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# Private Electric-Vehicle Charging Station Optimization and Sensitivity Analysis Using HOMER Microgrid Software: A Case Study of Kuwait

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## Abstract

This study investigated the optimization of a private electric-vehicle (EV) charging station in Kuwait that integrates solar photovoltaic (PV) systems with a grid backup using Hybrid Optimization of Multiple Energy Resources (HOMER) microgrid software. The research explored different configurations to minimize life-cycle costs while ensuring energy reliability. The optimized system consists of a 7-kW solar PV array and a 25-kW inverter, with grid support to handle energy shortages during periods of low solar irradiance. The simulation results show that the PV system can generate an average of 11,510 kWh/year, covering 82.9% of the charging demand while the grid provides the remaining 17.1% of the total energy. Additionally, the system potentially reduces carbon-dioxide emissions by 1,908 kg/year, aligning with Kuwait's Vision 2035 sustainability goals. Despite the absence of financial incentives for excess energy, the integration of solar power into EV charging stations presents substantial environmental and cost-saving benefits, especially in regions with high solar potential like Kuwait.

**Keywords:** solar PV system, EV solar charging station, HOMER simulation, renewable energy.

## Introduction

The global shift towards electric mobility has prompted significant investments into the development of electric-vehicle (EV) infrastructure, particularly charging stations. As the adoption of EVs grows, the demand for sustainable and efficient charging solutions has become a critical issue, especially in regions like Kuwait with high solar potential. Kuwait, with its abundant solar resources, offers a unique opportunity to leverage renewable energy in addressing the energy demands of private EV charging stations.

Traditional charging stations rely heavily on grid electricity, which in many regions is generated from fossil fuels. This dependence not only contributes to greenhouse gas emissions but also increases operational costs for EV owners. To address these challenges, integrating renewable energy sources, particularly solar photovoltaic (PV) systems, into EV charging infrastructure has emerged as a promising solution. Solar energy, combined with grid support, can provide a reliable and environmentally sustainable source of power for charging EVs.

However, optimizing such systems requires a careful balance between energy generation, storage, and consumption. To achieve such a balance, Hybrid Optimization of Multiple Energy Resources (HOMER) microgrid software provides a platform to model and analyze various configurations, allowing researchers to determine the most cost-effective and energy-efficient system. This study focused on optimizing a private EV charging station in Kuwait using HOMER software, with a specific emphasis on integrating solar PV with a grid backup. Our objective was to minimize life-cycle costs while ensuring reliable energy supply throughout the year, particularly during periods of low solar irradiance.

Our research explored the potential of solar-powered EV charging stations to reduce dependence on the grid, lower emissions, and provide economic benefits. Our study also assessed the environmental impact of the system by focusing on greenhouse gas reductions and alignment with Kuwait's Vision 2035, which emphasizes sustainable energy solutions. We aim to contribute to the growing body of knowledge on renewable energy integration in EV infrastructure by presenting a case study of Kuwait. Our findings should provide valuable insights for policymakers and energy planners looking to optimize EV charging stations in regions with similar environmental conditions.

## Literature Review

The integration of solar energy into EV charging infrastructure has garnered considerable attention in recent years, particularly as a means of reducing reliance on conventional energy sources. Numerous studies have highlighted the potential benefits of combining solar PV systems with battery storage and grid support to improve energy reliability and cost efficiency. One such study by Khan et al. (2016) explored the feasibility of solar-powered EV charging stations and found that grid integration enhanced energy reliability, especially in regions with variable solar irradiance. This research underscores the need for grid backup to ensure a continuous energy supply during periods of low solar generation.

In the Middle East, Al-Abdullah, Yousef M. et al. (2023) conducted a detailed study on the potential for solar energy utilization in Kuwait. Their research pointed out that although Kuwait experiences high levels of solar radiation, extreme temperatures pose significant challenges for maintaining system efficiency. They concluded that the incorporation of battery storage was crucial in mitigating these challenges, allowing for greater energy autonomy and reduced reliance on the grid. Malmgren (2016) echoed this conclusion and emphasized the role of battery storage in enhancing the resilience and sustainability of solar-powered EV charging systems in harsh environmental conditions.

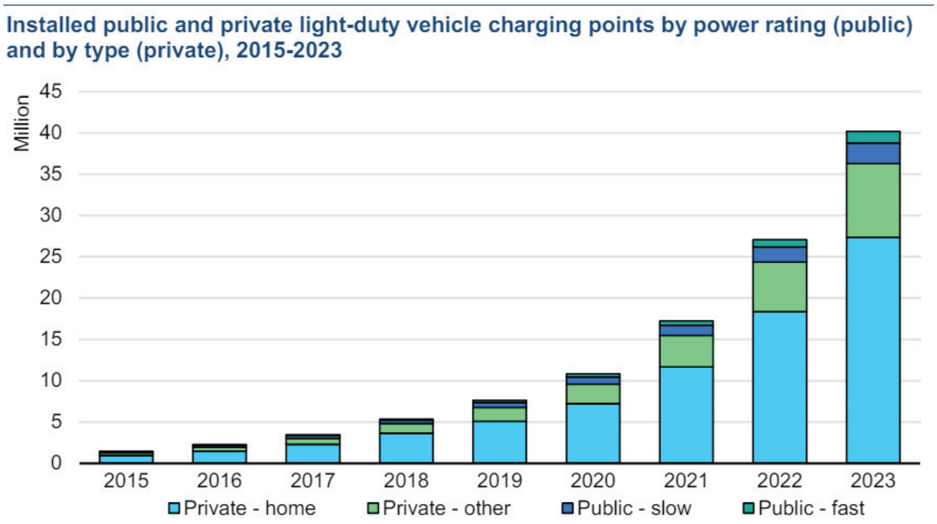
Globally, hybrid energy systems that combine solar PV, wind, and battery storage for EV charging have been shown to offer cost-effective and environmentally sustainable solutions. Amertet S et al. (2024) analyzed the performance of hybrid renewable systems and concluded that they were superior to traditional grid-dependent systems in terms of both cost efficiency and environmental impact. Similarly, Shrivastava, P. et al. (2021) examined the benefits of solar-powered EV charging stations in hot climates and found that such systems significantly reduced greenhouse gas emissions and operational costs when integrated with advanced energy-management systems.

The growing body of literature consistently highlights the importance of integrating renewable energy sources with battery storage for EV-charging infrastructure. Although these systems may require higher initial investments, the long-term benefits in terms of energy independence, cost savings, and environmental sustainability, particularly in regions with abundant solar resources like Kuwait, make them an attractive solution.

## Global Growth of EV Charging Stations

The expansion of EV-charging infrastructure is critical for supporting the global shift towards electric mobility. According to the *Global EV Outlook 2024* by the International Energy Agency (IEA), private EV chargers significantly outnumber public chargers, with a ratio of nearly 10:1 (International Energy Agency, 2024). This prevalence of private chargers is largely attributable to the convenience and cost-effectiveness of home-based charging solutions, which allow EV owners to charge their vehicles overnight at lower electricity rates (Figure 1). However, the expansion of public charging networks remains essential for supporting long-distance travel and for EV owners who do not have access to private charging.

**Figure 1:** *The Global Growth of EV-Charging Infrastructure,* Global EV Outlook 2024 https://www.iea.org/reports/global-ev-outlook-2024



The charging process for EVs is influenced by several factors including battery size, charger type, and power output. For instance, a typical EV with a 60-kW/h battery can be fully charged in approximately 30 min using a 150-kW/h rapid charger. In contrast, using a 7-kWh public charger would take roughly 8 hr while a 22-kW/h charger would reduce the charging time to 3 hr. Public charging stations often offer a range of charging speeds, with Level 2 chargers and DC fast chargers (Level 3) being the most common options. DC fast chargers are particularly effective for adding significant range in a short period, making them ideal for long-distance travel. Several additional factors affect charging speed. Table 1 presents a comparison of the charging levels.

| Current type | AC | AC | DC |
|---|---|---|---|
| Charging time from empty | 11–20 hr | 3–8 hr | 30–60 min |
| Power output (kW/h) | 1.3–2.4 | 3–19.2 | 150–360 |
| Output voltage | 120 V | 240 V | 480 V or 800 V |
| Driving distance for 1 hr charge time | 5–8 km | 16–100 km | Up to 360 km in 20–30 min |
| Utility | Doesn’t require any specialized equipment; not suitable for long-distance daily drivers | Suitable for daily use; needs professional installation | Requires high-power electrical systems and professional installation |
| Charging location and speed | Overnight home charging (slow) | Home and public charging stations (fast) | Highways and in commercial settings (faster) |

**Table 1:** *EV Charger Types: Levels 1, 2, and 3* - EvoCharge, 2021, (https://evocharge.com/resources/the-difference-between-level-1-2-ev-chargers/)

However, the length of automobile charging may be affected by three factors related to the EV’s charging system, a factor related to the station’s charging system, and a factor affecting charging efficiency (see Figure 2):

***Factors Related to the EV's Charging System***

- Battery size: Larger battery capacities require more time to charge.
- State of charge (SoC): Charging from an empty battery takes longer than topping up a partially charged one. Batteries tend to charge more quickly when they are nearly empty and slow down as they approach full capacity to preserve battery health (Hossain et al., 2022).
- Onboard charger capacity: The maximum charging rate of the vehicle's onboard charger limits the speed at which it can accept power, regardless of the power output of the charging station (Wolbertus et al., 2020).

***Factor Related to the Station's Charging System***

- Charger power output: Higher-output chargers provide faster charging while lower-output chargers take longer.

***Factor Affecting Charging Efficiency***

- Temperature: Extreme temperatures, especially cold, can reduce charging efficiency by slowing down the battery's ability to accept power (Lokhande, et al., 2024).

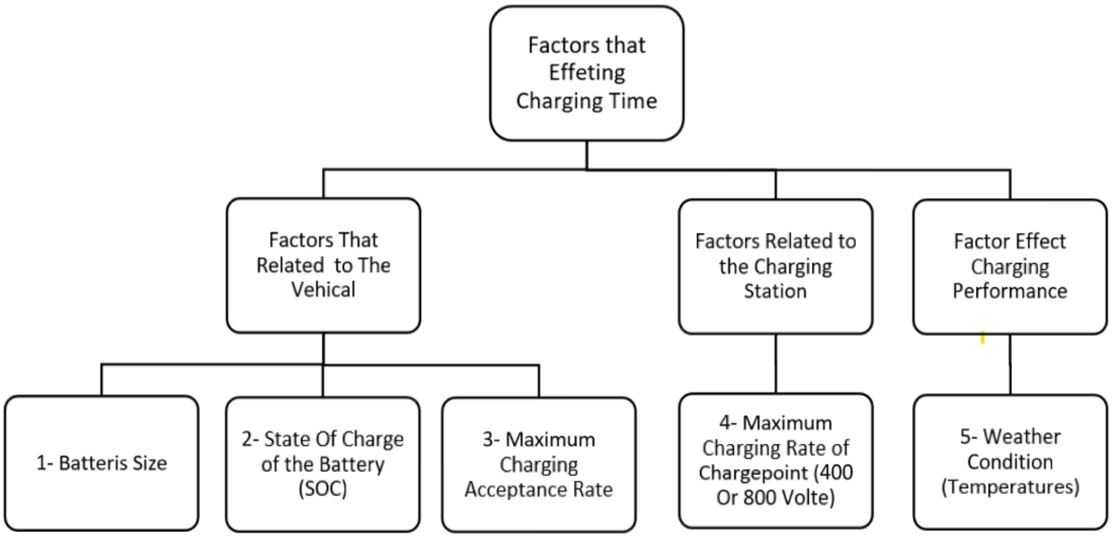


**Figure 2:** *Factors Affecting Charging Speed* - (https://www.kia.com/dm/discover-kia/ask/how-long-does-it-take-to-charge-an-electric-car.html).

Home charging remains the most practical solution for many EV owners. A 7-kW/h home charger can fully charge a 60-kW/h battery in under 8 hr, making it an ideal option for overnight charging. Although faster chargers, such as those rated at 22 kW/h, are available, they require three-phase power, which is uncommon in residential settings and expensive to install (Malmgren, 2016). In conclusion, the expansion of both private and public charging infrastructure is essential for supporting the widespread adoption of EVs. Although home charging offers convenience and cost savings, public charging stations are critical for enabling long-distance travel and ensuring accessibility for all EV users.

## Methodology

In this study, we employed the HOMER microgrid software to model and optimize a private EV charging station powered by a solar PV system with a grid backup in Kuwait. The methodology involved several key steps to assess the system's performance, economic viability, and environmental impact.

### Site Selection and System Design

The chosen site for the charging station was located in Kuwait, which experiences high levels of solar irradiance for most of the year. The system was designed with a 7-kW solar PV array, a 25-kW inverter, and a Level 2 EV charging station. This setup was intended to meet the daily energy demands of a single EV while utilizing grid power during periods of low solar generation.

### Sensitivity Analysis

We conducted a sensitivity analysis to evaluate the system's performance under varying conditions, such as changes in solar irradiance, electricity prices, and system costs. This analysis helped us to determine the robustness of the system's design and identify key factors that influenced its performance and cost-effectiveness.

### HOMER Software Modeling

HOMER software was used to simulate different configurations of the solar PV system with grid backup. The software evaluated the system's performance under various scenarios, taking into account factors such as solar irradiance, grid availability, and energy demand. A total of 480 configurations were simulated to identify the most cost-effective and energy-efficient setup.

### Energy and Economic Analysis

The system's energy performance was evaluated based on its ability to meet the charging demands of an EV over a 1-year period. Key metrics such as total solar energy production, grid energy consumption, and excess energy were analyzed. Additionally, life-cycle costs, including initial investment, operational costs, and maintenance expenses, were calculated to determine the economic feasibility of the system over a 25-year period.

### Environmental Impact Assessment

The environmental impact of the system was assessed using emission factors for carbon dioxide ($CO_2$), sulfur dioxide ($SO_2$), and nitrogen oxide ($NO_x$) emissions, as specified by the AlRukaibi & AlSalem (2022) and Alsayegh (2021). HOMER's simulation provided estimates of the reduction in greenhouse gas emissions resulting from the use of solar power for EV charging as well as the role of grid power in supplementing energy needs during periods of low solar production.

### *System Design and Geographic Conditions*

Usually, the Privet solar charging station, PV panels mounted to the rooftop of a building provide electricity for EV charging and are linked to the utility grid, constituting an on-grid solar rooftop system (Sharma & Goel, 2017). This technology enables EV charging stations to use two distinct power sources: solar energy and grid electricity, without the need for battery storage. The solar output is directly connected to the supply network by grid-tied inverters, which need the grid's voltage and frequency for optimal functionality. These technologies are designed to disconnect under atypical grid situations. When EV load demand exceeds solar output, electricity comes from the grid; alternately, when solar power is in excess, the surplus may be returned to the grid. The distinctions between these two systems are shown in Figure 3, showcasing the operational mechanisms of each system and the associated trade-offs in their implementation.

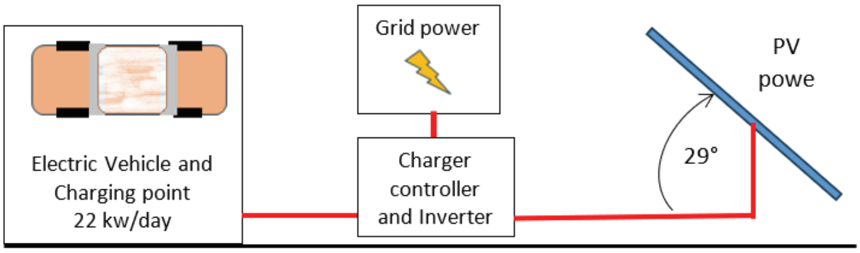


**Figure 3:** *Solar Grid Backup for the Privet EV Charging Station*

Before initiating the HOMER program, it was essential to collect significant data and technical information related to the location, including global solar radiation; PV costs, sizes, and features; tracking system types; and ambient temperatures for the HOMER program.

Furthermore, we determined the geographical coordinates for the research location (Figure 4), which facilitated the installation orientation of PV systems. Specifically, we used $29.3^0$ for slope angle and an azimuth angle of $0^0$ (0° azimuth in the northern hemisphere and 180° azimuth in the southern hemisphere).

### *HOMER Modelling for Solar Grid Backup at the Privet EV Charging Station*

For the solar grid backup EV charging station, the system was designed to support one EV using a Level 2 charging system. The Level 2 charging system can add electrical power from 3.7 kW/h to 22 kW/h to the EV, allowing driving distances from 19 to 117 km (EVESCO, 2024).

Figure 5 shows the HOMER software schematic system that we used to simulate 480 different system configurations. Based on the component size ranges outlined, the optimized configuration system was chosen by minimizing the life-cycle cost for 25 years. The chosen optimized system is shown in Figure 6, which consists of a 7-kW solar PV array, a 25-kW inverter, and a connection to grid power for a backup.

**Figure 4:** *Geographical Coordinates for Location in Kuwait (29°12.8' N, 47°52.4' E)*

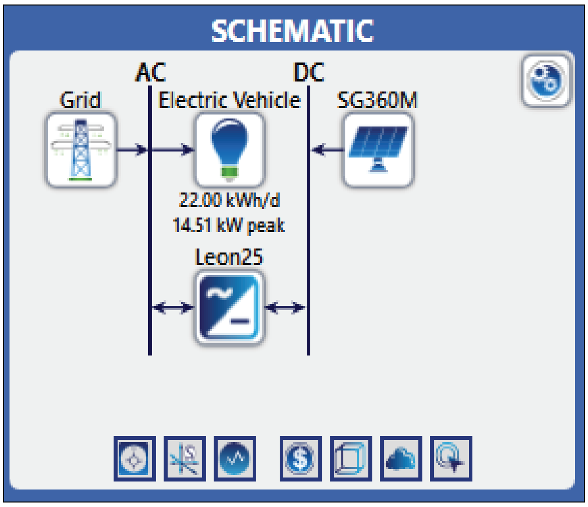
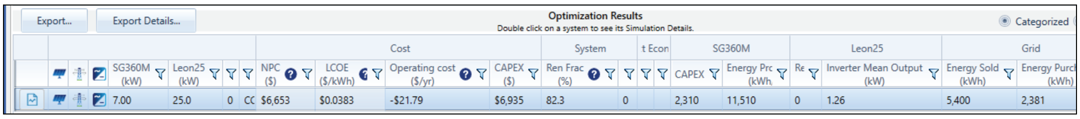


**Figure 5:** *Privet Charging Station Using Solar Energy and Advanced Grid Backup*



Optimization Results
Double click on a system to see its Simulation Details.

| | | | | Cost | | | | System | | t Econ | | SG360M | | Leon25 | | Grid | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SG360M (kW) | Leon25 (kW) | | | NPC ($) | LCOE ($/kWh) | Operating cost ($/yr) | CAPEX ($) | Ren Frac (%) | | | | CAPEX | Energy Prc (kWh | Re | Inverter Mean Output (kW) | Energy Sold (kWh) | Energy Purc (kWh) |
| 7.00 | 25.0 | 0 | CC | $6,653 | $0.0383 | -$21.79 | $6,935 | 82.3 | 0 | | | 2,310 | 11,510 | 0 | 1.26 | 5,400 | 2,381 |

**Figure 6:** *Optimized EV Charging System*

The chosen system was designed to provide an average of approximately 22 kW/h of electrical power each day, which is sufficient to fully charge 88 kW/h of an EV's battery for a period of four days, enough for 450 km of driving distance.

## 2. *HOMER Results for Solar Grid Backup at the Privet EV Charging Station*

### 2.1. PV Output Power

The yearly performance of the EV solar charging station with grid backup is shown in Figures 7 and 8. The density map indicates that the PV array produced a substantial daily output from February to October, with power levels between 4 and 6 kW. However, energy production decreased from November to January due to lower solar irradiance.

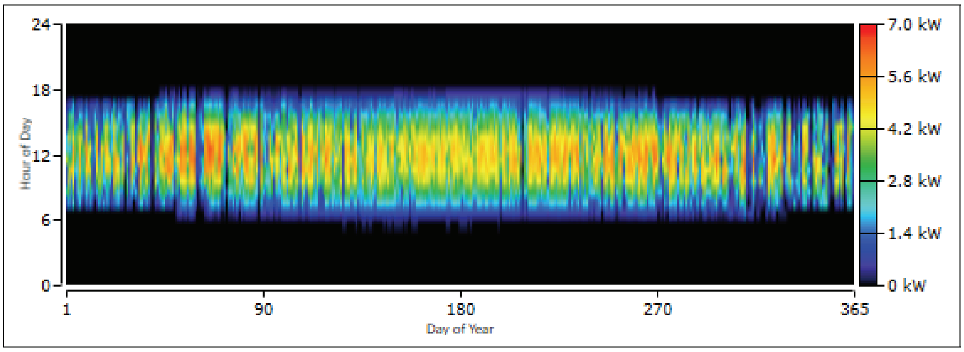


**Figure 7:** *Density Map of Annual PV Production*

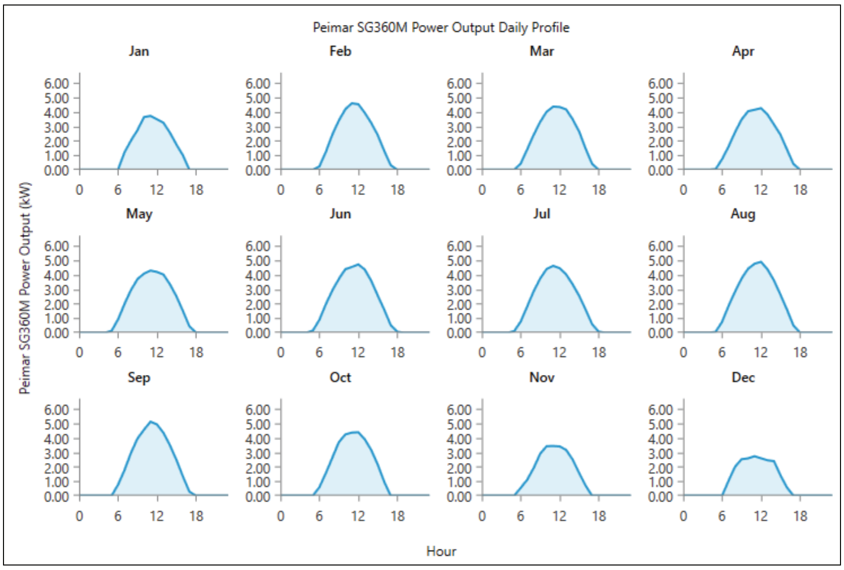


**Figure 8:** *Monthly PV Production*

The PV system was rated at 7 kW and reached a peak output of 6 kW. Throughout the year, it generated a total of 11,510 kW. The net energy purchased from the grid over the year amounted to 2,381 kW (Table 2), which was calculated by subtracting the 5,400 kW/year fed back into the grid from the -3,019 kWh delivered to it.

| Production | kW/year | % |
|---|---|---|
| Peimar SG360M | 11,510 | 82.9 |
| Grid purchases | 2,381 | 17.1 |
| Total | 13,891 | 100 |

**Table 2:** *Total Energy Input*

Due to the absence of a buy-back policy for surplus PV electricity in Kuwait, the system did not gain any financial advantage from the excess energy returned to the grid.

**System Load**

The annual EV charging load for the Kuwait grid-connected station is represented in Figure 9. HOMER proved that the station could easily meet the daily EV demand. The PV system could operate from 6 a.m. to 5 p.m. for the majority of the year, aligning with the constraints of PV energy output. From November to December, the PV output declined, causing more demand for grid power to compensate for any potential energy shortages. As a result, the EV had to be charged concurrently with PV production and for an extended duration at PV output, resulting in considerable grid power use.

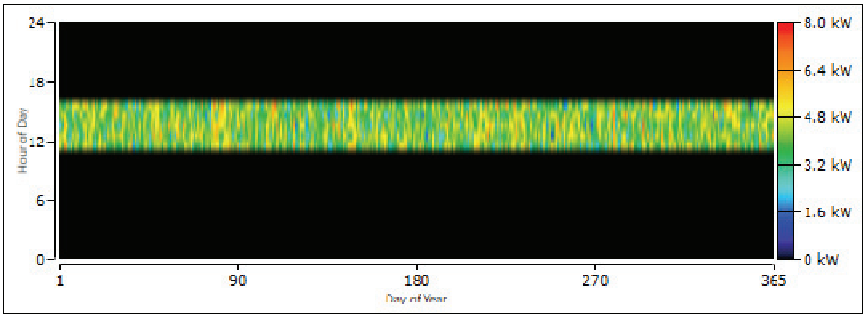


**Figure 9:** *Annual Charging Load*

The yearly electric vehicle consumption amounted to 8,030 kW/year (Table 3), constituting 59.8% of total output and enabling an approximate travel distance of 42,705 km (EVESCO, 2024). The input power during EV charging varied from 3 kW/h to 6 kW/h between 11 a.m. and 4 p.m. On the other hand, Figure 10 shows an accurate analysis of the EV charging demand over the course of many months. It demonstrates that the month of December was the month that was most impacted in terms of a reduction in global solar, which dipped considerably around or below 4 kW/h. In contrast, energy production remained above 4 kW/h throughout the rest of the year.

| | Consumption | | | Excess electricity | | |
|---|---|---|---|---|---|---|
| | AC primary load | Grid sales | Total | Excess electricity | Unmet electric load | Capacity shortage |
| kW/year | 8,030 | 5,400 | 13,430 | 0 | 0 | 0 |
| % | 59.8 | 40.2 | 100 | 0 | 0 | 0 |

**Table 3:** *Total Energy Consumption and Excess Electricity*

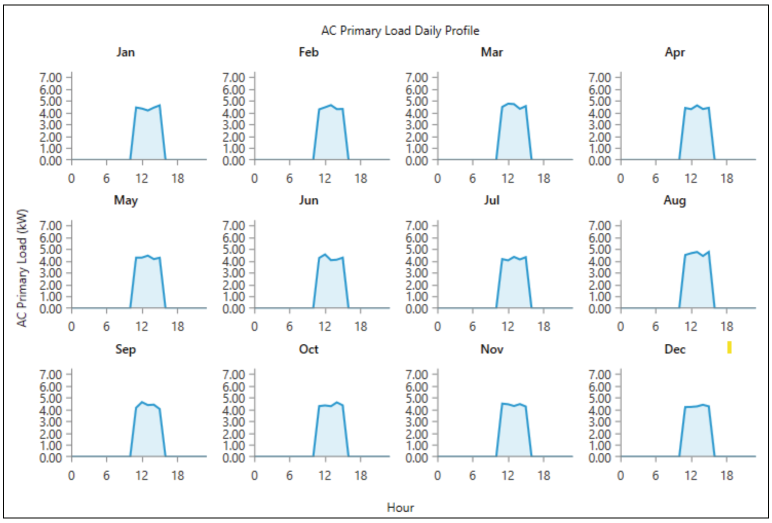


**Figure 10:** *Monthly Charging Load Density*

## Grid Backup Power (Electricity Purchases)

The EV purchase input power for the Kuwait grid-connected station is shown in Figures 11 and 12 and consequently, Figure 13 shown a comparison between purchased electricity and photovoltaic electrical production. The grid electricity operated from 11 a.m. to 4 p.m. for most of the year, aligning with the charging of EVs. From November to January, grid electricity needed to be increased to make up for a shortage in PV production. The yearly purchased grid electricity totaled 2,381 kW/year, constituting about 17.1% of the total energy, in contrast to the PV generation, which accounted for 82.9% of total energy (Table 2).

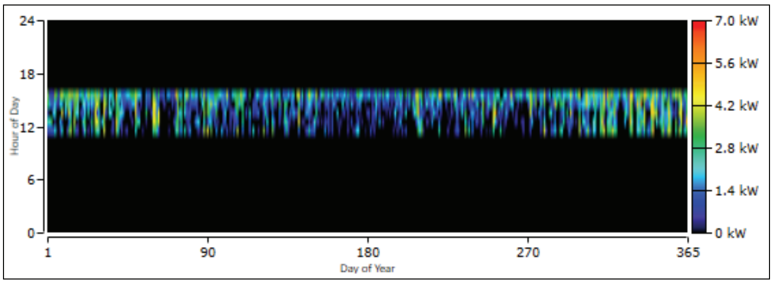


**Figure 11**: *Annual Purchased Power*

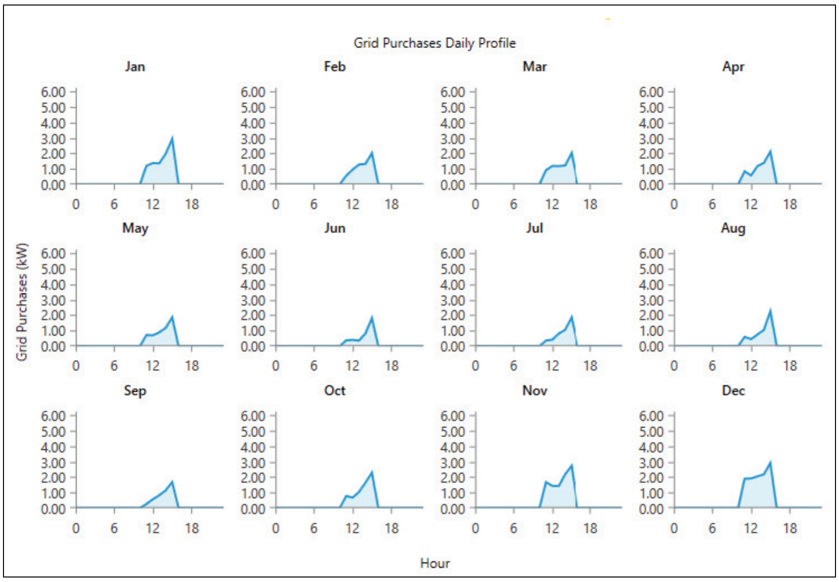


**Figure 12**: *Monthly Purchased Power Totaling 2,381 kW/year*

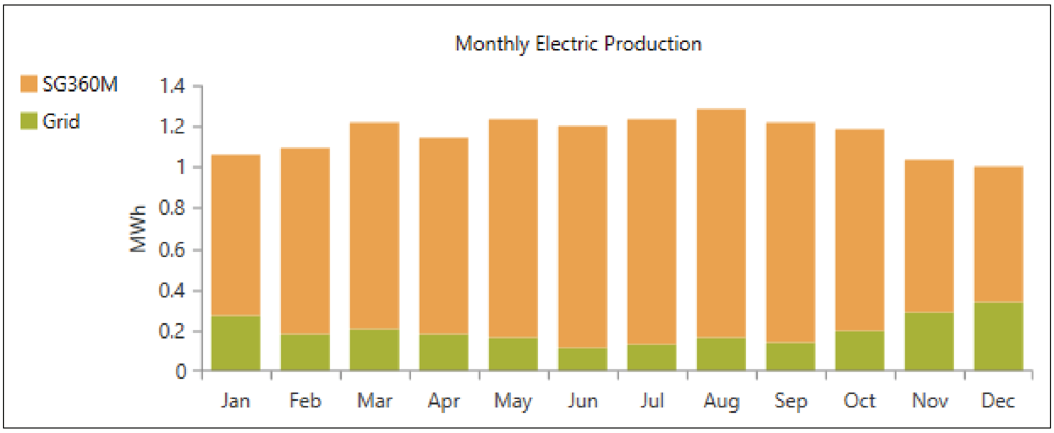


**Figure 13**: *Purchased Electricity Compared to PV Electrical Production*

## Excess Electricity (Grid Sales)

An advanced grid solar system does not generate extra energy because any surplus is sold or transferred to the grid. The Kuwait Electricity System does not benefit financially from the excess energy returned to the power grid; nonetheless, the system could benefit from decreasing the mount of purchased electricity to around -3,019 kW/year (Table 5) (Figures 14 and 15).

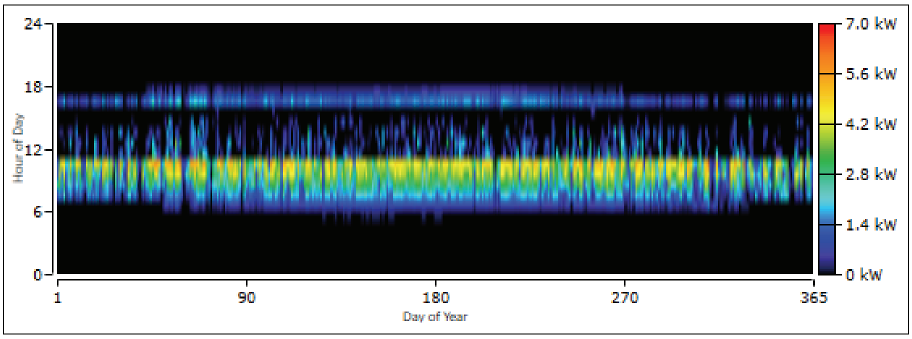


**Figure 14:** *Annual Excess Electricity Transferred to Grid Power*

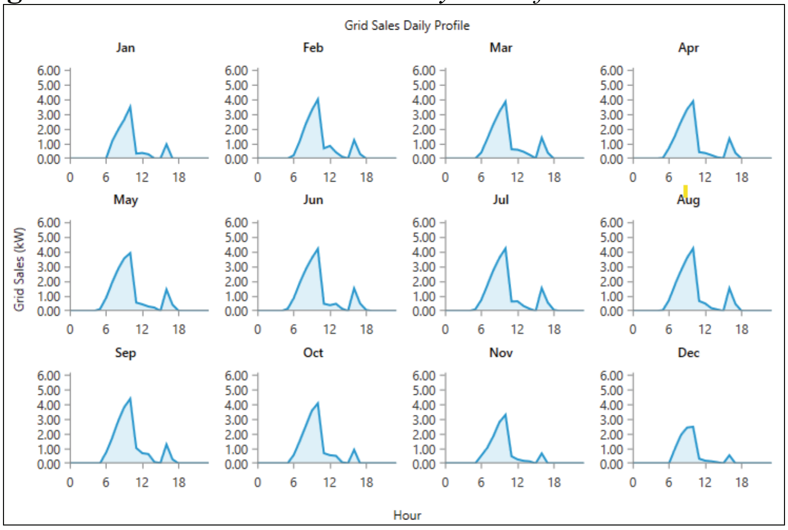


**Figure 15:** *Monthly Purchased Power Totaling 5,400 kW/year*

Therefore, HOMER did not show any excess electricity or any unmet demand because it transferred any excess electricity to grid power or used the grid power as a secondary energy source. However, per Table 3, HOMER showed the total amount of generated energy intended for sale to the grid or to offset purchased electricity. Another benefit of transferring power is the decrease in emissions.

## Environmental Impact (Emissions)

HOMER enables the specification of emission factors for many contaminants (Table 4). This experiment demonstrated that the EV solar-powered private charging station with grid backup was not inherently a zero-emission technology. The volume of greenhouse gas released into the environment was contingent upon the emission intensity and the quantity of energy procured by the station from the grid. According to Climatiq Technologies, the emission factor for the power system in Kuwait was 0.842 kg $CO_2$/kW/h (Climatiq, 2017). The HOMER simulations for Kuwait stations computed emissions from energy usage based on the specified emission factors. HOMER demonstrated that EV charging stations could contribute to a reduction of approximately 1,908 kg/year in $CO_2$, 8.27 kg/year in $SO_2$, and 4.05 kg/year in $NO_x$. This contribution aligns with Kuwait's Vision 2035 for sustainable energy and pollution reduction.

| Quantity | Value |
|---|---|
| Carbon dioxide | -1,908 kg/year |
| Carbon monoxide | 0 kg/year |
| Unburned hydrocarbons | 0 kg/year |
| Particulate matter | 0 kg/year |
| Sulfur dioxide | -8.27 kg/year |
| Nitrogen oxides | -4.05 kg/year |

**Table 4:** *Emissions Reductions*

## 6.6. System Economics (PV, Backup)

The cash flows for Kuwait's EV solar charging station with grid backup over a 25-year period are illustrated in Figure 16 with components of the cash flow and Figure 17 with a cost summary. The graph in Figure 17 breaks down the annual costs associated with key components, PV arrays, inverters, grid power, and operational and maintenance expenses. These numbers also account for the costs of the inverter maintenance after 10 and 20 years.

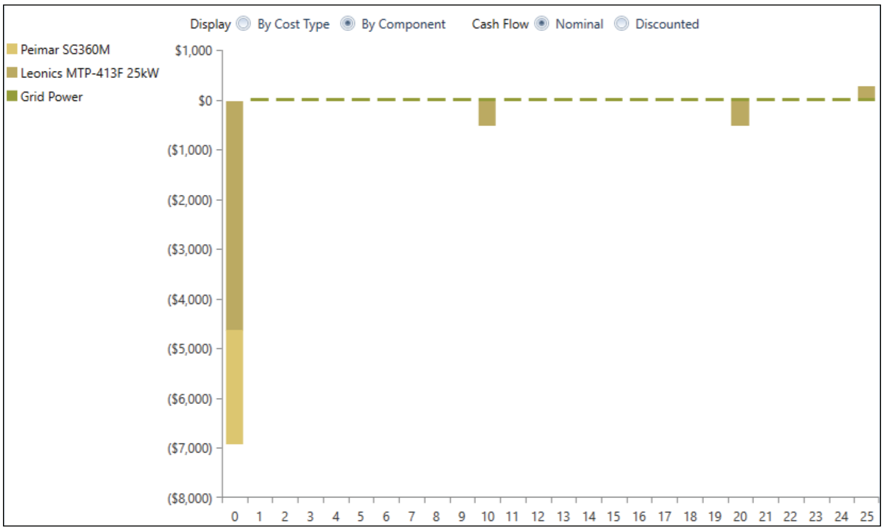
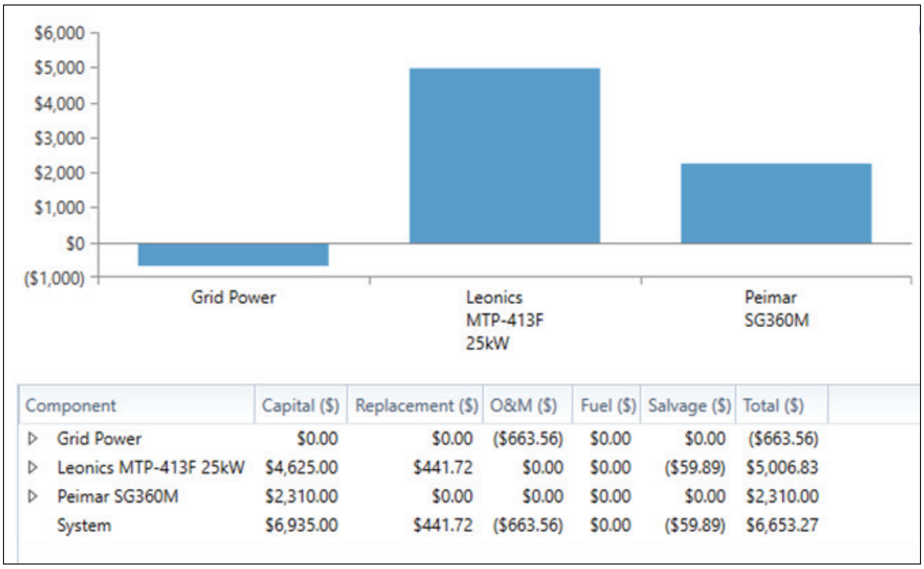


**Figure 16:** *Components of Cash Flow*



| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| ▷ Grid Power | $0.00 | $0.00 | ($663.56) | $0.00 | $0.00 | ($663.56) |
| ▷ Leonics MTP-413F 25kW | $4,625.00 | $441.72 | $0.00 | $0.00 | ($59.89) | $5,006.83 |
| ▷ Peimar SG360M | $2,310.00 | $0.00 | $0.00 | $0.00 | $0.00 | $2,310.00 |
| System | $6,935.00 | $441.72 | ($663.56) | $0.00 | ($59.89) | $6,653.27 |

**Figure 17:** *Cost Summary*

The initial capital investment for the main components totals $6,935, distributed as follows: 67% allocated to the inverter and 33% to PV. The system does not require annual maintenance.

In Kuwait, where the Ministry of Electricity and Water is the sole provider, there is no buy-back system for excess electricity generated by PV installations. As a result, a solar EV charging station does not benefit financially from any surplus energy returned to the grid. The system is anticipated to purchase approximately 2,381 kW of grid electricity each year, with an annual reduction cost estimated at $51.33 (calculated at $0.0038/kWh; see Table 5).

## Discussion

The results of the HOMER simulation provide valuable insights into the performance and optimization of solar-powered EV charging stations in Kuwait, particularly in regions with high solar irradiance but fluctuating seasonal performance. The integration of solar PV systems with a grid backup presents several advantages in terms of energy reliability, cost savings, and environmental impact although certain challenges remain.

One of the key findings was the significant contribution of solar energy to the overall energy needs of the charging station, with 82.9% of the total energy demand met through solar generation. The station's grid dependency, constituting only 17.1% of the total energy input, underscores the potential for high solar penetration in Kuwait's EV charging infrastructure. However, during the winter months (November to January), when solar irradiance was lower, the system's reliance on grid power increased. This fact highlights the importance of grid support to ensure uninterrupted EV charging, particularly during periods of reduced solar output.

| Month | Energy purchased (kWh) | Energy sold (kWh) | Net energy purchased (kWh) | Peak load (kWh) | Energy charge $ | Demand charge $ |
|---|---|---|---|---|---|---|
| January | 274 | 349 | -75 | 5 | ($1.27) | $0 |
| February | 177 | 406 | -229 | 6 | ($3.89) | $0 |
| March | 203 | 464 | -261 | 5 | ($4.43) | $0 |
| April | 180 | 453 | -272 | 5 | ($4.63) | $0 |
| May | 167 | 522 | -355 | 5 | ($6.04) | $0 |
| June | 116 | 516 | -400 | 4 | ($6.80) | $0 |
| July | 134 | 540 | -406 | 5 | ($6.90) | $0 |
| August | 165 | 520 | -355 | 5 | ($6.04) | $0 |
| September | 137 | 523 | -387 | 6 | ($6.57) | $0 |
| October | 200 | 466 | -266 | 5 | ($4.52) | $0 |
| November | 286 | 343 | -57 | 5 | ($1) | $0 |
| December | 341 | 299 | 42 | 6 | $0.70 | $0 |
| | | | | | | |
| Annual | 2,381 | 5,400 | -3,019 | 6 | ($51.33) | $0 |

**Table 5:** *Grid Power*

The lack of a financial incentive for feeding excess electricity back into the grid presents a limitation in the system's economic performance. In regions like Kuwait, where there is no buy-back policy for surplus solar energy, the financial benefits of the system are primarily derived from reducing grid purchases rather than selling excess energy. Nevertheless, the overall economic savings are substantial, with the system achieving significant reductions in grid energy consumption during peak solar months. This finding is particularly relevant for policymakers in Kuwait who are looking to incentivize renewable energy adoption but face challenges in integrating buy-back schemes into the grid infrastructure.

From an environmental perspective, the system provides clear benefits in reducing greenhouse gas emissions. The simulation estimated a reduction of approximately 1,908 kg of $CO_2$ annually along with reductions in $SO_2$ and NO□, contributing to Kuwait's environmental sustainability goals under Vision 2035. This finding reinforces the role of renewable energy in reducing the carbon footprint of the transportation sector, particularly in regions with high solar potential.

The study also highlights the potential benefits of incorporating battery storage into the system to enhance energy autonomy. Although the grid-connected system provides reliability, the inclusion of battery storage could further optimize cost efficiency by storing excess solar energy for use during periods of low production. This would reduce the need for grid support and enhance the station's ability to operate independently during peak solar-production hours.

Our study demonstrates that solar-powered EV charging stations, supported by a grid backup, present a feasible solution for reducing reliance on conventional energy sources, lowering operational costs, and contributing to environmental sustainability in Kuwait. The findings highlight the need for further research into integrating battery storage and optimizing system configurations to maximize the benefits of renewable energy in EV infrastructure.

## Conclusions

This study presents an in-depth analysis of the optimization of a private EV charging station in Kuwait, using the HOMER microgrid software to integrate solar PV systems with a grid backup. The simulation results demonstrate that solar energy, combined with grid support, offers a reliable, cost-effective, and environmentally sustainable solution for EV charging infrastructure in regions with high solar potential, such as Kuwait.

The optimized system, consisting of a 7-kW solar PV array and a 25-kW inverter, was able to meet 82.9% of the station's energy needs through solar generation, with the grid providing support during periods of low solar irradiance. Although the absence of a buy-back policy for excess electricity limited financial gains, the system's reliance on grid energy was minimized, resulting in significant cost savings and a reduction in greenhouse gas emissions. The environmental benefits, including a reduction of 1,908 kg of $CO_2$ emissions annually, align with Kuwait's Vision 2035 for sustainable energy development.

The study also highlights the potential for further optimization through the integration of battery storage. This could reduce the need for grid dependency, particularly during peak solar production hours, and increase the overall energy autonomy of the system. Such improvements would further enhance the feasibility of solar-powered EV charging stations in Kuwait and similar regions with abundant solar resources.

In conclusion, the integration of renewable energy, particularly solar PV systems, into EV-charging infrastructure offers a promising pathway for reducing fossil fuel reliance, lowering operational costs, and supporting environmental sustainability. Policymakers in Kuwait and other regions should consider these findings when developing frameworks for EV infrastructure expansion, particularly with regard to incentivizing renewable-energy integration and optimizing energy-management systems.

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