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Electric Vehicle Charging Station Utilizing Highly Concentrated Photovoltaic System Combined with Lithium-Ion Batteries

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ABSTRACT
Combining highly concentrated photovoltaic (HCPV) modules and battery storage systems attain high power- density than other ones using separate elements. This work aims to examine the performance of electric vehicle (EV) charging station utilizing an HCPV system integrated with lithium-ion batteries in Kuwait. HCPV system is integrated with EV, battery storge system, and AC grid as a four-component system for EV charging station at an educational building located in Kuwait. A theoretical technique is developed to calculate the proposed system efficiency. A simple algorithm is utilized to calculate the reduction of greenhouse emissions due to the use of HCPV-EV. Energy produced from HCPV modules is used to charge four EVs, battery system, supplying energy to building electrical appliances and feeding remaining energy to the grid. Present results reveal that HCPV energy utilized for EV charging represents 81% of the total load needed to charge EVs and about 90% of the energy required for EV charging through the utilization of HCPV modules and battery system which can potentially reduce operating costs of charging EVs. Only about 10% (1218 kWh) is required to be exported from the grid to fully charge EVs. Also, an integrated HCPV system and battery can provide 93% of the total load required resulting in a big saving in electricity bill. Also, the HCPV system can feed the utility by 11458 kWh, resulting in an additional decrease in building consumption costs. In all months, the performance ratio (PR) of the proposed integrated system is higher than 80%, indicating the reliability of the proposed HCPV integrated system. Battery state of charge (SOC) exceeds 70% through most year months indicating the reliability and durability of lithium-ion storage batteries. Finally, predicted CO2 emissions avoided because of utilizing an integrated HCPV system at an optimum tilt angle is 12410 kg/year resulting in significant environmental enhancement.

Keywords: High concentrated PV; multi-junction solar cells; lithium-ion battery; electric vehicle; weather conditions.

1. Introduction

Using electric vehicles integrated with photovoltaic and battery storage as backup can help with two main goals: low operating cost of the proposed system and a cleaner environment with less CO_2 emissions. The scientific problems and technical challenges of this integration process of using photovoltaics as a renewable energy source for power systems with a battery storage system integrating with EV charging station could be solved by improving materials and designs of PV devices, increasing the reduction in peak-load, and overcoming the overloading of charging station component. The integration of HCPV, EV charging station, and battery storage systems plays an important role in environmental sustainability, grid stability, cost efficiency, reduced power losses, and voltage stability. Employing solar energy for EV charging systems has the following

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advantages: environmental benefits, energy independence, cost savings, and grid support. These advantages highlight the importance of EV stations charged from solar energy to promote sustainable transportation and energy practices while addressing the challenges associated with traditional grid-powered charging infrastructure.

Integrating HCPV systems, lithium-ion batteries, and EV charging stations **has many challenges.** HCPV-grid charging systems face the challenge of intermittent solar power generation. This inconsistency necessitates high-efficiency converters with wide operational bandwidths to maximize energy harvest from solar HCPV. Integrating solar-powered EV charging stations into the electrical grid is complex due to the bidirectional nature of power flows and the variable output of solar generation. This integration requires sophisticated power electronic converters (multiport converters) and control algorithms (Sri, et al., 2023). The grid must be designed in a modular fashion to accommodate the growing number of EV charging stations and solar arrays. This approach allows for scalability without significant redesign. Effective **advanced distribution management systems** are essential to monitor and control the dispersed assets of distributed solar-powered charging stations. Estimation algorithms within **advanced distribution management systems** provide real-time awareness of the grid state, ensuring stability and reliability (Aanya, Shaha, Sekhar, Saboor, & Ghosh, 2021). The strategic incorporation of energy storage systems buffers the intermittent nature of solar power, enhancing the stability and dependability of the charging infrastructure. Developing smart grid technologies capable of managing distributed generation and bidirectional energy flows is vital. These technologies ensure robust and dynamic grid management systems that can adapt to the evolving landscape of energy resources. The power output of EV charging stations must be compatible with the grid's voltage and frequency levels. Power electronic converters with grid-tie inverter functions synchronize the phase and magnitude of the grid's AC to maintain grid stability (Fachrizal & Munkhammar, 2020). Overall, while solar-powered EV charging infrastructure presents challenges in terms of integration and scalability, advancements in power electronics, energy management, and grid technologies play a crucial role in ensuring grid stability and reliability.

The adaptation of green energy as solar and wind for EV charging can contribute to reducing carbon footprints. EVs are more efficient than traditional fossil fuel-based vehicles and can utilize most of the supplied energy during their journeys (Barman, et al., 2023). Using renewable sources to charge EVs plays a significant impact in electrifying personal transport by decreasing carbon fingerprints and promoting sustainability. Also, the transportation sector can significantly reduce its carbon footprint and reliance on non-renewable resources. This aligns with the broader goal of decarbonizing the transport sector and transitioning to achieve more sustainable and environmentally friendly personal transport. Transformative changes in the mobility market, focusing on the growth of EVs and concurrent expansion of the renewable energy sector, particularly PV systems. Challenges arise in integrating intermittent energy sources like EVs, PV, and wind into the grid, requiring solutions such as adjusting transmission lines for higher power peak demands.

Syla, Rinaldi, Parra, & Patel (2024) explored the interaction among adaptable charge and structure in the case of large EVs. Their study analyzes the advantages of variable methods of EV charging. They concluded that flexible EV charging has a great

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impact on the configuration of optimal systems, with implications for capacity planning, grid reinforcement, and energy system expenses. So, careful capacity planning is essential for promoting personal transport electrification.

The contributions of the transportation sector are about 33.7% of the total emission of greenhouse gases. Electric vehicles and their charge station infrastructure could help in the reduction of these emissions by applying renewable power sources. Nishimwe & Yoon (2021) integrate PV and energy storage to attain the requirements for a fast charging station that effectively integrates with electric vehicles and presents an optimized technique for maximum gain. They showed the potential of photovoltaic and energy storage as well as the effect of different factors on system performance.

Knowledge of energy needs and times of arrival for smart charging of EVs for office parking places is investigated (Winscherman, Arias, Hoogsteen, & Hurink, 2023). The study uses measurements from an office building to analyze EV charging sessions. The analysis considers the clustering of charging sessions based on different factors. Manousakis, Karagiannopoulos, & Kanellos (2023) emphasize the need for advanced control and management techniques to control the demand for both EV charging and renewable generation, as well as the integration of storage technologies to support EV charging. They identified critical research gaps, including requirements of power systems, smart energy control systems, power system resiliency, charging infrastructure capacity, and environmental effects of solar systems. The performance and economics of wind turbines and PV for environmentally beneficial EV charge stations are explored (Li, Chan, Zhang, & Fu, 2022). A sensitivity study revealed that EVs with higher demand have the lowest charging station reliability.

Solar cells with multi-junctions are considered the most promising technique for enhancing renewable energy utilization. This is because of their superior conversion efficiency compared to traditional solar cells with single junction, and their capacity to achieve maximum energy output through concentration of solar radiation using cost-effective optical light concentrators. Reflective mirror concentrators are typically employed to concentrate radiation from large optical areas into tiny multi-junction cells. So, the density of energy is enhanced and reduces system price, which is anticipated to motivate the growth of the multi-junction solar cells market (Zaghloul, Abdelrahman, Rabbo, Emam, & Zaghloul, 2023). Triple-junction solar cells are commonly adapted in HCPV units because of their high-efficiency conversion (up to 40%) and low thermal decay, permitting a higher concentration ratio and consequently higher produced energy (Abo-Zahhad, Ookawara, Radwan, El-Shazly, & ElKady, 2018). HCPV systems offer higher conversion efficiencies and increased electricity generation per square meter of solar panels, contributing to their potential success. High efficiency, low price, and climate unpolluting are the prime benefits of these systems (Ejas, et al., 2021).

The growth rate of HCPV is attributed to factors like increased installations in utility-scale solar projects, supportive government policies, and rising demand for clean energy in emerging economies. Ali, et al. (2022) provided an extensive survey of the latest advancements in energy storage for EV charging stations. Their work highlights the questions raised by the growing electricity demand for EVs and the insufficient present-generation systems, leading to a focus on developing hybrid systems for EVs charging. They discussed future energy storage technologies as well as inexpensive and highly efficient hydrogen storage. The main conclusion of their work is that the adoption of energy storage trends in EV stations can help accelerate the transition towards sustainable transportation and consequently decrease dependence on conventional energy sources, leading to sustainable and cleaner sources of energy. Also, the inclusion of battery storage in EV-PV charging stations ensures a fixed and continuous power supply.

Gabbar, Elsayed, Siddique, Elshora, & Adeleke (2021) installed a fast-charging station for e-Buses. They integrated a hybrid storage system with a micro energy grid including a photovoltaic design to decrease the need for a fast-charging station for grid energy. The efficiency of the suggested system is analyzed to guarantee elevated fast-charging station performance for e-buses. The optimization of lithium-ion battery thermal management systems is investigated (Farulla, et al., 2023). They stated that at high temperature of passive system, the battery is not running at the optimum level. Verma, Saikia, Saikia, Rakshit, & Ugalde-Loo (2023) investigated thermal behavior of lithium-ion batteries for EV charging. Inefficient use of battery power requires an efficient battery cooling system. Energy management techniques are introduced (Gogoi, Bharatee, & Ray, 2024). They concluded that EV charging stations can have a high performance through an exact balance of system power in addition to accurate charging methods.

Prodjinonto, Godonou, & Nadjo (2022) concluded that LiFePO4 batteries have emerged as a leading technology for stationary energy storage, offering advantages such as fixed voltage values, high capacity, and cycling durability. Despite these benefits, challenges related to reduced conductivity and small lithium-ion diffusion coefficient in $LiFePO_4$ cathode elements have been identified. Extensive analysis to explore the impact of battery management systems (BMS) has been carried out (Mishra, Tripathi, Sharma, & Laxshmi, 2024) by performing a thorough comparison study of different energy storage techniques for EVs. Through detailed analysis and simulated data, the study compares key features of various kinds of batteries to reveal their distinct performance characteristics. They provided important information for choosing an appropriate storage system, taking into account factors like capacity, price of kWh, life cycles, and energy density. This data enables EV manufacturers to make the right decision about the improved performance of electric vehicles as well as their feasibility.

Using a multiport power converter configuration provides the necessary flexibility and control to efficiently manage power flow between different sources and loads in a dynamic and variable energy environment. The bidirectional capabilities of DC/DC converters and DC/AC converters allow for optimal utilization of photovoltaic, energy storage, and grid resources in the overall energy management strategy. The multiport converter has a great influence in optimizing power flow, improving efficiency, and ensuring effective utilization of renewable energy within the EV-PV fast charging infrastructure. By integrating a multiport converter, the system can dynamically allocate energy from the solar HCPV system to the EV charging station, while also directing excess energy to the battery storage unit (BSU) for storage. At maximum load times, energy stored can be utilized to supplement the energy requirements of the EV charging station or the grid at peak load when the vehicle is charged, thereby contributing to grid stability and reliability.

Acharige, et al. (2023) examined the technologies, standards, and configurations involved in the charging of EVs. The architectures of charging stations and power

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converters are covered by assessing the status of charging technologies by considering various aspects such as EV types, modes, and levels of charging and batteries utilized in charging EVs. A detailed study is performed including the design of the charging station, considering AC/DC control strategies, energy passage as well as benefits and drawbacks. The work also presents different configurations of EV power converters, outlining AC-DC and DC-DC converters with circuit topologies. Esfahani, Darwish, & Williams (2022) concluded that PV-EV charging units can be efficiently operated using multiport converters. The article discusses various operation modes of EVs using a PV charging system with a multiport converter, including PV-EV, PV and grid-EV, grid-EV, grid-BSU, PV-grid, and BSU-EV modes. Work carried out highlights the importance of high efficiency, soft switching, good isolation, and high-power density for EV charging stations and converters.

A comprehensive survey regarding PV-EV charging system methods and their performance is presented (Alrubaie, Salem, Yahya, Mohamed, & Kamarol, 2023). In addition, they offered insights into the fundamental basics of electric vehicles, batteries, and a detailed explanation of PV systems. Results indicate that PV charging connected to the grid has the potential to generate more energy. However, PV and batteries limited capacity may pose challenges to power system feasibility. Additionally, the intermittent nature of PV raises concerns about its ability to consistently generate sufficient electricity to meet consumer demand. The parameters of various converters, comprising five non-isolated converters against one flyback converter have been investigated (Dwivedi, et al., 2023). The MATLAB design of each converter is scrutinized, and output waveform is analyzed, considering resulting current, resulting voltage, and output power.

In the current research, it is proposed to integrate HCPV, electric vehicle EV, and Battery storage system (BSS) with the AC grid as a four-component system for fast charging stations at homes or workplaces. The HCPV solar module has a high-power output enough to fulfill the high-power requirements for fast charging stations. Connecting fast charging stations directly to the grid will strain grid stability, overload the peak demand, and cause voltage sag with power gaps impacting the power system. Also, BSS will be adapted to balance solar module late response of immittance, and grid at peak hours for shaving the grid load. So, the proposed system utilizes the grid as one of the available EV charging options or charging battery storage units where there is no load stress on the grid. The battery storage system will be employed to compensate for the grid at peak load hours instead of vehicle-to-grid interface.

The contributions of the present work in comparison to previous studies are as follows:

- Employing a theoretical model to examine integrated HCPV-EV system performance
- Introducing a highly efficient and smart system for charging EVs at educational building, driven by renewable energy systems (HCPV integrated with battery storage).
- Investigating the impact of weather conditions on the HCPV-EV system.
- Exploring different parameters' effects on proposed integrated system efficiency.
- Finding HCPV modules' optimum tilt angle to achieve maximum energy output.
- Calculation of the reduction in CO_2 emission resulted from adapting the integrated HCPV-EV system.

2. Operation Modes of the HCPV-Grid Charging System

HCPV-grid charging systems normally function in various modes owing to the interaction between HCPV modules, EVs, battery storage system, and grid. The operation of the charging station can be modified so that it is fulfilled by HCPV or utility or both. Achievement in the techniques of power conversion has a great impact on the spread of solar systems for charging EVs. Techniques of a converter in HCPV connected to a grid are categorized as non-integrated and integrated. In a non-integrated design, a minimum of 3 converters are utilized. The first one is a unidirectional DC-DC converter named "HCPV-interfaced converter" which is adapted for MPPT. HCPV converter energy is then linked with a second one named grid interfaced converter, which commonly functions in inversion and rectification processes. Then, a DC-DC bidirectional converter is used for charging EVs. Converters have self-control for effective charging adding power losses and system complexity. Instead, a multiport converter interfaces HCPV, grid and EVs (Figure 1). Overall integrated systems have fewer components than nonintegrated ones.

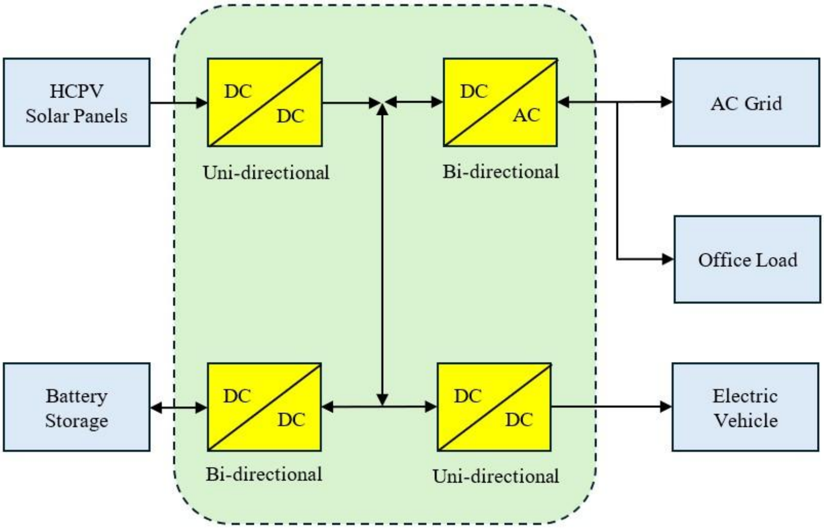

Figure 1: Electric vehicle charging using multiport converter

The different modes of HCPV-grid charging systems utilized for the present work are:

Mode 1 (HCPV-to-EV and office load): if HCPV power is enough for EV charging and office load, HCPV will manage the complete charging operation, so grid energy is not utilized in charging EV or providing office load. HCPV DC-DC converter and EV charger are employed to charge EV. At the same time, the HCPV supplies the required office load through the interfaced DC-AC office load inverter. When EV state of charge (SOC) achieves peak value, charging of EV ends, and charging of office load continues. Extra power produced by HCPV array will be directed into the battery storage

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unit (BSU) with its DC/DC bidirectional interface until completely charged. The excess energy is supplied to grid through grid DC-AC converter.

Mode2 (HCPV to battery storage): if there is no need to charge EV, all accessible HCPV power is fed to the office load and BSU through the DC-DC bidirectional interface. Thus, the need for grid energy is reduced, and energy is stored in the battery for later utilization.

Mode 3 (HCPV and battery storage to EV and office load): this mode is functioning when HCPV energy is not enough to provide EV's charging and office load and at the same time battery storage has sufficient SOC, and both office load and EV charging is supplied by power from both HCPV modules and battery storage. To maximize power from HCPV modules, an HCPV DC–DC converter with one-directional is employed. The bi-directional DC-DC converter interface battery storage as well as unidirectional AC-DC interface EV. In that case, grid stress resulting from charging EVs is reduced.

Mode 4 (HCPV and grid-to-EV and office load): when HCPV power is not sufficient for complete EV and office load charging because of lack of solar irradiation, the grid will supply the shortage. The grid converter runs at rectification mode, and EV interface unidirectional converter runs at buck process. Since HCPV production is not continuous, MPPT controls power output of HCPV and improves grid input to ensure that the needed EV and office load energy are sufficient.

Mode 5 (HCPV to grid): When the battery storage unit is completely charged and no EV or office load is required, HCPV-generated power is directed to grid via an HCPV converter and grid bidirectional DC-AC one. This process is commonly running if utility cost significantly expensive leading to money benefit for consumers.

Mode 6 (Battery storage to grid): this mode is operative when battery storage has enough SOC, and energy stored in battery s is fed to the grid in a two-step process utilizing battery storage converter at boost way and grid converter at inversion process.

Mode 7 (Battery storage to EV and office load): energy stored in battery storage from HCPV, or the grid power is used for EV and office load charging through battery storage and EV-interfaced DC-DC converters. Hence, grid helps in charging EVs from battery storage at maximum load times, during the night or when HCPV energy not adequate for supplying EVs charging load.

Mode 8 (grid to battery storage): energy is fed from grid to battery storage when grid is not overcrowded, and grid costs are small. Grid bidirectional DC-AC converter is at rectification mode. Low utility cost is used to enhance the benefits of charging station.

Mode 9 (grid-to EV and office load): EV and office load are charged only from grid alone if HCPV power is not adequate to produce energy due to poor climate conditions, at night, or if HCPV not functioning well, and battery SOC is small. The grid bi-directional converter at rectification process, transferring energy of the grid to DC. Finally, EVs-interface DC converter is adapted for controlling DC power. In this situation, the office load needed is provided directly by the grid.

3. Thermal Model

HCPV solar module is combined with lithium-ion batteries. Batteries are mounted in HCPV module back surface at a specific space from a back sheet of HCPV. The goal is to evaluate the HCPV module and battery temperatures. Two-dimensional numerical technique is introduced to study power transfer between battery and HCPV systems. At every node for the control volume, an equation of energy balance utilizing energy conservation law is used to get finite-difference formulae. In current research, a numerical technique at constant conditions is proposed employing energy balance schemes.

The assumptions made in the current technique are:

- Temperature of solar cells is consistent because of larger thermal conductivity in comparison to other layers.
- HCPV module properties are fixed.
- Back side temperature of HCPV cell (T_g) is similar to the ambient temperature (T_a).
- Surface emissivity is constant.
- View factor of heat radiation is 1.
- Each surface has the same HCPV module area.

The energy balance of the proposed system is obtained by applying the first law of thermodynamics:

$$Q_{abs} = Q_{el} + Q_{opt} + Q_{loss} \tag{1}$$

where Q_{el} is HCPV module generated energy, Q_{opt} is optical elements waste, Q_{loss} is energy lost by convection and radiation to surroundings and Q_{abs} is energy gained by solar module:

$$\mathrm{Q_{abs}} = (\mathrm{G} - \mathrm{G_r})\mathrm{A} \tag{2}$$

Where HCPV module area, A, G incident radiation on module area of unity, and G_r is radiation reflected for unit module area. HCPV produced energy (Q_{el}):

$$\mathrm{Q_e} = \mathrm{X\,G\,A_{rec}}\,\eta_{\mathrm{op}} \tag{3}$$

where X is concentration ratio of HCPV, η_{op} is optical elements efficiency and A_{rec} is the area of receiver. The efficiency of triple-junction cell (η_{el}) is expressed as (Buonomano, Calise, Dentice, & Vanoli, 2013):

$$\eta_{\mathrm{el}} = 0.2980 + 0.01420\ \ln \mathrm{X} + [0.000697\ \ln \mathrm{X} - 0.000715 +](\mathrm{T_{PV}} - 298) \tag{4}$$

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η_{el} electrical efficiency is related to the temperature of HCPV (T_{HCPV}), efficiency of reference temperature (η_{Tref}), thermal coefficient (β_{th}), and reference conditions temperature (T_{ref}):

$$\eta_{el} = \eta_{Tref} - [\beta_{th} \ (T_{PV} - \ T_{ref})] \tag{5}$$

Q_{opt} is a function of optical efficiency (η_{opt}) as:

$$Q_{opt} = Q_{abs} \ (1 - \eta_{opt}) \tag{6}$$

Q_{rad} and Q_{conv} are radiation and convection heat lost to the environment by:

$$Q_{loss} = Q_{rad} + Q_{conv} \tag{7}$$

Positioning the HCPV back surface reduces both radiative and convective heat losses. Radiative heat losses are reduced due to reflected radiation from aluminum flat plates having low emissivity. Emitted infrared from HCPV back cover is a function of temperature fourth degree. The aluminum sheet works as a heat shield and decreases the surplus warming of batteries. Furthermore, batteries restrict convective heat transfer because of air circulation via air gaps. Conductive and radiative heat exchanges decrease at the back sheet leading to higher HCPV temperatures.

Applying thermal energy balance gives:

$$Q_{condalb} + Q_{convbg} + Q_{convbb} + \ Q_{radbb} + \ + Q_{radbg} = 0 \tag{8}$$

Where $Q_{condalb}$ is conduction energy exchanged among aluminum sheet and battery, Q_{convbg} is convection energy transformed to ground from battery, Q_{convbb} is energy transformed by convection to battery from the back cover, Q_{radbb} is radiation energy transformed to battery from back cover and Q_{radbg} is radiation energy transferred to the ground from the battery.

Calculation of Q_{rad} is made simple when using surfaces having parallel plans and identical areas (A):

$$Q_{rad} = h_{rad} A \ (T_1^4 - T_2^4) \tag{9}$$

T_1 and T_2 are the temperatures of the sides. The radiative transfer factor (h_{rad}) is expressed as (Incropera, Dewitt, Bergman, & Lavine, 2006):

$$h_{rad} = \frac{\sigma}{\frac{1-\varepsilon_1}{\varepsilon_1}+\frac{1}{F12}+\frac{1-\varepsilon_2}{\varepsilon_2}} \quad (10)$$

where ε_1 and ε_2 are the two surfaces emissivity coefficients, F_{12} is view factor between the two surfaces and σ Stefan-Boltzmann constant. Therefore, (h_{rad}) is reduced to:

$$h_{rad} = \frac{\sigma}{\frac{1-\varepsilon_1}{\varepsilon_1}+1+\frac{1-\varepsilon_2}{\varepsilon_2}} \quad (11)$$

Using equation (8) and equation (10) to evaluate energy exchanged by sky to front side of HCPV, back sheet-ground, radiation, battery to ground, and back sheet to aluminum plate.

Heat transfer radiative coefficient (h_{rad}) to ambient (Incropera, Dewitt, Bergman, & Lavine, 2006):

$$h_{rad} = \varepsilon\,\sigma\,(T_{sky}^2 + T_f^2)(T_{sky} + T_f) \quad (12)$$

Where the average fluid temperature is T_f, the temperature of outside sky is T_{sky} is needed to calculate radiative transfer as a function of ambient temperature, T_{amb}:

$$T_{sky} = 0.0552\, T_{amb}^{1.5} \quad (13)$$

Heat transfer by convection (Q_{conv}) is:

$$Q_{conv} = h_{conv} A\, \Delta T \quad (14)$$

Where A is convective heat transfer area, ΔT is surface temperature change. Coefficient of convection (h_{conv}) is evaluated utilizing the shape of HCPV module, wind speed, and air temperature. Q_{conv} is also expressed as:

$$h_{conv} = \frac{Nu\, k}{L} \quad (15)$$

Where k is fluid thermal conductivity at reference temperature ($\frac{W}{mK}$), Nu is Nusselt number and L is the area of HCPV module divided by a perimeter.

Nusselt number (Nu_f) for enforced convection is given by (Duffie & Beckman, 2013):

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$$Nu_f = 0.664 Re^{0.5} Pr^{1/3}$$
(16)

Correlations suggested by Adrian (2013) are used for natural convection to determine Nusselt number (Nu_n):

$$Nu_n = \left(0.825 + \frac{0.387 Ra^{1/6}}{\left[1+(\frac{0.492}{Pr})^{9/16}\right]^{8/27}}\right)^2$$
(17)

To determine the temperature of HCPV accurately, energy transferred through two flat plates is studied.

The following equation introduced by Guyer (1999) defines Ra number:

$$Ra_{planes} = \frac{g\beta(T_{av}-T_a)L^3}{\mu\alpha}\left(\frac{d}{L_1}\right)$$
(18)

4. Battery and Converter Energy Generation

Battery-produced heat ($Q_{battery}$) considers energy generation from discharging and charging processes and it is evaluated utilizing the equation:

$$Q_{battery} = \frac{1}{V_{battery}}\left(V - V_{oc} + T\frac{\partial V_{oc}}{\partial T}\right)$$
(19)

where I is charging or discharging current. V_{OC} is open circuit voltage and $\frac{\partial V_{oc}}{\partial T}$ The entropy factor is provided by battery manufacturer. Converters produced heat:

$$Q_{converter} = \frac{P_{in}}{V_{converter}}(1 - \eta_{converter}))$$
(20)

where ($\eta_{converter}$) is converter instantaneous efficiency and $V_{converter}$ converter volume.

Thermal energy in triple-junction is transferred through conduction and a part of heat is dissipated to surroundings by forced and natural convective heat. Thermodynamics second law is employed to accurately determine system efficiency. Energy change between total and unattained heat (exergy) is equivalent to transformed work.

The state of health (SOH) of battery expresses degeneration at a certain time. So, OH is the real capacity (C_{actual}) divided by operated capacity (C_{rated}):

$$\mathrm{SOH} = \frac{C_{actual}}{C_{rated}} \quad (21)$$

Testing of batteries for a long time should be carried out to obtain accurate SOH, so in the present study, a data sheet provided by the battery manufacturer is used to determine capacities. SOH is a function of the number of running cycles and battery operating temperature.

5. Numerical Model of HCPV module

A numerical model is introduced to examine HCPV modules combined with lithium-ion batteries. Various models have been presented previously to calculate IV features of multi-junction PV modules as single diode approach, two diodes circuit, and lumped diode technique. A numerical model representing HCPV performance must precisely predict module output change with concentration ratio, solar radiation, and ambient temperature. The single-diode approach is adapted to explain triple-junction PV characteristics at various concentration ratios, temperature, and solar radiation. The model of one diode provides dependable, accurate results and needs less factors meaning less computational efforts compared to the corresponding two-diodes model at which each sub-cell factors must be calculated.

Solar cell model comprises a current source related to irradiation linked to a parallel diode. Current technique can be employed for HCPV modules to consider voltage differences resulting from series resistance (R_s).

The technique of a triple-junction cell comprises 3 series junctions. I-V equation for each joint considering shunt resistance (R_{sh}):

$$I_i = I_{sc,i} - I_{o,i}\left[e^{\frac{q(V_i + I_i R_{s,i})}{n_i k_B T}} - 1\right] - \frac{V_i + I_i R_{s,i}}{R_{sh,i}} \quad (22)$$

Every subcell indicated employing 5 parameters: $R_{s,\,i}$ series resistances, shunt resistance $R_{sh,i}$, diode ideality factor, short circuit current (I_{sc}), and saturation current ($I_{o,\,i}$). Stefan-Boltzmann constant k_B, load current $I_{i,}$ and charge of electron q. Shockley diode rule indicates that n should be equal to one, however, n greater than 1 is more suitable to represent a deficit in the manufacturing process. The important parameter to achieve higher performance of HCPV is series resistance. V_{oc} is evaluated by putting I equal to zero in equation (22). The last expression in equation (22) causes implicit and nonlinearity which necessitates massive evaluations. So, existent techniques typically do not consider it presuming that R_{sh} is infinite. The mentioned presumption has a massive impact on prediction precision. So, the present study includes R_{sh}. Equation (22) can be varied from implicit to explicit form using Lambert W-function (Jain & Kapoor, 2004).

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The authors have previously studied the numerical electrical model of the HCPV module, focusing on how high incident radiation and temperature impact its performance in hot climates like Kuwait. The model accounts for variations in the junction alloy composition between cells, affecting the junction band gap. The single diode equivalent circuit model was developed to examine multi-junction cells' performance under Kuwait's weather conditions, considering temperature and concentration ratio effects. It also included the impact of material composition, allowing for more flexibility in handling different cells with the same model. Spectral variations were analyzed using spectral simulation programs, and the shunt resistance of the diode, often neglected in other models, was considered in this numerical model.

The model's accuracy and reliability were validated by comparing its predictions with measured data, showing good agreement. It was tested across a wide range of cell temperatures and irradiance concentrations, considering band gap dependence on alloy composition, cell temperature, and shunt resistance. An investigation into the effect of atmospheric parameters on HCPV modules' performance was also conducted. The results concluded that the single diode model is suitable for practical applications, as it performed well with a total root mean square error of less than 2% compared to experimental data. However, it was noted that there are limitations to using simulated data versus real-world testing, particularly under varied environmental conditions, given Kuwait's high annual solar radiation (Kandil, Kadad, Ghoneim, & Altawash, 2022).

6. Results and Discussions

Kuwait weather parameters are recorded utilizing a weather station setup at the College of Technological Studies, Kuwait. Values monitored are surroundings temperature, hourly global radiation, and speed of wind. TRNSYS (Klein, et al., 2023) simulation program is adapted to obtain tilted radiation from available horizontal radiation. The data are provided to the developed numerical model to evaluate HCPV modules' generated energy as well as the performance of the battery. In this work, the performance of a vehicle charging station utilizing HCPV integrated with lithium-ion batteries has been investigated over an entire year in Kuwait climate. The accuracy of the present developed HCPV integrated model is validated through comparison with corresponding published data. Kuwait monitored weather data containing hourly solar radiation and hourly temperature data are adapted to evaluate proposed system performance. HCPV utilizes tiny multi-junction solar cells that double the efficiency of conventional solar cells. The efficiency of multijunction solar cells has greatly improved and cell efficiencies over 40% are already available. To efficiently absorb and convert solar energy with a broad range of wavelengths, a three-multijunction of GaInP/GaInAs/Ge is utilized. Generated HCPV energy is calculated at different modules' tilt angles. The optimum tilt angle to achieve maximum energy output in Kuwait's climate was found to be equal to 24° (Kuwait latitude-5°).

The HCPV cell area (A_{cell}) is 1×10^{-4} m^2, the HCPV module area (A_{mod}), is 1.4 m^2, and the module is composed of twenty cells with concentration ratio X=700. Reflective area (A_{mod}) of module is (System Advisor Model, Version 2023.12.17, 2023):

$$A_{mod} = X \times A_{cell} \times N_{cell} \tag{23}$$

where A_{cell} is the cell area and N_{cell} is the number of cells.

Module maximum power (P_{max}) is related to many factors such as reference irradiance, A_{mod}, reference cell efficiency (η_{cell}), etc. Module efficiency (η_{mod}) is a function of (η_{cell}) and other factors (System Advisor Model, Version 2023.12.17, 2023):

$$\eta_{mod} = \eta_{cell} \times \text{alignment factor loss} \times (1 - \text{wind loss factor} \times 4) \times \text{optical error factor} \times \text{air mass modifier} \tag{24}$$

For AM equals 1.5, a modifier of air mass is determined as [29]:

$$AM = a_0 + (a_1 \times 1.5) + (a_2 \times 2.25) + (a_3 \times 5.0625) + (a_4 \times 7.59375) \tag{25}$$

Where coefficients of a_0, a_1, a_2, a_3 and a_4 are \ 0.935, 0.06557, -0.017012, 0.0015426, and -4.57×10^{-5} (System Advisor Model, Version 2023.12.17, 2023).

The numerical model adapted for the present work utilizes linear interpolation to calculate η_{cell} for normal conditions.

In the HCPV system, an adaptation of dual axis tracker is very important, it provides HCPV with an energy curve for smart utilization of energy. This is because the sun tracker traces the path of the sun, so HCPV modules continuously absorb normal radiation, and instantly maximize power after sunrise. In contrast, the power given by constant HCPV modules gives the nominal rated power of the system only at noon. The decrease of feed-in tariffs generated by HCPV necessitates the utilization of storage systems. Without a storage system, the only possibility for HCPV system owners to take advantage of energy generated is to sell it back to utility. However, utility purchases energy much less in comparison to utility selling prices. So, storage is necessary to prevent this situation.

For the current proposed 12 kW_{dc} HCPV system, two sun trackers are used, modules number on the tracker is 16. Power rating of the module is 375.553 Wdc, so the proposed HCPV system capacity = 2× 16×375.553 Wdc ≅12 kWdc. The HCPV-grid system is mounted on parking lots of building CTS20 located in College of Technological Studies, Kuwait. Solar array consists of 16 HCPV modules contained in a frame of a double-axis solar tracker with a maximum tracking error of 0.25° to absorb maximum radiation. Axes have two drive options to allow rotation of modules in horizontal and vertical directions leading to maximum radiation benefit and at the same time minimizing energy losses.

Inverter power is 10.3 kW which is selected according to experimental experience (System Advisor Model, Version 2023.12.17, 2023):

$$P_{inv} = P_{HCPV}/1.17 \qquad [26]$$

So, for HCPV power of 12 kW, A 10.3 kW inverter with an inverter efficiency of 97% is utilized.

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The system requires a single battery with a nominal output of 2 kW, AC coupling, and energy of 14.45 kWh. A lithium-ion battery with a capacity of 2V,1050 Ah is employed. Different losses happen in different HCPV components which should be taken into consideration to precisely evaluate system efficiency. The present model regards various losses and determines HCPV system's overall conversion efficiency [29]:

Overall energy conversion efficiency=$\eta_{mod}\times$ tracking error× soiling loss× DC wiring loss × inverter AC to DC capacity ratio× DC module discrepancy loss ×AC wiring loss ×diode and connection loss

The annual degradation rate of HCPV system output is assumed to be about 0.5 %, i.e. annual energy reduction is 0.5 % every year in comparison to the prior year.

6.1 Building Consumption and Electric Vehicle Charging Loads

An on-grid HCPV system to charge four EVS in a building's parking lot is examined in current work and they are parked for 8 hours daily. The system's advantages incorporate grid capacity removal resulting in a large reduction in EV-charging structure expenses. The annual consumption of building appliances is 5000 kWh. Consumption of building appliances load, and EV charging are handled on a daily basis to predict charging energy needs. Also, grid energy is combined as a backup choice when HCPV energy is not able to supply the requirement of the charged station. If the battery of the charge station is completely charged, HCPV system can provide surplus energy directly to the grid. Four Kia EVs are in charging mode at the same time from the charging station, AC charging for each EV is 4.6 kW and the battery capacity of the car is 39.2 kWh.

6.2 Energy Productions of HCPV Integrated Battery System

Appliances of building and charging station of EVs are treated on daily consumption. The location is an academic building (CTS 20) at the College of Technological Studies, Kuwait (longitude 47.5° and latitude 29.3°). An electric vehicle charging station is designed at the parking lots of the building. The maximum solar radiation is 191 kWh/m^2 and occurs in June when temperature reaches its maximum 39.2°C in August. The building is designed to accommodate 50 college staff utilizing the building for 5 days/week from Sunday to Thursday starting from 8 am to 4 pm. Light bulbs and personal computers are part of the broad range of electrical devices that are utilized. Figure 2 represents the utilization of HCPV generation for building load, charging of EVs, battery charging, and grid export.

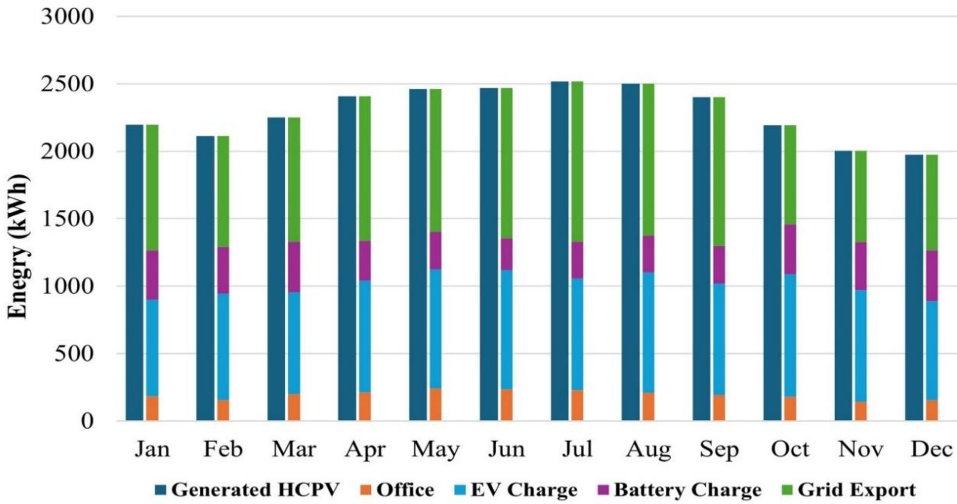

Figure 2. Use of HCPV Generation for building load, electric vehicle charging, battery charging, and grid export

Figure 2 indicates that July month production of HCPV energy (2519 kWh) is the highest and December month production of HCPV energy is the lowest (1976 kWh). The annual energy generated from HCPV is 27498 kWh, 9865 kWh is utilized for electric vehicle charging, 3835 kWh is used for battery charging, 2340 kWh is used for building appliances and the remaining energy 11458 kWh is used for grid feeding. The total energy required for EV charging is 12178 kWh. The HCPV energy utilized for EV charging is 9865 kWh which represents 81% of the total energy needed for EV charging. The battery energy utilized for EV charging is 1095 kWh which represents about 9% of the total energy required to charge EVs. Most of the energy required for EV charging, about 90% is achieved through HCPV modules and battery system. Only about 10% (1218 kWh) is required to be exported from the grid to fully charge EVs.

Figure 3 shows the consumption of building electrical appliances covered by HCPV, battery, and grid. Annual load consumption is 5000 kWh, HCPV generated energy supplies 2340 kWh, battery supplies 2443 kWh, and grid supply 217 kWh. So, electric building appliances obtain about 47% of the energy required from HCPV, 49% of energy required from the battery, and only 4% of energy required from the grid.

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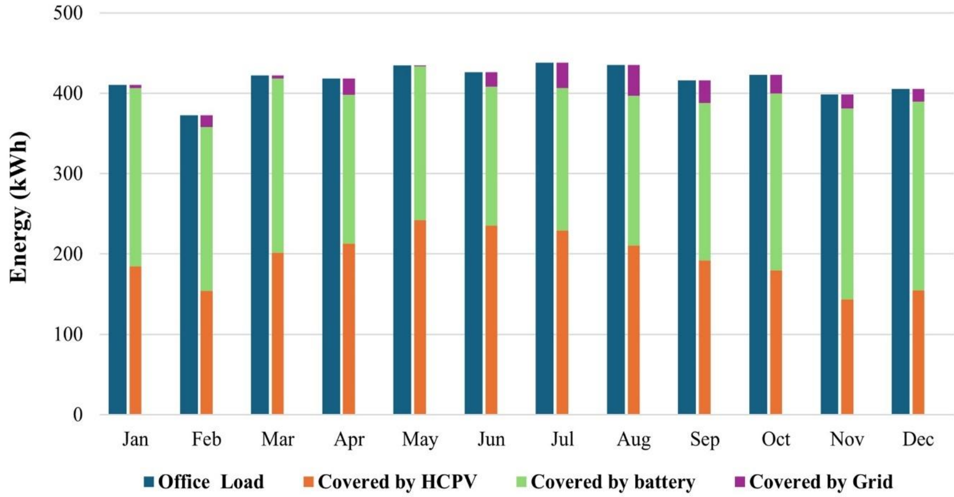

Figure 3. Electrical Appliances Consumption

Figure 4 shows total energy consumption and utilization. The annual energy consumption by EV charge (HCPV+ battery+ grid), battery charge (HCPV+ grid), and building load (HCPV+ grid+ battery) is 21190 kWh. The energy covered by HCPV generation is 16040 kWh which represents a significant part of about 76% of the total load required. The energy covered by battery generation is 3538 kWh representing about 17% of the total load required, while grid generation is 1612 kWh representing only 7% of the total load required. So, an integrated HCPV system and battery can provide 93% of the total load resulting in a big saving in electricity bill. Also, the HCPV system can feed the utility by 11458 kWh, which can be sold to the utility resulting in a potential decrease in office consumption cost.

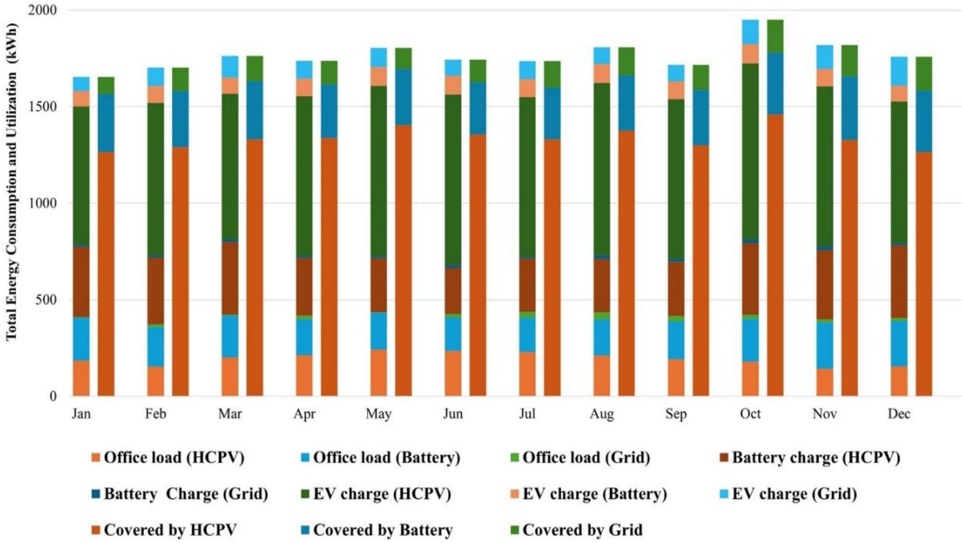

Figure 4. Total Energy Consumption and Utilization

Figure 5 represents the annual energy consumption diagram. The total energy produced from HCPV=27498 kWh, 9865 kWh is utilized to charge EVs, 3835 kWh is used for battery charging, 2340 kWh is used for building appliances, and the remaining part 11458 is fed to the grid. The total energy required to charge EVs is 12178 kWh. The portion supplied by HCPV (9865 kWh) represents 81% of the total energy required to charge EVs. Also, the HCPV system provides 3835 kWh to charge a battery of which 1095 kWh is utilized to charge EVs. The total energy supplied by both HCPV and battery to charge EVs is 10960 kWh representing about 90% of the power needed to charge EVs. Only about 10% (1218 kWh) is required to be exported from the grid to fully charge EVs. HCPV energy sold to the grid is 11458 kWh which can contribute significantly to money saving and potentially reduce the building consumption cost. HCPV-generated energy supplies the building appliances with 2340 kWh, while battery supplies 2443 kWh, so HCPV and battery satisfy 96% of the energy required for building appliances and only 4% of the energy required can be exported from the grid.

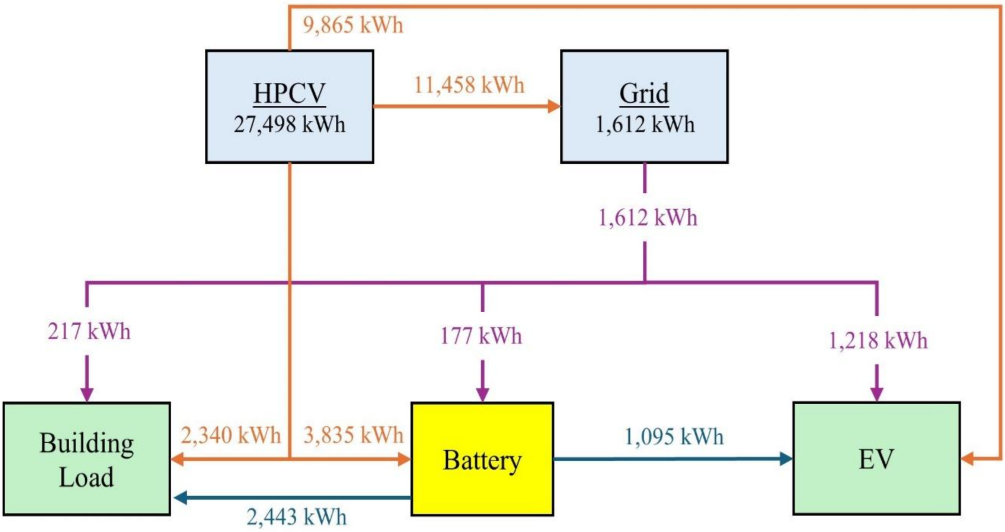

Figure 5. Annual Energy Consumption Diagram

6.3 Performance Ratio of HCPV Integrated System

Performance Ratio is a significant parameter in determining solar system efficiency. It measures losses of energy in the system compared to an optimum running system. Performance ratio judges HCPV system quality and does not depend on site position, so it is usually defined as a quality factor. Performance ratio (PR) is expressed in percentages and explains the relation between actual and theoretical HCPV system energy outputs. Performance Ratio is a useful tool for comparing HCPV system performance at

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various locations in the world. The parameters that have a significant impact on the PR value are solar radiation, HCPV module temperature, energy losses, and location of HCPV module in the shade or soiled.

Performance ratio represents the relation between actual output energy and theoretical maximum output energy that could be produced under optimal conditions, considering energy losses. The equation to determine performance ratio (PR) is:

$$\mathrm{PR} = \frac{\text{actual output energy (kWh/year)}}{\text{theoretical maximum output energy (kWh/year)}} \times 100\ \%$$

(27)

The annual actual energy output in kWh can be calculated from the developed HCPV model. Theoretical maximum energy output is the same as the calculated nominal annual HCPV energy output. The nominal output is obtained from the following formula: Annual incident radiation on HCPV module x Active area of HCPV module x HCPV module efficiency at standard test conditions (25 °C ambient temperature and 1,000 W/m² radiation).

Figure 6 shows the calculated system performance ratio at different months. As depicted in the figure, the increase in HCPV temperature outputs small efficiency. Therefore, seasonal variation has higher PR values at cold months while it has smaller values at hot months. In hot months, the performance ratio is equal to or higher than 80%, and in cold months its value is very close to 85% indicating the reliability and effectiveness of the proposed HCPV integrated system.

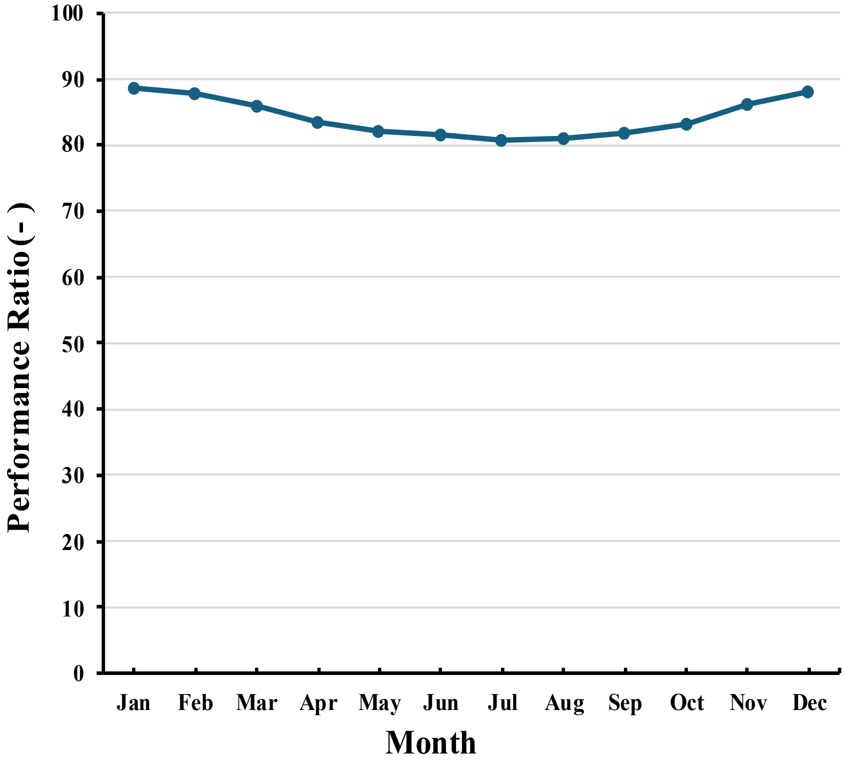

Figure 6. HCPV Integrated System Performance Ratio

6.4 State of Charge (SOC)

State of charge (SOC) of a cell represents available capacity related to the rated capacity. SOC value changes from 0% to 100%. When the cell is completely charged, SOC equals 100%, whereas a SOC of 0 % indicates that the cell is fully discharged. So, SOC is a measurement of energy that exists in the battery at a certain time. Knowledge of SOC is essential to determine the capacity that remains in the battery to carry out the necessary control procedure. So, SOC is described as the ratio of battery's remaining charge, divided by the maximum charge delivered by the battery:

$$\mathrm{SOC} = \frac{(Q_o + Q)}{Q_{max}} \times 100\% \quad (28)$$

Where Qo is battery's initial charge, Q is electricity supplied to the battery and Q_{max} is the peak charge stored in the battery.

Figure 7 demonstrates SOC calculated for lithium-ion storage battery. As depicted from the figure, battery SOC exceeds 70% through most of the year months indicating the reliability and durability of the adapted lithium-ion battery.

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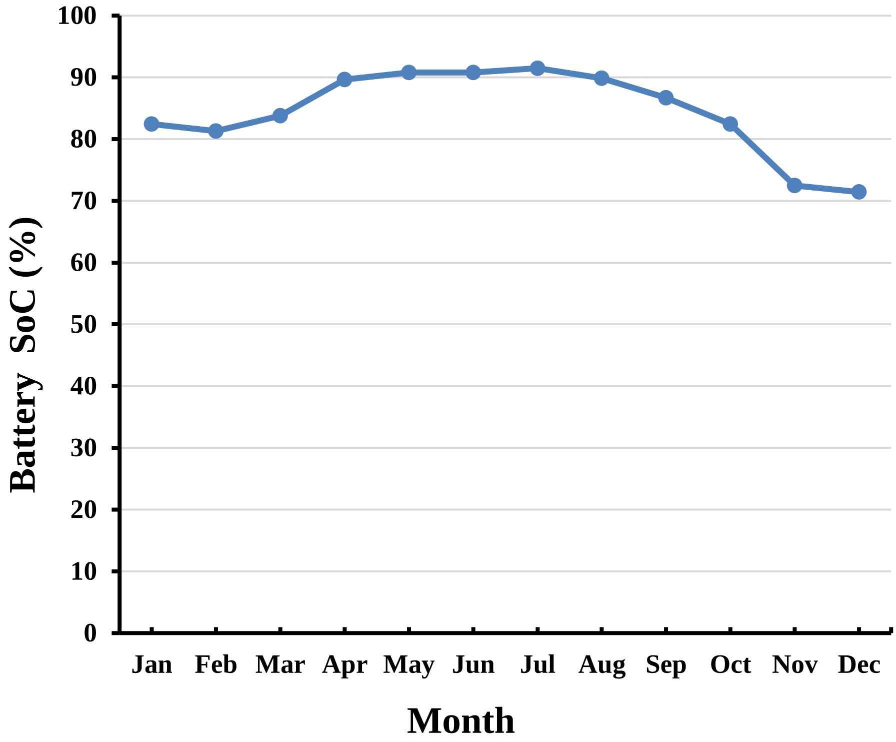

Figure 7. Battery State of Charge Variation through the Year

The state of charge (SOC) of the battery of an electric vehicle defines energy stored in battery of **an EV** at a certain time expressed in percentage. Utilizing efficient charging techniques is essential to guarantee that EV batteries will remain for longer times. Adapted methods can enhance the lifespan of battery, increase driving range and elevate efficiency. Lithium-ion batteries have higher efficiency when running in the range 20-80%. Luckily, the majority of nowadays EVs have advanced management methods to avoid overcharging through decreasing rate of charge when battery full capacity is achieved. The SOC for electric vehicle batteries throughout all year months are evaluated. It is found that electric vehicles SOC almost equals 40% through the whole year which lies in the range of optimal efficiency of EV battery (20 -80%. This means that workers in the building can use EVs charged from HCPV integrated system in their journeys all over the year.

6.5 Avoided CO_2 Emissions

Besides great money savings on utility energy bills, the advantage of HCPV system is that it also helps in keeping the environment clean by decreasing the emissions of greenhouse gases. CO_2 is the main factor impacting global warming, so the impacts of CO_2

emissions are only taken into account in current work. Fossil carbon emissions prevented by utilizing HCPV modules instead of fossil fuel energy generation options is a function of the kind of fossil fuel and the conversion process that is utilized to generate energy from traditional fuel. Employing a lower or non-CO2 emitting system instead of a higher CO_2 emitting system results in reduction of CO_2 amount to the environment. The difference in CO_2 value emitted is defined as avoided CO_2 emission. A theoretical technique is developed to calculate avoided CO_2 emission obtained by utilizing an integrated battery storage system. Conversion efficiencies and emission parameters of different fuel types are model data. The model evaluates CO_2 emission reduction for each fuel type. Usually, emissions produced in manufacturing HCPV cells are greatly lower than that produced from traditional fuel and can be neglected. Avoided CO_2 emission (E_A) is:

$$E_A = F_E \times P_g \tag{29}$$

where F_E is the system factor of emission and P_g is the energy production (kWh). A precise study of HCPV systems' avoided emissions should take into regard the emission generated in fabrication process of HCPV system elements. However, CO_2 emission in this process is significantly lower than CO_2 emission by fossil fuels and consequently will not be considered. The variation of yearly CO_2 emission avoided against tilt angle is examined. Results reveal that optimum tilt angle which maximizes the reduction in CO_2 emission is 24° (Kuwait latitude - 5°). The reduction in CO_2 emission at the ideal tilt angle is equal to 12410 kg/year.

Removing or reducing energy fed by grid results in a great decrease in the expenses of EV charging design and installation which can be advised to stakeholders and encourage them to adopt solar energy sources for EV charging on a large scale. Great benefits are a good incentive for the electrical grid to build more EV charging stations, leading to a widespread of EVs in the near future since the Kuwait solar market is now providing a fair cost for buying energy produced by solar energy systems.

Multi-port converters are useful for integrating diverse energy sources with varying power or voltage levels to achieve regulated output voltage. Diverse input levels can be merged for diverse output levels using these new converter topologies, which increase their possibilities from single input-single output setups to multi-input-multiple configurations. Different topologies of non-isolated DC-DC converters offer distinct advantages in renewable energy and hybrid vehicle applications, with multi-input converters showing promise due to reduced integration costs and enhanced reliability through loss reduction of soft switching circuits.

Multi-port converters are used to integrate different input sources to enhance the efficiency of the system, which is low-cost by sharing components and reducing power conversion stages by reducing component counts, making the design compact with low volume; such multi-port converters could be very useful in power management in photovoltaic power generation systems. The proposed converter has the capability of combining several energy sources. It is also possible to flexibly distribute the load power among different power sources. This converter maximizes solar panel power due to its buck-boost characteristic (Aravind, Chokkalingam, Verma, Aruchamy, & Michet-Popa, 2024). In this work, a non-isolated multiport converter, such as buck, boost, and buck-boost converters, is adapted since they have the advantage of being compact, more

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efficient, and with higher power density than isolated converters. The proposed converter has three different paths of power flow, one is the main voltage source (HCPV Panel) that delivers power to the system (mainly EV charging station), the Second is the battery that supplies power to the load, and the third is the grid. As a result of the proposed Multiport Converter, nine different modes have been developed as discussed. This leads to the input power source (HCPV) BSS (Battery Storage System) and the grid being able to transfer power independently to the load (EV charge station) by taking advantage of the three distinct power flow paths. Power can also be transferred from the three sources (HCPV) and/or the ESS and/or the grid to the load simultaneously, as well as the power to the load while simultaneously charging the BSS (Battery Storage System) or feeding the grid from the input power source (HCPV).

Leutz, (2022) analyzed **in** detail the environmental performance results of innovative high-concentration photovoltaic (HCPV) technologies. The study thoroughly examines and compares the environmental impacts of HCPV with those of electricity generated from oil and coal. Using the Life Cycle Assessment (LCA) method, it is demonstrated that HCPV has a carbon footprint ranging from 16.4 to 18.4 grams of CO_2 equivalent per kilowatt-hour (g CO_2-eq/kWh). Comparisons across 16 impact categories, including primary energy demand and particle emissions, reveal that the environmental footprint of HCPV is generally 50 to 100 times lower than that of fossil fuels. Furthermore, HCPV's footprint is three times lower than crystalline photovoltaic solutions and is similar to the environmental performance of wind and hydropower. In contrast, solar energy technologies, such as PV, CPV, or hybrid PV/CPV systems, typically emit between 10 to 100 g CO_2 eq/kWh. The carbon footprints of individual systems are approximately 40 g CO_2eq/kWh for flat-plate PV and 20 g CO_2eq/kWh for CPV. This suggests that while hybrid systems have a higher footprint compared to standalone technologies, they still have significantly lower emissions than fossil fuel-based energy generation.

A new framework to evaluate the life cycle environmental impacts, specifically focusing on primary energy use and greenhouse gas (GHG) emissions, of lithium-ion battery (LIB) production and recycling is introduced (Jorge A. Llamas-Orozco, et al., 2023). The framework provides spatial and temporal details to determine where in the global supply chain GHG emissions occur and predicts how these emissions will change over time (from 2020 to 2050) due to the expected adoption of various battery chemistries and the decarbonization of the electricity sector. Life cycle inventories for LIB materials and manufacturing processes are combined with location-specific emission data for energy and material inputs to assess the global GHG emission impacts of battery production. The study also includes a forward-looking analysis to project future GHG emission trends to 2050, considering the mix of LIB chemistries and the evolution of energy systems. Recovered materials from used batteries are reintegrated into the battery supply chain through closed-loop recycling. It was shown that the system boundary encompasses all battery production stages and their impacts, from raw material extraction (cradle) to the assembly of the finished battery pack (gate). Two environmental impact categories are examined in this life cycle assessment study: primary energy demand, which includes both fossil and renewable energy use in production, and GHG emissions (CO_2, CH_4, and N_2O), calculated based on 100-year global warming potentials, expressed in kilograms of CO_2 equivalent (kgCO_2eq).

7. Conclusions

In the current work, HCPV system is integrated with an electric vehicle, battery storge system, and AC grid as a four-component system for fast charging stations at a building located in Kuwait. A lithium-ion battery storage system is adapted to control the slow response of solar module immittance, and grid at peak hours for shaving the grid load. The HCPV energy production is employed to charge eight EVs, battery system charging, supply the required load for office building appliances, and feed energy to the grid. Present results let us conclude the following:

- HCPV energy utilized for EV charging represents 81% of the total energy needed for EV charging. The battery energy utilized for EV charging represents about 9% of the total energy required to charge EVs.
- Most of the energy required for EV charging is about 90% achieved through the utilization of HCPV modules and battery system. Only about 10% (1218 kWh) is required to be exported from the grid to fully charge EVs.
- Annual building load consumption is 5000 kWh, HCPV generated energy supplies 2340 kWh, battery supplies 2443 kWh, and grid supplies 217 kWh. Electric appliances obtain about 47% of energy required from HCPV, 49 % of energy required from a battery, and only 4% of energy required from the grid.
- Integrated HCPV system and battery can provide 93% of the total load resulting in big savings in electricity bills. Also, the HCPV system can feed the utility by 11458 kWh, which can be sold to the utility resulting in a potential decrease in office consumption cost.
- The total energy supplied by both HCPV and battery to charge EVs is 10960 kWh representing about 90% of the power needed to charge EVs (12178 kWh).
- Only about 10% (1218 kWh) of energy required to charge EVs is exported from the grid to fully charge EVs.
- In all months, the performance ratio is higher than 80%, and in some months its value is very close to 85%, indicating the reliability and effectiveness of the proposed HCPV integrated system.
- Battery SOC exceeds 70% throughout the year indicating the reliability and durability of the adapted lithium-ion battery.
- Electric vehicles SOC almost equals 40% through the whole year which lies in the range of most efficient working EV batteries (20 -80%).
- Workers in the building can use EV charged from HCPV integrated system in their journeys throughout the year.
- Predicted CO_2 emissions avoided because of utilizing an integrated HCPV system at an optimum tilt angle is 12410 kg/year resulting in significant environmental enhancement.

The conclusion suggests the reliability of the system, but future research could investigate its scalability for larger EV fleets or different geographic locations, specifically on adapting the system for diverse climates and load demands. Electric vehicle (EV) fleets offer significant long-term savings on maintenance and fuel costs compared to traditional

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fossil fuel-powered fleets. They also help decrease business emissions and improve environmental sustainability. EV fleets consist of zero-emission vehicles that do not produce harmful carbon emissions, contributing to net-zero goals. The rapid adoption of EVs necessitates the development of advanced EV charging infrastructure. Coordinating EV charging in community parking lots through energy management systems, and integrating solar photovoltaics, wind energy, and energy storage systems, can reduce electricity bills and carbon emissions. Effective management can enhance charging infrastructure efficiency, reduce operational costs, and improve fleet performance, providing a scalable solution for urban EV transportation.

It is worth mentioning that the following policy, financial, and technical measures are required to encourage widespread adoption of HCPV-integrated EV charging systems:

- Policy Measures:
  - Government Support for Infrastructure: Governments should provide direct investment to install publicly accessible chargers and offer incentives for EV owners to install charging points at home.
  - Building Code Requirements: New construction or substantial remodels should be required to include charging points in apartment blocks and retail establishments.
  - Integration and Decarbonization: Policies should focus on integrating EVs into power systems, decarbonizing electricity generation, and deploying recharging infrastructure.
  - Fuel Economy and Emissions Standards: Tightening fuel economy and emissions standards will support the uptake of EVs.
  - Broaden Focus on Commercial Vehicles: Addressing the impact of light-commercial vehicles, medium- and heavy-duty trucks, and buses on energy use, air pollution, and CO_2 emissions.
- Financial Measures:
  - Subsidies and Tax Breaks: Providing subsidies and tax breaks for purchasing environmentally friendly vehicles (electric, hybrid, etc.) and developing charging infrastructure.
  - Support for Emerging Economies: Leveraging lessons from advanced economies to support EV production and uptake in emerging economies.
- Technical Measures:
  - Advanced Charging Infrastructure: Developing efficient EV charging infrastructure, particularly in community parking lots.
  - Energy Storage Systems: Integrating energy storage systems, renewable energy sources, and building consumers to reduce peak load and electricity costs.
  - Innovative Converter Topologies: Advancing semiconductor technology and power electronic converters for efficient energy management.
  - Sustainable Battery Manufacturing: Focusing on the production of sustainable batteries with improved performance and lower environmental impact.

The previously mentioned measures collectively aim to overcome the barriers to the widespread adoption of HCPV-integrated EV charging systems by providing policy support, financial incentives, and technical advancements, ultimately contributing to environmental sustainability and efficient energy use.

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