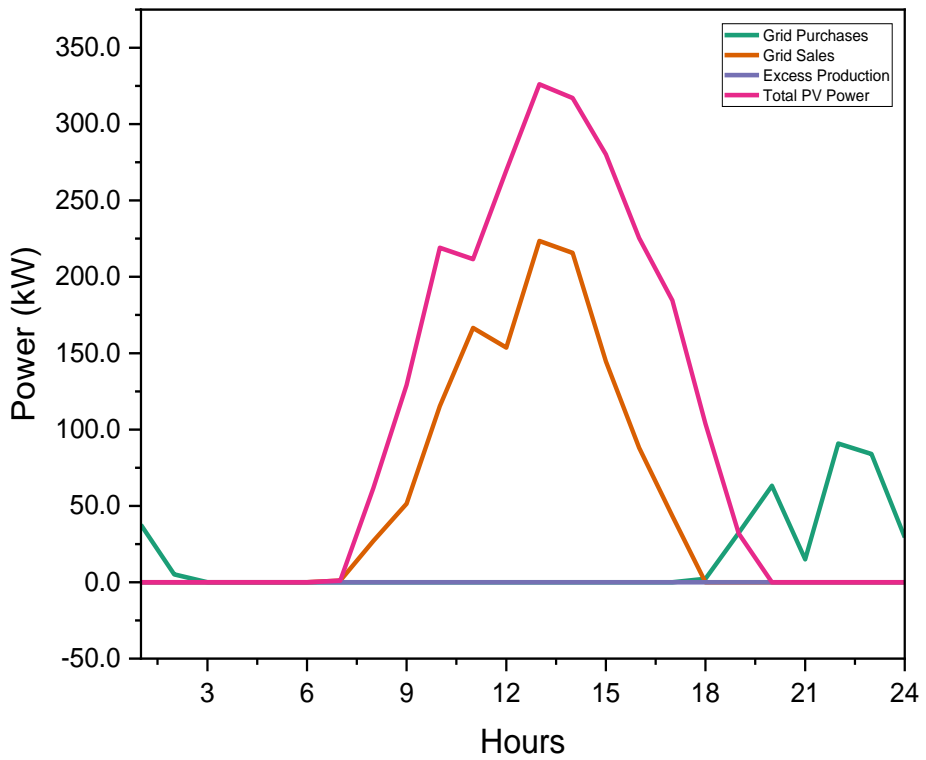
### **4.7.1 Power Source Interactions in Scenario 1**

In Scenario 1 for January, the energy dynamics show varied interactions between grid purchases and PV power generation. During night hours (1-6, 18-24), grid purchases are reliant due to no PV power, peaking at 150.91 kW at hour 21. Conversely, during daylight hours (9-17), substantial PV generation leads to grid sales, with maximum export at hour 12 (205.70 kW). This pattern reflects a significant shift from grid dependence at night to PV self-sufficiency and surplus energy export during the day. In April's energy sharing dynamics for Scenario 1, the system primarily relied on grid purchases during nighttime and early morning hours (1 AM to 6 AM), with minimal energy intake ranging from 5.09 kW to 37.54 kW. From 7 AM, the PV system started generating excess power, leading to grid sales, peaking at 223.50 kW at 1 PM. The highest PV power generation was observed at 326.06 kW around midday. Late afternoon and evening saw a gradual shift back to grid reliance, with purchases increasing to 90.81 kW by 10 PM. This pattern demonstrates a strong reliance on the PV system during daylight hours with grid support required during night hours. Energy sharing dynamics in Scenario 1 for July illustrate a nuanced interaction between power sources. Notable instances include grid purchases during peak demand hours, grid sales in non-peak hours, and excess production from the PV system contributing to overall power generation. For instance, at the 11th hour, substantial grid purchases of 202.85 kW are recorded, maximizing total PV power generation to 263.44 kW. The month showcases a dynamic interplay, with varying contributions from the grid and PV system across different hours, reflecting adaptability to demand fluctuations. In December, Scenario 1 exhibits dynamic

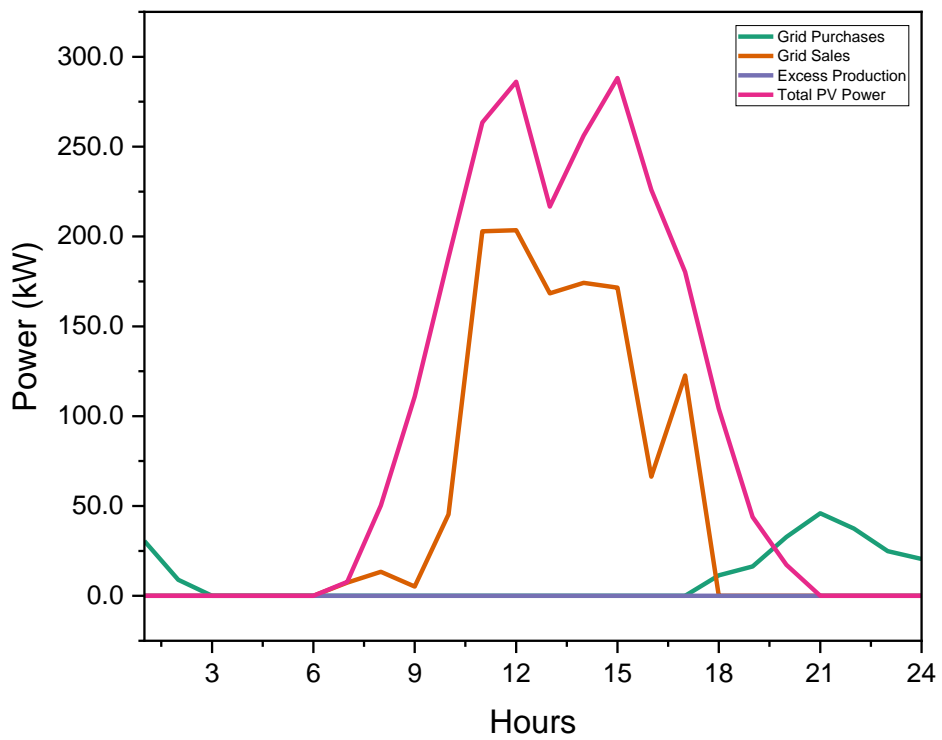
energy-sharing dynamics between different power sources. The grid purchases range from 2.14 kW to 126.47 kW, while grid sales and excess production remain consistently at zero. Total PV power varies, reaching its peak at 186.93 kW during the 16th hour. Notably, grid purchases and PV power generation contribute to the overall energy dynamics, emphasizing the integration of solar power into the system.



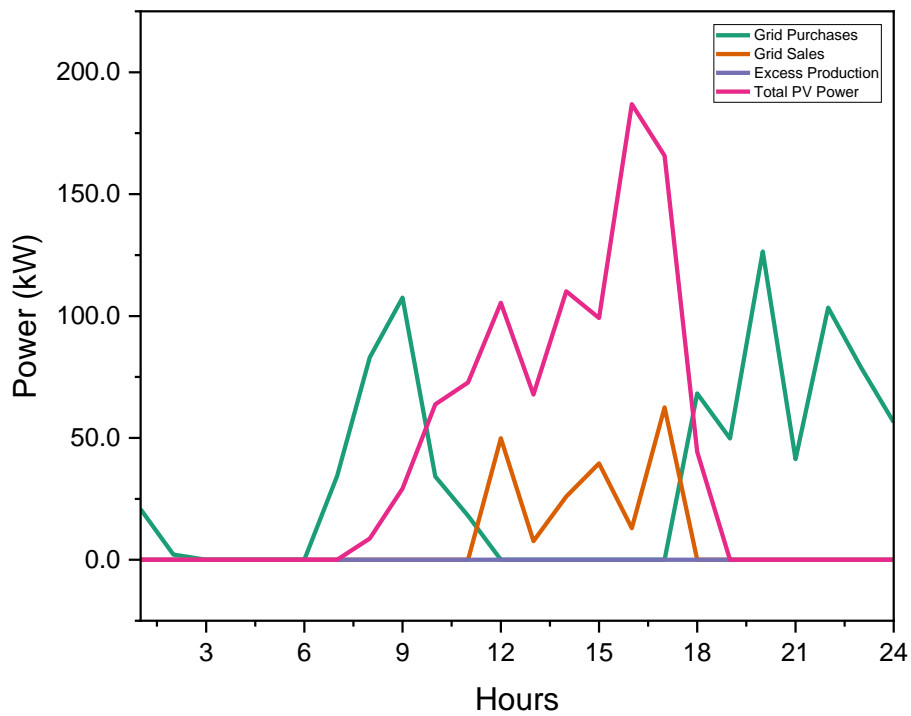
**Figure 13.** Energy Dynamics and Power Source Interactions in Jan in Scenario-1



**Figure 14.** Energy Dynamics and Power Source Interactions in Apr in Scenario-1



**Figure 15.** Energy Dynamics and Power Source Interactions in Jul in Scenario-1

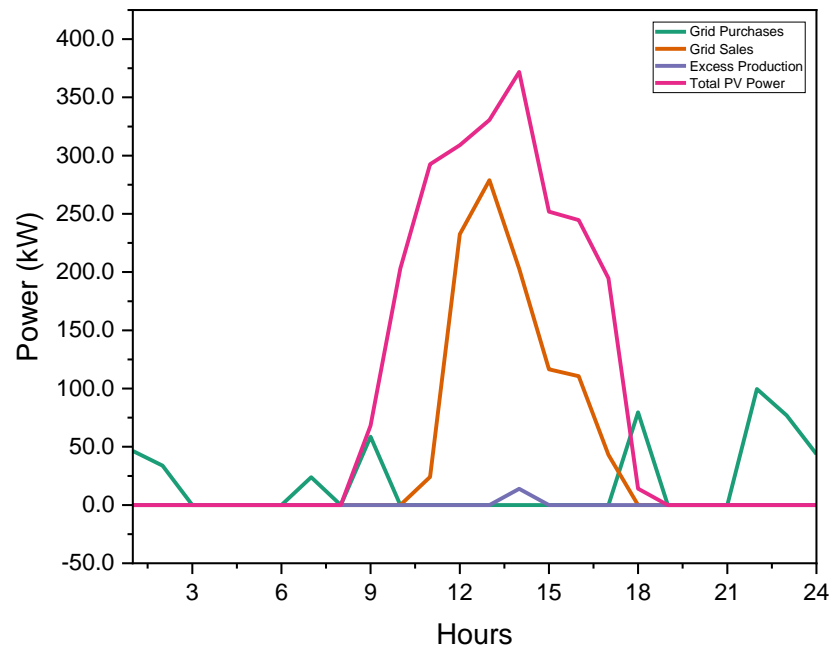


**Figure 16.** Energy Dynamics and Power Source Interactions in Oct in Scenario-1

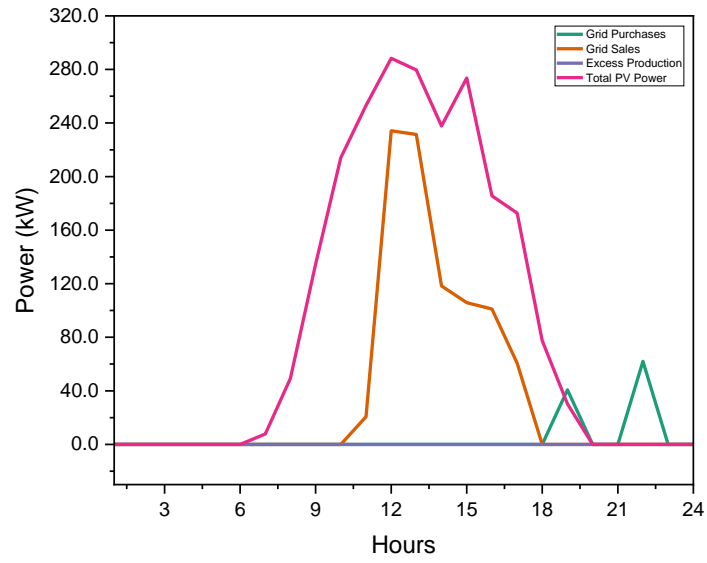
#### 4.7.2 Power Source Interactions in Scenario 2

In January under Scenario 2, the energy-sharing dynamics exhibit a significant shift from grid dependence to solar energy utilization as the day progresses. Initially, during the early hours (1-2 AM), grid purchases are notable, at 46.49 kW and 33.82 kW respectively, with no solar production. From 3 AM to 7 AM, there's no activity in either grid purchases or solar production. A slight grid purchase occurs at 7 AM (23.8 kW), followed by a period of inactivity until 9 AM. From 9 AM, solar power starts contributing, beginning with 68.14 kW at 9 AM and peaking at 330.57 kW at 1 PM, which leads to substantial grid sales ranging from 24.18 kW at 11 AM to 278.82 kW at 1 PM. The peak of excess solar production over consumption is noted at 2 PM with 13.95 kW. As solar production wanes post 5 PM, grid purchases resume, peaking at 99.64 kW at 10 PM, and then gradually decreasing towards midnight. In April for Scenario 2, the energy-sharing dynamics reveal intricate patterns. Grid purchases remain minimal, with peak values at 62.06 kW and 40.77 kW. Grid sales occur during the 11th and 12th hours, reaching 20.69 kW and 234.17 kW, respectively. Excess production is observed consistently, with notable peaks at 253.15 kW during the 11th hour and 288.31 kW during the 12th hour. The total PV power generated fluctuates, reaching its zenith at 273.62 kW during the 15th hour. Overall, this snapshot underscores the dynamic interplay between grid purchases, sales, and surplus PV production throughout the day. In July's Scenario 2, the energy dynamics show distinct trends in grid purchases, sales, and photovoltaic (PV) power generation. During nighttime hours (1-6 AM), there's no PV production, resulting in zero grid sales or purchases. At dawn (7 AM), a minimal grid purchase (0.16327 kW) occurs, with PV power beginning at 14.88076 kW. Midday (8 AM - 5

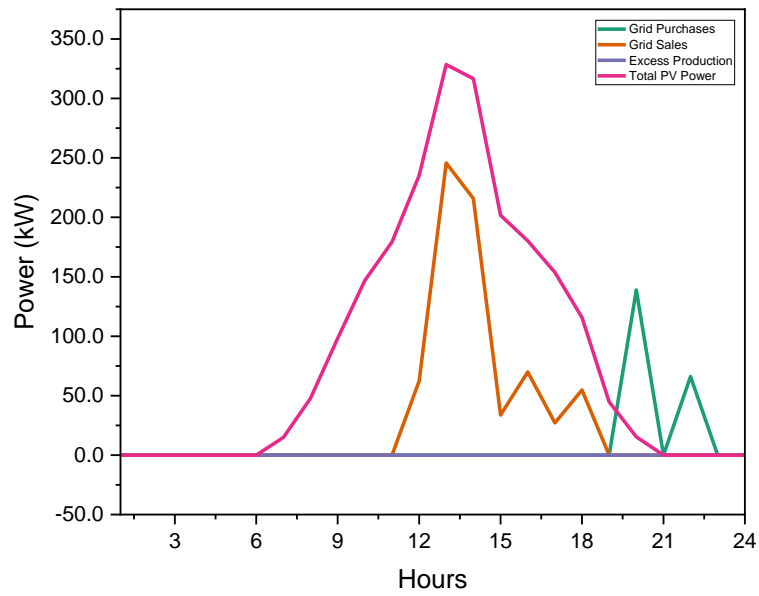
PM) marks peak PV activity, eliminating grid purchases and enabling significant grid sales, peaking at 328.4666 kW at 1 PM. As the sun sets (6 PM - 8 PM), PV output declines from 115.784 kW to 44.86264 kW, leading to minimal or no grid interaction. However, in the late evening (8 PM - 11 PM), grid reliance increases with purchases reaching 138.8352 kW at 8 PM and 66.01846 kW at 10 PM, reflecting the absence of solar generation during these hours. In October, Scenario 2 exhibits dynamic energy-sharing dynamics. Grid purchases occur at varying levels throughout the day, peaking at 86.33 kW. Notably, excess production is observed during several hours, reaching up to 271.80 kW during midday. Grid sales are minimal, with the system occasionally exporting power. The total PV power generated ranges from 43.62 kW to 280.14 kW, showcasing the system's reliance on solar energy and its ability to contribute excess power back to the grid during certain periods.



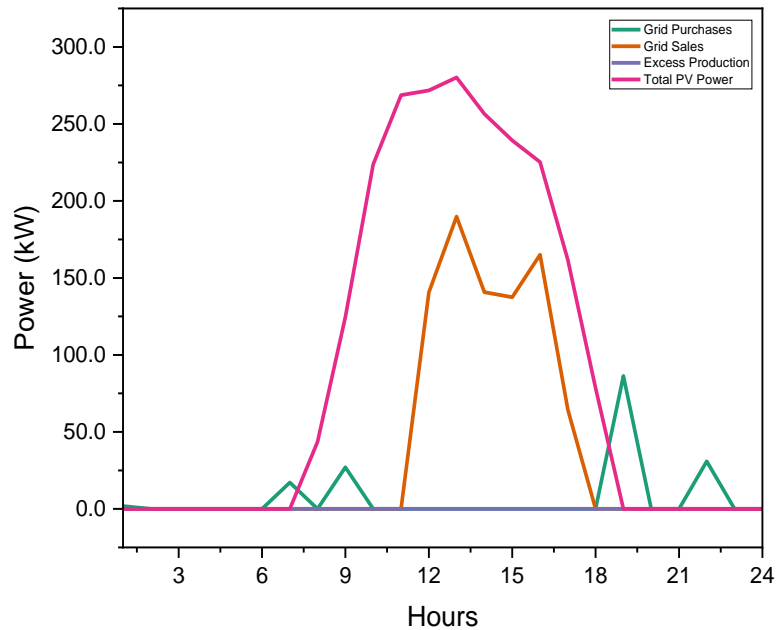
**Figure 17.** Energy Dynamics and Power Source Interactions in Jan in Scenario-2



**Figure 18.** Energy Dynamics and Power Source Interactions in Apr in Scenario-2



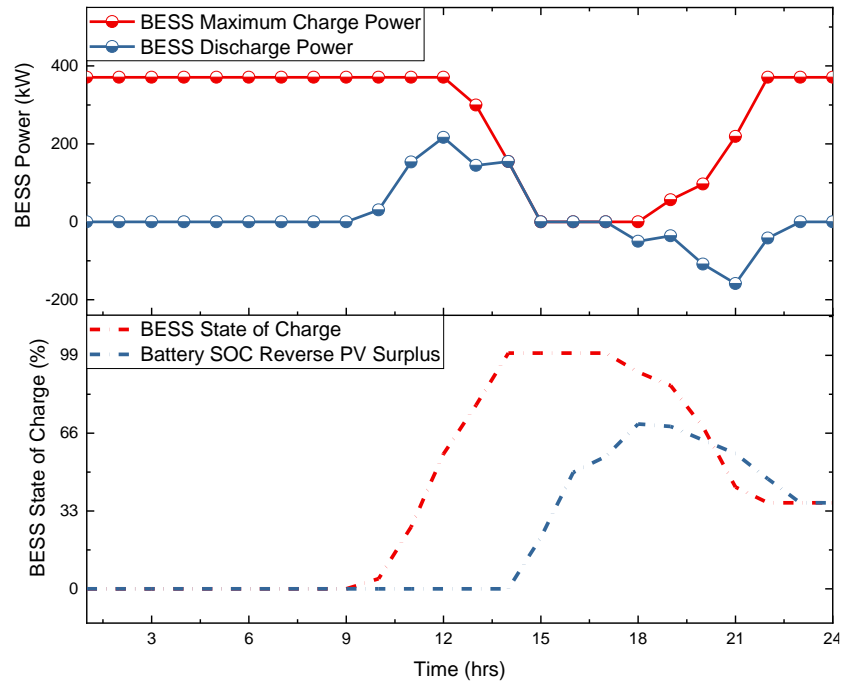
**Figure 19.** Energy Dynamics and Power Source Interactions in Jul in Scenario-2



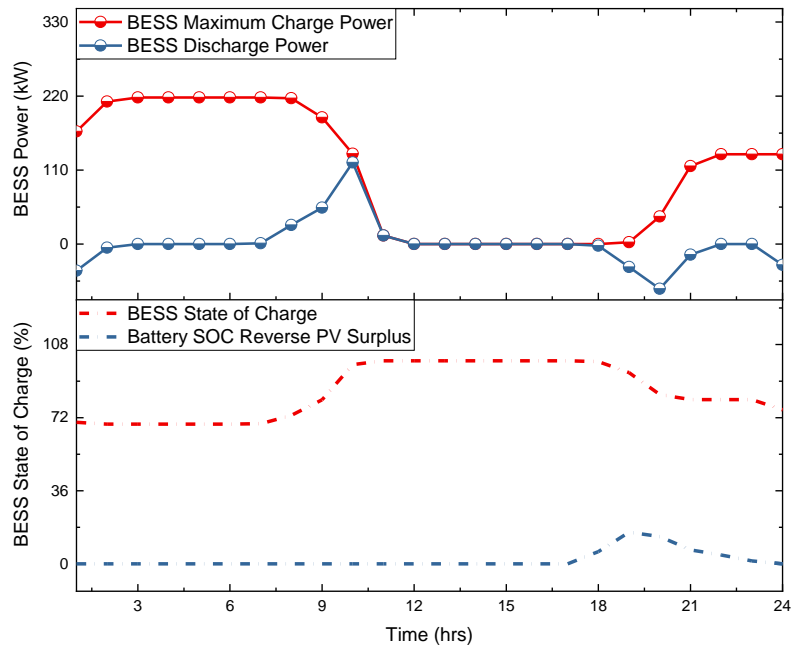
**Figure 20.** Energy Dynamics and Power Source Interactions in Oct in Scenario-2

In January, Scenario 2 exhibits dynamic behavior in the BESS. The BESS discharges power starting from the 10th hour, reaching a maximum discharge of 216.52 kW at the 12th hour. The SOC rises to 100% at the 14th hour. Subsequently, surplus PV energy begins to reverse the SOC, with notable values at the 15th (21.88%) and 16th (49.38%) hours. Despite subsequent discharge events, the BESS maintains a SOC above 36% for the remaining hours. This highlights the system's ability to efficiently manage power flows, ensuring optimal utilization of stored energy. In April for Scenario 2, the Battery Energy Storage System (BESS) demonstrated dynamic charging and discharging patterns. Starting at 69.7% State of Charge (SOC) at 1 AM, the BESS experienced maximum charging power of 217.88 kW during early hours (3-7 AM) with minimal discharge. A notable increase in charging occurred between 8-10 AM, reaching a peak of 98.17% SOC. The BESS achieved full charge (100% SOC) from 11 AM to 5 PM, maintaining this level without any discharging. Discharging commenced in the evening, with significant discharge power of -66.56 kW at 8 PM, reducing the SOC to 83.45%. The SOC further decreased to 75.94% by midnight, reflecting the BESS's role in managing energy demands and surplus throughout the day. In July, Scenario 2 reveals dynamic energy management in the BESS. The BESS exhibits a maximum charge power of 112.54 kW and discharge power ranging from -39.45 kW to 47.70 kW. The SOC fluctuates, reaching 100% during periods of high solar generation and tapering to 80.45% during discharge. Notably, the BESS responds to reverse PV surplus, with a peak SOC of 9.62% and a reverse PV surplus of 8.86% observed during specific hours. This nuanced control mechanism showcases the BESS's ability to optimize energy flow in response to varying grid conditions, maximizing efficiency and storage capacity. In October, the BESS in Scenario 2

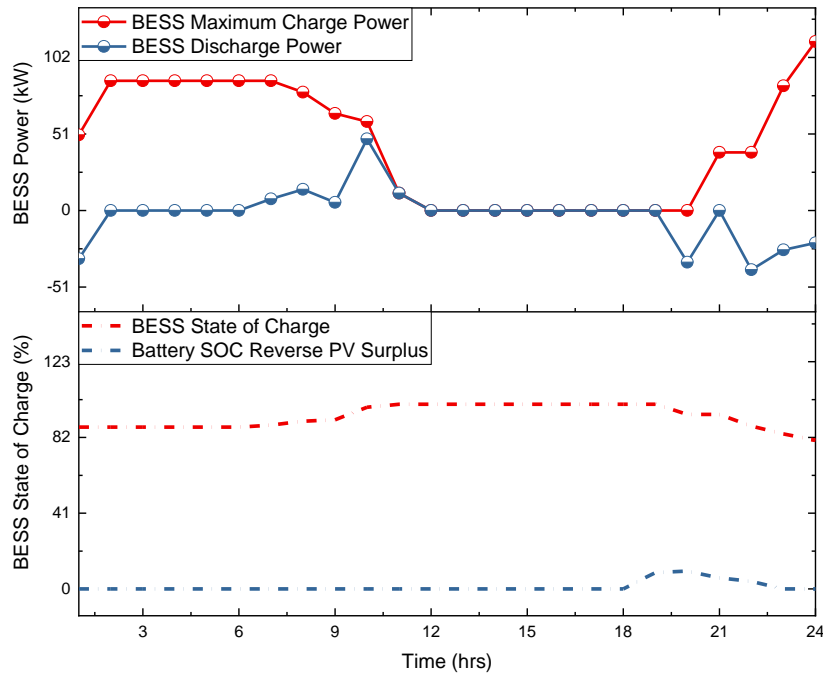
exhibits dynamic behavior. The BESS maximum charge power peaks at 370.79 kW, while discharge power reaches -83.14 kW during the 23rd hour. The SOC fluctuates from a minimum of 34.99% to a maximum of 75.29%. Notably, the reverse PV surplus remains at 0% throughout the observed period, indicating efficient management of energy flow. This concise overview reflects the BESS's ability to respond dynamically to varying energy demands and maintain a balanced state of charge throughout the day.



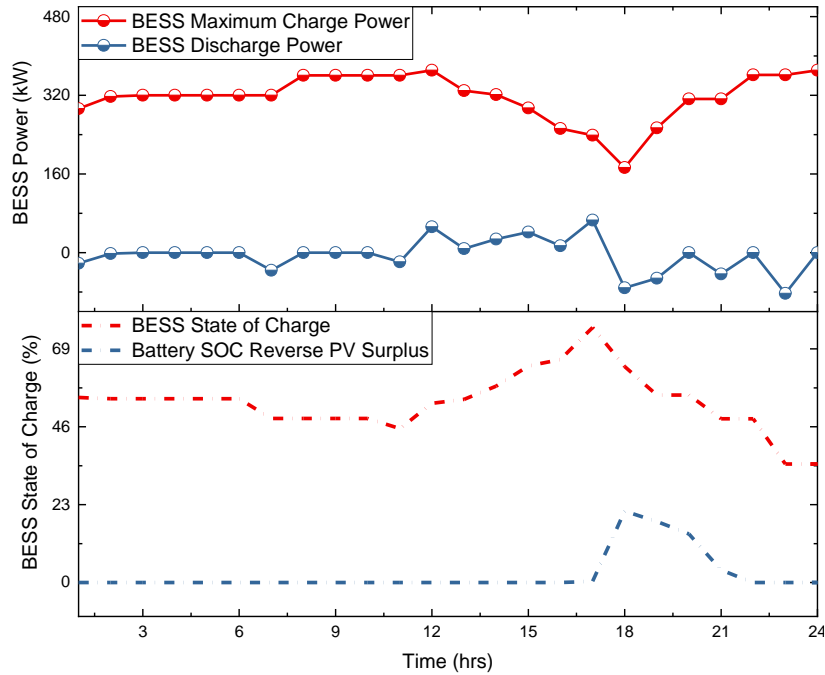
**Figure 21.** Monthly Dynamics of the BESS in Scenario 2 in Jan



**Figure 22.** Monthly Dynamics of the BESS in Scenario 2 in Apr



**Figure 23.** Monthly Dynamics of the BESS in Scenario 2 in Jul

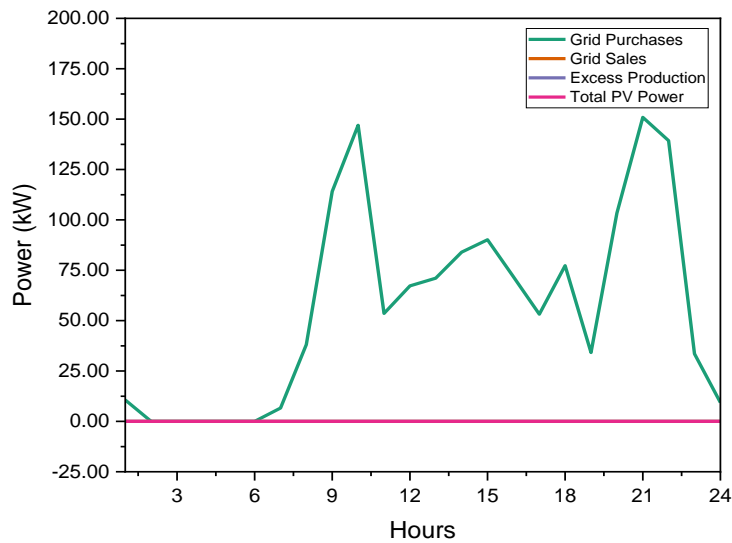


**Figure 24.** Monthly Dynamics of the BESS in Scenario 2 in Oct

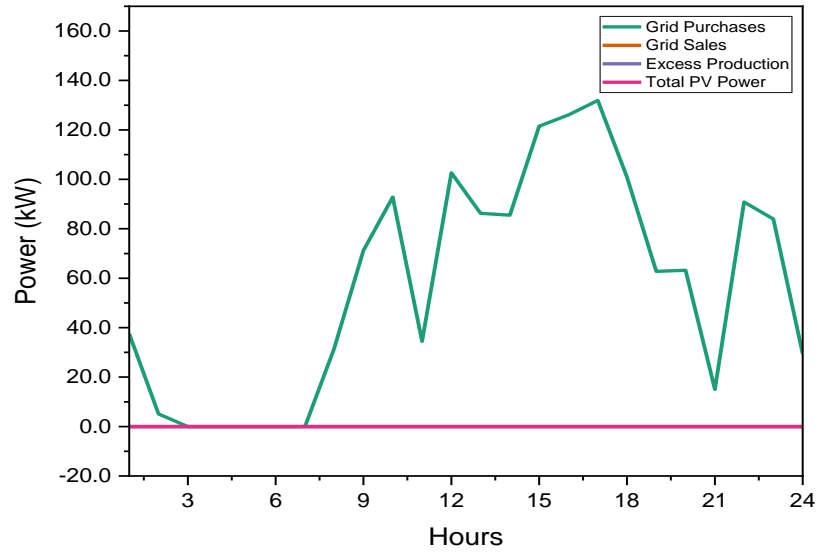
### 4.7.3 Power Source Interactions in Scenario 3

In January, the energy-sharing dynamics in Scenario 3 exhibit a consistent pattern of grid purchases with varying power inputs. The grid purchases range from 6.6 kW to 150.91 kW, while there are no instances of grid sales or excess production. Total PV power generation remains at zero throughout the day, indicating that the power demand is entirely met through

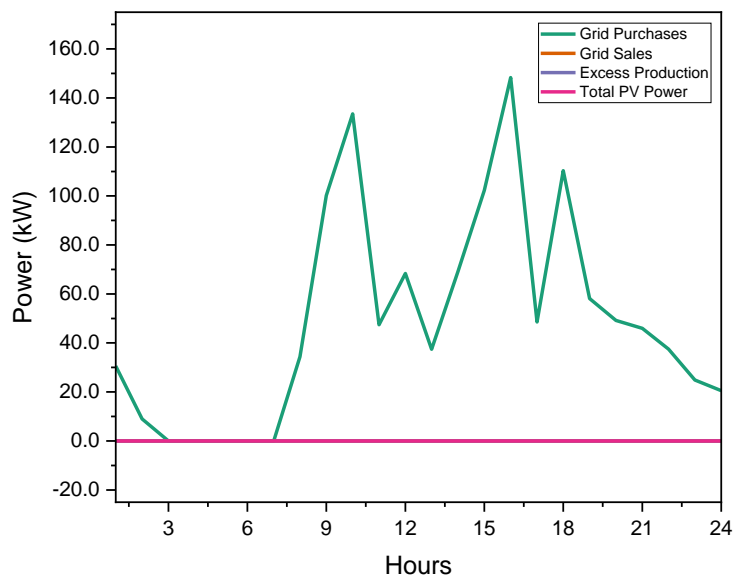
grid purchases during this period. In April, Scenario 3 exhibits a dynamic energy-sharing environment with grid purchases ranging from 5.09 kW to 131.92 kW. However, there are no instances of grid sales or excess production, indicating that the energy demands are consistently met through grid purchases without surplus or export. The total PV power generation for each hour aligns with the grid purchases, emphasizing the reliance on grid power throughout the day, while PV contributions remain unused in terms of excess production or sales. In Scenario 3 for July, the energy dynamics illustrate minimal reliance on the grid, with grid purchases ranging from 0 kW to 148.31 kW. Grid sales and excess production remain consistently at 0 kW throughout all 24 hours. The total PV power generated, while varying hourly, doesn't contribute to grid sales or excess production during this period, indicating self-sufficiency without exporting excess energy or relying on grid sales. In Scenario 3 for October, the energy-sharing dynamics reveal a grid-dependent system with grid purchases ranging from 0 kW to 164.60 kW across different hours. Notably, there are no grid sales or excess production, indicating a lack of energy surplus. The total PV power remains constant at 0 kW throughout the day, reflecting a scenario where the grid serves as the sole energy source without contributions from alternative power generation. This succinctly underscores the grid-only nature of the system during the specified month.



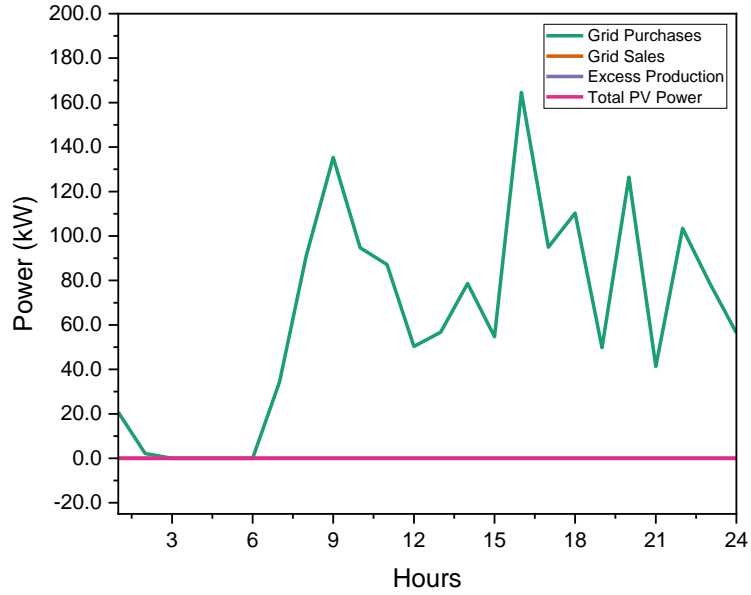
**Figure 25.** Energy Dynamics and Power Source Interactions in Jan in Scenario-3



**Figure 26.** Energy Dynamics and Power Source Interactions in Apr in Scenario-3



**Figure 27.** Energy Dynamics and Power Source Interactions in Jul in Scenario-3

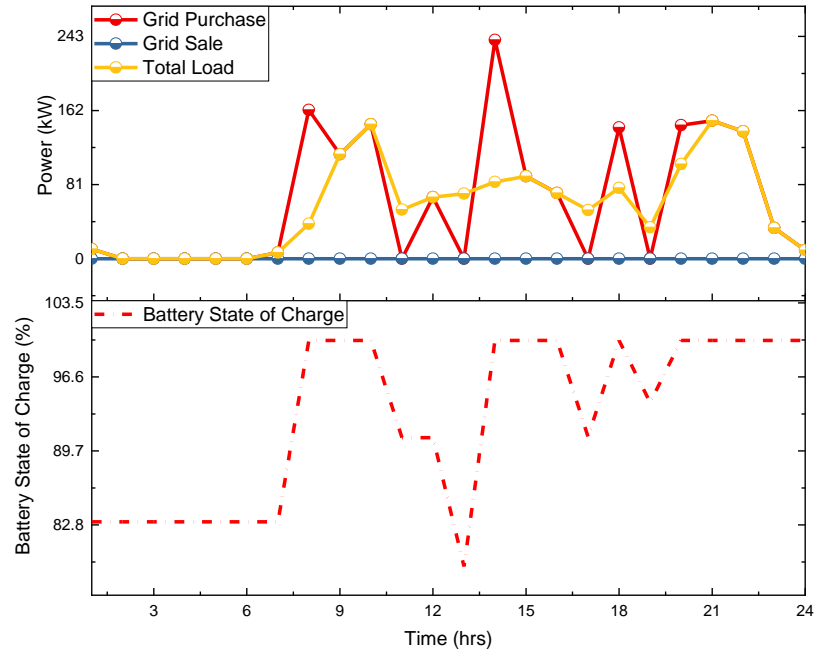


**Figure 28.** Energy Dynamics and Power Source Interactions in Oct in Scenario-3

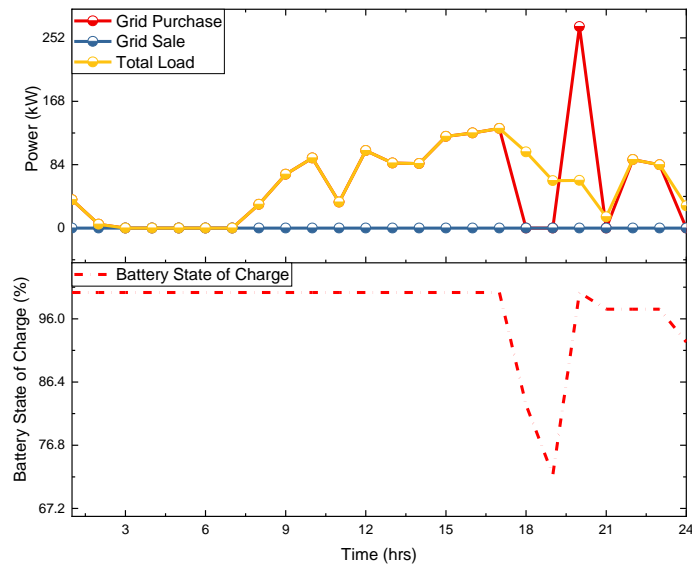
#### 4.7.4 Power Source Interactions in Scenario 4

In Scenario 4 for January, the energy-sharing dynamics demonstrate efficient utilization of power sources. The SOC consistently maintains high levels, ranging from 78.93% to 100%. During peak hours, the system draws power from both the grid and BESS, with a maximum total load of 150.91 kW at the 21st hour. The battery, fully charged by the 8th hour, allows for grid sales and efficient power distribution, ensuring optimal use of grid energy throughout the day. In April's Scenario 4, the energy-sharing dynamics are characterized by a consistently high battery SoC, maintained at 100% for most of the day. This indicates a full energy storage capacity ready to supply power. Grid interaction is varied, with grid purchases peaking at 267.0503 kW at hour 20, but with no grid sales recorded. The total load on the system fluctuates throughout the day, from a low of 0 kW during hours 3 to 7, to a high of 131.9201 kW at hour 17. This variability showcases the system's ability to adapt to changing energy demands, utilizing stored energy and grid purchases efficiently. In July, the energy-sharing dynamics in Scenario 4 showcased efficient utilization of power sources. The battery SoC maintains full capacity at 100% during most hours. Notably, the grid is actively utilized for purchase and sale, with peak grid purchase and sale values at 247.40 kW and 69.15 kW, respectively. During hours of lower grid dependence, the battery plays a crucial role, contributing to a dynamic load distribution. For instance, at the 11th hour, the battery compensates for a grid purchase of  $7.11E-15$  kW, aligning with a total load of 47.42 kW. Overall, the system demonstrates effective coordination between the battery, grid, and total load, ensuring optimal energy utilization. In October for Scenario 4, the energy sharing dynamics reveal a consistent pattern. The battery state of charge frequently reaches 100%, particularly during off-peak hours (1-6 AM, and late evening), indicating sufficient charging.

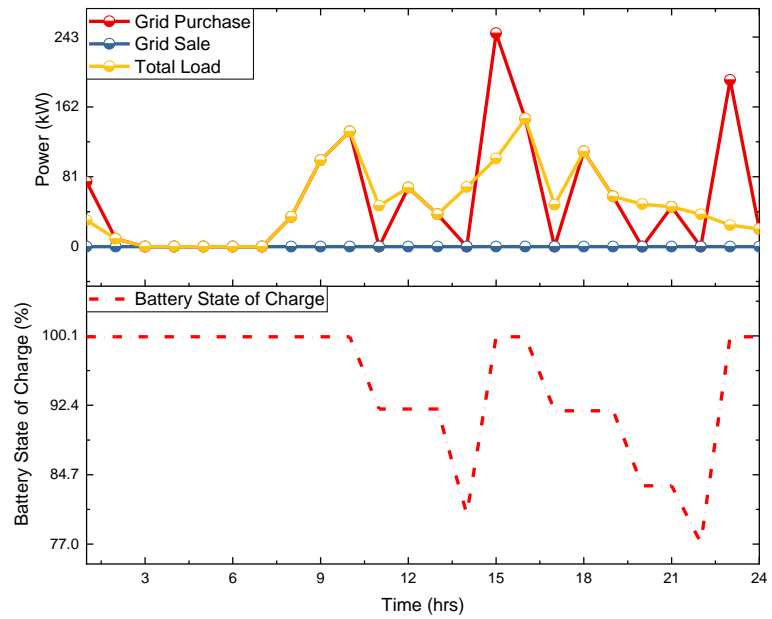
Grid purchases are significant during high-demand periods, peaking at 330.5986 kW at 4 PM and 329.7624 kW at 11 PM, aligning with increased total loads, the highest being 164.5991 kW at 4 PM. Notably, there are no instances of grid sales, suggesting that all generated or stored power is utilized for meeting the demand, which varies substantially throughout the day, from as low as 2.13884 kW at 2 AM to 135.2943 kW at 9 AM.



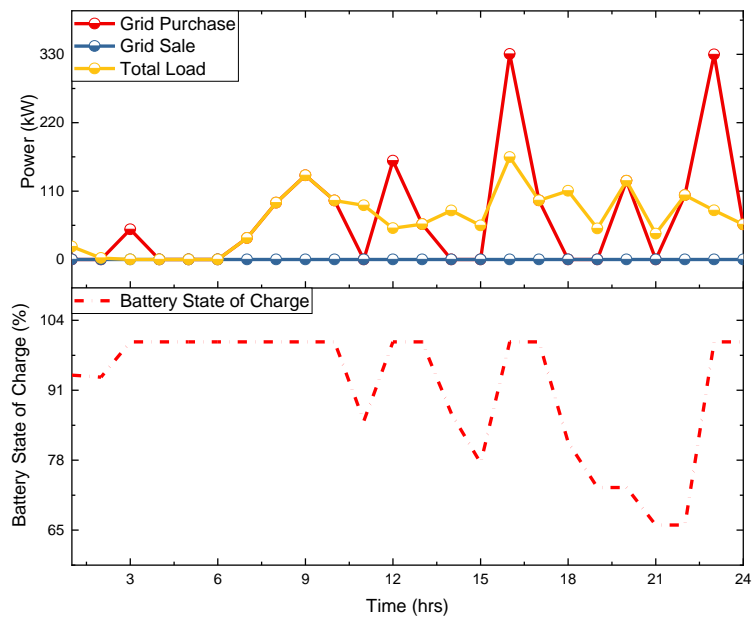
**Figure 29.** Energy Dynamics and Power Source Interactions in Jan in Scenario-4



**Figure 30.** Energy Dynamics and Power Source Interactions in Apr in Scenario-4



**Figure 31.** Energy Dynamics and Power Source Interactions in Jul in Scenario-4



**Figure 32.** Energy Dynamics and Power Source Interactions in Oct in Scenario-4

#### **4.8 Performance Analysis of Fast and Slow EV Charging Units**

The study presents a comprehensive analysis of the operational efficiency of fast and slow EV charging stations over a year. It examines key metrics such as the number of charging sessions, energy delivered, and utilization factors.

#### 4.8.1 Fast Charger Utilization

For fast chargers, there were 9,127 charging sessions in a year, delivering a total of 182,270 kWh of energy. On average, each session provided 20 kWh. The charger was used for about 25 sessions per day, reaching a peak power of 127.5 kW. However, there were about 75 missed sessions per day, leading to a utilization factor of 34.7%. This lower utilization might be influenced by charger availability, location, or user preference for slower charging.

#### 4.8.2 Performance of Slow Chargers

The slow charger exhibited higher usage, with 13,276 sessions annually and a total energy output of 342,782 kWh. The average energy per session was slightly higher at 25.8 kWh. This charger averaged 36.4 sessions per day and had a peak power of 196.9 kW. The missed sessions averaged 63.6 per day, contributing to a higher utilization factor of 70%. The preference for the slow charger could be due to longer parking durations or cost-effectiveness.

#### 4.8.3 Combined Infrastructure Insights

Collectively, both charging systems accounted for 22,403 sessions annually, delivering a total of 525,052 kWh. The average energy delivered per session across both types was 23.4 kWh. The daily total sessions reached 61.4, with a combined peak power of 230.9 kW. The average missed sessions per day for both systems were 138.6, leading to an overall utilization factor of 67.5%. This indicates a moderately high-efficiency level in meeting EV charging needs, highlighting the importance of a balanced approach in providing both fast and slow charging facilities. This analysis is crucial for understanding user behavior and preferences in EV charging, which can guide future infrastructure development to optimize efficiency and user satisfaction in EV charging systems.

**Table 14.** Annual Charging System Performance Metrics

	Sessions Per Year	Annual Energy Served (kWh)	Energy Per Session (kWh)	Session Per Day	Peak Power (kW)	Missed Sessions per Day (avg.)	Utilization Factor (%)
Fast Charger	9,127	182,270	20.0	25.0	127.5	75.0	34.7
Slow Charger	13,276	342,782	25.8	36.4	196.9	63.6	70.0
Total	22,403	525,052	23.4	61.4	230.9	138.6	67.5

#### 4.9 Carbon Emission Analysis Across Scenarios

This section provides a comprehensive analysis of carbon emissions for each scenario, offering insights into the environmental impact of the proposed electric vehicle (EV) charging infrastructure. In Scenario 1, carbon emissions exhibit a monthly variation, ranging from -8.6 tons in July to 7.9 tons in December. Negative values indicate a reduction in carbon emissions, showcasing the environmental benefits of the integrated PV and grid charging

system. Notably, the system consistently contributes to emission reduction throughout the year, aligning with sustainable energy practices. Similar to Scenario 1, Scenario-2 demonstrates a reduction in carbon emissions, varying from -8.1 tons in July to 8.7 tons in December. The integration of BESS alongside PV and grid enhances the environmental performance, further emphasizing the potential of hybrid energy solutions. In Scenario 3, where the EV charging system relies solely on the grid, the carbon emissions remain relatively high, fluctuating between 25 tons and 29 tons throughout the year. This scenario highlights the environmental impact of traditional grid-based charging systems, underscoring the importance of integrating renewable energy sources. Scenario 4, integrating BESS with the grid, shows an increase in carbon emissions, ranging from 28 tons to 31 tons. This emphasizes the negative environmental impact of incorporating energy storage solutions in conjunction with grid-based charging, leading to an overall emission boost. These findings underscore the significance of renewable energy integration in mitigating carbon emissions associated with EV charging. The negative values in Scenarios 1 and 2 affirm the potential for a greener and more sustainable future, while Scenarios 3 and 4 showcase the importance of energy storage solutions in enhancing environmental performance.

**Table 15.** Monthly Carbon Emissions Analysis for Different EV Charging Scenarios

Carbon Emission (metric tons)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Scenario-1	4.8 t	-1.7 t	-5.3 t	-5.2 t	-5.2 t	-6.6 t	-8.6 t	-5.3 t	-4.4 t	2 t	5.9 t	7.9 t
Scenario-2	5.5 t	-1.2 t	-4.7 t	-4.6 t	-4.8 t	-6.2 t	-8.1 t	-4.8 t	-3.9 t	2.6 t	6.6 t	8.7 t
Scenario-3	29 t	25 t	28 t	27 t	28 t	27 t	28 t	29 t	27 t	28 t	27 t	29 t
Scenario-4	30 t	26 t	30 t	29 t	29 t	28 t	29 t	31 t	28 t	29 t	29 t	30 t

#### **4.10 Comparative Analysis**

##### **4.10.1 Cost Efficiency and Renewable Energy Penetration**

The comprehensive comparative analysis across all scenarios provides valuable insights into the interplay of cost dynamics and renewable energy penetration. Scenario 1, characterized by the integration of PV systems and the grid, demonstrates compelling economic and environmental advantages. With a negative NPC of -\$1,807,750 and a renewable fraction of 70.84%, it signifies not only substantial cost savings but also a significant reliance on renewable energy sources. In Scenario 2, the inclusion of BESS alongside PV and grid integration yields higher cost savings, evidenced by a negative NPC of -\$1,250,850, and achieves a slightly increased renewable fraction of 78.23%. On the other hand, Scenario 3, representing a grid-only system, showcases lower cost savings with a negative NPC of -\$984,671.9 and lacks renewable energy sources, resulting in a 0% renewable fraction. Similarly, Scenario 4, integrating BESS with the grid, exhibits moderate cost savings (NPC: -\$266,239.1) and lacks renewable sources (0% renewable fraction). These findings underscore the economic and environmental benefits associated with renewable energy integration, with

Scenario 2 emerging as a favorable compromise between cost efficiency and increased reliance on renewable energy sources.

Architecture							Cost				System		
☰	☰	☰	☰	PV (kW)	TeslaPW2 (#)	G	Converter (kW)	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$/yr)	CAPEX (\$)	Ren Frac (%)	Total Fuel (L/yr)
☰		☰	☰	400		1	340	-\$1.81M	\$0.0339	-\$160,108	\$262,000	70.8	0
☰	☰	☰	☰	400	50	1	340	-\$1.25M	\$0.0996	-\$142,169	\$587,000	78.2	0
		☰				1		-\$984,715	\$0.172	-\$76,172	\$0.00	0	0
	☰	☰	☰		50	1	340	-\$266,247	\$0.278	-\$53,626	\$427,000	0	0

**Figure 33.** Comparative Analysis of Scenarios 1-4 - Economic and Environmental Dynamics

#### 4.10.2 Comparative Analysis of Energy Production, Storage, and Costs Across Different Scenarios

The comparative analysis across scenarios highlights distinctive patterns in energy production, storage, and associated costs. In Scenario 1, where PV systems contribute 589,782 kWh annually, no energy is drawn from or pushed into the Tesla Powerwall 2 (TeslaPW2). The energy cost stands at \$3,767.44, with 230,251.6 kWh purchased and 264,581.8 kWh sold. Scenario 2 introduces TeslaPW2, processing 93,988.59 kWh annually, resulting in an energy cost reduction to \$2,257.40. Notably, 152,686.4 kWh is purchased, and 176,289.8 kWh is sold. In Scenario 3, no energy is produced by PV, and TeslaPW2 remains inactive, with an energy cost of \$90,460.51 for the purchased 525,052.3 kWh. Scenario 4, with no PV production but an annual TeslaPW2 throughput of 123,085.9 kWh, incurs an energy cost of \$90,838.06. Intriguingly, 552,076.9 kWh is purchased, and a minimal 1.97E-12 kWh is sold, emphasizing the varying dynamics of energy utilization and costs across the scenarios.

Architecture							System				PV	TeslaPW2	G			
☰	☰	☰	☰	PV (kW)	TeslaPW2 (#)	G	Converter (kW)	Cap Short (kWh/yr)	Elec Prod (kWh/yr)	Elec Cons (kWh/yr)	CO <sub>2</sub> (kg/yr)	Energy Production (kWh/yr)	Annual Throughput (kWh/yr)	Energy Cost (\$)	Energy Purchased (kWh)	Energy Sold (kWh)
☰		☰	☰	400		1	340	0	820,034	789,634	-21,697	589,782		\$3,764	230,252	264,582
☰	☰	☰	☰	400	50	1	340	0	742,372	701,201	-14,889	589,782	94,259	\$2,255	152,590	176,149
		☰				1		0	525,052	525,052	331,833			\$90,457	525,052	0
	☰	☰	☰		50	1	340	0	552,112	525,052	348,935		123,246	\$90,837	552,112	0

**Figure 34.** Comparative Analysis of Energy Production, Storage, and Costs Across Scenarios

#### 4.10.3 Financial Outcomes of Energy Scenarios

In an analysis of financial outcomes across four distinct energy scenarios, notable variations emerge in terms of present worth, return on investment (ROI), internal rate of return (IRR), and payback periods. Scenario 1 demonstrates strong financial performance, with a present worth of \$823,078, an ROI of 28%, an IRR of 33%, and a simple payback period of 3 years, extending slightly to 3.4 years for the discounted payback. This scenario also boasts significant annual bill savings of \$86,693, culminating in net bill savings of \$1.12 million. Scenario 2, while still profitable, shows a lower present worth of \$266,173, a 7% ROI, and an 11% IRR, alongside a longer simple payback period of 6.7 years and a discounted payback of

8.7 years. However, it slightly outperforms Scenario 1 in annual bill savings at \$88,203, leading to a net saving of \$1.14 million. In stark contrast, Scenario 3 shows no financial returns or savings, reflecting a null scenario in all financial metrics. Finally, Scenario 4 presents a challenging financial picture, with a negative present worth of -\$718,467, a -9% ROI, and no IRR, accompanied by annual bill losses of \$380.23 and a total net bill loss of -\$4,915. These contrasting outcomes highlight the varying degrees of financial viability and efficiency across different energy management scenarios.

**Table 16.** Comparative Financial Performance Across Four Energy Scenarios

Case	Present Worth (\$)	ROI (%)	IRR (%)	Simple Payback (yr)	Discounted Payback (yr)	Bill Saving (\$/yr)	Net Bill Saving (\$)
Scenario-1	823,078	28	33	3.0	3.4	86,693	1.12M
Scenario-2	266,173	7	11	6.7	8.7	88,203	1.14M
Scenario-3	0	0	0	0	0	0	0
Scenario-4	-718,467	-9	0	0	0	-380.23	-4,915

#### **4.11 Discussion**

The comprehensive examination of various EV charging infrastructure models undertaken in this thesis yields crucial insights into the intricate dynamics of energy, environment, and economics. The findings affirm the significant environmental and economic advantages associated with the integration of RESs in EV charging scenarios. Notably, Scenario 1, which combines PV systems with the grid, and Scenario 2, incorporating a BESS, stand out for their substantial reduction in carbon emissions. The environmental drawbacks of conventional grid reliance become evident in Scenario 3, which solely relies on the grid, resulting in higher emissions. From an economic perspective, the integration of renewable resources in Scenarios 1 and 2 proves highly advantageous. Scenario 1 demonstrates a NPC of -\$1,807,750 and a renewable fraction of 70.84%, while Scenario 2 cost savings (NPC) of -\$1,250,850 and boosts the renewable fraction to 78.23%. Conversely, the grid-dependent Scenarios 3 and 4 exhibit less economic efficiency, underscoring the economic viability of renewable integration. The operational evaluation of EV charging stations in various scenarios emphasizes the need for adaptable and effective infrastructure. Scenario 1, with its largely self-reliant system and minimal external energy dependency, contrasts sharply with Scenario 3, which incurs significantly higher energy expenditure due to sole reliance on the grid. Financial outcomes further support the case for integrating renewable energy. Scenario 1 demonstrates an impressive present worth of \$823,078, a ROI of 28%, an IRR of 33%, and a swift payback period of just 3 years. Scenario 2, though slightly less profitable, outperforms grid-dependent scenarios with a present worth of \$266,173 and an ROI of 7%. In summary, this thesis underscores the substantial benefits of incorporating renewable energy into EV charging infrastructure. The simultaneous reduction in carbon emissions and economic advantages advocate for a sustainable and economically viable direction in the development of EV charging infrastructure.

**Table 17.** Overall Comparison of Four EV Charging Scenarios

Case	COE (\$/kWh)	ROI (%)	NPC (\$)	Carbon Emission (kg/yr)	Rene. Fract. (%)	Bill Saving (\$/yr)	Capital Investment (\$)
<b>Scenario-1 (PV and Grid Integration)</b>	0.0339	28	-1.81M	-21,697	70.8	1.12 M	262,000
<b>Scenario-2 (PV, BESS, and Grid Integration)</b>	0.0996	7	-1.25 M	-14,889	78.2	1.14 M	587,000
<b>Scenario-3 (Grid-Only System)</b>	0.172	0	-984,715	331,883	0	0	0.00
<b>Scenario-4 (BESS and Grid Integration)</b>	0.278	-9	-266,247	348,935	0	-4,915	427,00
<b>Optimal Solution (Scenario-1)</b>	<b>0.0339</b>	<b>28</b>	<b>-1.81M</b>	<b>-21,697</b>	<b>70.8</b>	<b>1.12 M</b>	<b>262,000</b>

## 5. Conclusions

This thesis has undertaken an extensive examination of the energy dynamics, environmental consequences, and economic feasibility of different EV charging infrastructure models. A detailed analysis of four distinct scenarios was carried out, revealing the intricate interplay between RESs, energy storage systems, and grid dependence. The research findings present a conspicuous environmental and economic superiority in scenarios that incorporate renewable energy. Specifically, Scenario 1, which combines PV systems with the grid, and Scenario 2, introducing a BESS, markedly diminish carbon emissions. The reductions observed are significant, with Scenario 1 achieving a decrease of up to -8.6 tons per month and Scenario 2 showing -8.1 tons, in stark contrast to the higher emissions of Scenario 3 (grid-only system), which ranged from 25 to 29 tons, highlighting the environmental drawbacks of traditional grid reliance. From a financial perspective, the integration of renewable resources in Scenarios 1 and 2 proves to be highly advantageous. Scenario 1 records a NPC of -\$1,807,750 and a renewable fraction of 70.84%, while Scenario 2 offers cost savings of (NPC of -\$1,250,850) and boosts the renewable fraction to 78.23%. In comparison, the grid-dependent Scenarios 3 and 4 exhibit less economic efficiency, with Scenario 3 having an NPC of -\$984,671.9 and Scenario 4 showing a negative NPC of -\$266,239.1. The operational evaluation of EV charging stations, accounting for both rapid and standard charging preferences, underscores the necessity for adaptable and effective infrastructure. For example, in Scenario 1, the annual energy output of 589,782 kWh from PV systems and no energy trading with the BESS suggests a largely self-reliant system with minimal external energy dependency. On the other hand, Scenario 3, which relies solely on the grid, faced a considerably higher energy expenditure of \$90,460.51 for the 525,052.3-kWh purchased. Concerning financial outcomes, the analysis strongly supports the case for integrating renewable energy. Scenario 1 shows impressive figures with a present worth of \$823,078, a ROI of 28%, an internal IRR of 33%, and a payback period of just 3 years. Scenario 2, although slightly less profitable, still surpasses the grid-dependent scenarios with a present worth of \$266,173 and an ROI of 7%. Overall, Scenario 1 has emerged as the winning EV charging system among the four EV charging scenarios. In summary, this thesis highlights the significant benefits of incorporating renewable energy into EV charging infrastructure. The substantial reduction in carbon emissions coupled with the notable economic advantages in renewable-inclusive scenarios advocate for a sustainable and economically viable direction in the development of EV charging infrastructure. As the shift towards EVs gains momentum, these insights are invaluable for policymakers, urban planners, and stakeholders in the energy sector. It provides essential guidance for future investments and strategies in the creation of sustainable EV infrastructure.

## **6. Future Work**

Future research should extend into exploring a broader array of RERs like wind power, to diversify and strengthen EV charging infrastructure. Emphasis on scalability across diverse geographic and socio-economic settings is vital, alongside the integration of emerging technologies such as smart grids and AI-driven energy management for enhanced efficiency and reliability. Investigating consumer behavior and EV usage patterns will offer insights for user-centric infrastructure design, potentially boosting EV adoption. Additionally, expanding the environmental impact assessment to encompass a wider range of pollutants and resource usage will provide a more comprehensive understanding of the ecological footprint of different charging scenarios. These solutions promise to refine and advance the development of sustainable, efficient, and economically viable EV charging systems globally.

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