Feasibility analysis of solar-powered electric vehicle charging stations considering peak demand periods and renewable energy potential

Musa TERKES[1], Alpaslan DEMIRCI [2]

[1]E-mail: musa.terkes@yildiz.edu.tr; [2]E-mail: ademirci@yildiz.edu.tr;
Yildiz Technical University, Faculty of Electric-Electronics, Department of Electrical Engineering, Istanbul / Türkiye.

Abstract
Photovoltaic panel arrays (PV) to be integrated into electric vehicle charging stations (EVCS) for clean transportation goals can increase hybrid power system (HPS) potentials, especially in countries with lower energy purchase prices. In this study, the optimum HPSs with minimum cost considering PV capacity and solar radiation for morning, midday and night peak demand profiles are comprehensively analyzed from technical, economic and environmental perspectives. Moreover, possible PV capacity and solar radiation threshold points are determined depending on the power quality issues at critical bus nodes by considering self-consumption. The results show that increases in solar radiation and PV capacity can reduce the payback period by up to 2.73 years and increase HPS opportunities by up to 31.1%. Power quality issues cannot be eliminated due to lower SCR for PV capacity of 800 kW and above and solar radiation of 5.5 kWh/m^2/day and above, except for midday peaks.
Keywords: Electric vehicle, electric vehicle charging station, peak demand period, hybrid power systems, optimization.

INTRODUCTION

Countries are moving towards carbon-neutral policies as global temperatures reach alarming levels. Electric vehicles (EVs) in transportation and renewable technologies in energy are growing in popularity. Although a growing EV population can guarantee clean transportation, careful planning is needed depending on charging demands. Can renewable energy technologies on their own address the growing demand for electric vehicle charging? Renewables lead to intermittent energy generation profiles by their nature, reducing energy supply reliability margins. In addition, the excess energy generated by high renewable capacities needs to be curtailed. The integration of lithium-based battery energy storage systems (ESS) with superior performance compared to their peers is critical to matching supply and demand and widening prosumers' profiles. Related hybrid power systems (HPS) can obtain unit electricity prices 74.7% cheaper than energy tariffs (Karmaker, Hossain, Pota, Onen, & Jung, 2023). HPS can reduce EV charging demands by up to 18% in parking lots with high charging unit installation capacity (Deshmukh & Pearce, 2021). Revenues from selling electricity to the grid could be increased by 43% (Singh & Kumar, 2023), and carbon emissions reduced by 55.8% (Jianwei et al., 2022). Cost-effective system designs with a high share of renewable energy generation can promise a reliable sustainable action program.

The design and feasibility of HPSs, closely linked to the operating environment and climate potential, must be managed appropriately for feasible sustainable city and development plans. Considering

climatic conditions as an example, a possible 0.2 m/s increase in wind speed and a 1 kWh/m^2/day increase in solar radiation could raise the renewable rate (RF) by 1.2% and 6.6% (Nishanthy, Charles Raja, Praveen, Jeslin Drusila Nesamalar, & Venkatesh, 2022). Higher radiation and wind speed potentials could reduce unit energy and total costs, and increase electricity sales revenues by up to 6% via the coordination of optimized energy sales prices (dos Santos et al., 2021). It can also reduce the cost of energy, even in regions with different economies (Merrington, Khezri, & Mahmoudi, 2023). However, higher radiation (>7.6 kWh/m^2/day) will not affect the overall system performance (AlHammadi et al., 2022). Another perspective is that the variability in photovoltaic panel array (PV) capacities needs to be well managed. A 33.3% increase in PV capacity raises RF by up to 9.2% (Himabindu, Hampannavar, Deepa, & Swapna, 2021). Managing PV based on EV charging demand provides a reduction of under-voltage problems, transformer overloads, and losses, and eliminates the possibility of power outages (Bartolucci et al., 2023). It is also estimated that 1-1.5 kWp PV arrays can maximize the performance of individual EV charging units (Sierra, Gercek, Geurs, & Reinders, 2020).

On the other hand, EV charging demand variability for many reasons is the second factor that can affect HPS design. Higher EV charging uncertainties increase renewable energy waste by up to 36.1% (J. Li, He, Yang, Ma, & Wei, 2022), raise energy loss by up to 3% (Alphonse, Raj, & Arumugam, 2022), reduce COE by 2.7% (C. Li, Shan, Zhang, Zhang, & Fu, 2022) and cause extra investments (Leone, Longo, Fernandez-Ramirez, & Garcia-Trivino, 2022). Feasibility is even more difficult during daily (Long et al., 2021) and seasonal time peaks (Khan, Sudhakar, Yusof, Azmi, & Ali, 2023). Moreover, underestimating the uncertainties in EV charging can cause investors to make mistakes in their business plans by up to 10% (Emrani-rahaghi, Hashemi-dezaki, & Hasankhani, 2021). The lack of a single EV dispatch scale encourages collaborative planning of PV and EV synergies in the electricity sector. Even a small synergy can reduce peak energy demands and extra costs on the electricity bill by up to 74.2% (Domínguez-Navarro, Dufo-López, Yusta-Loyo, Artal-Sevil, & Bernal-Agustín, 2019). The reduction in load fluctuation rate via PV can effectively reduce operating costs based on the balance of purchased electricity and sold electricity (Jiao & Månsson, 2023). PV penetration over 50% is estimated to compensate for variable EV charging load (Good, Shepero, Munkhammar, & Boström, 2019), and up to 45% variability in EV demand and up to 40% variability in energy price could increase revenues by up to 18.3% (Ahmad, Alam, Shariff, & Krishnamurthy, 2019). EV charging variability can be reduced by up to 30% by selling the residual electrical energy that cannot be stored in ESSs (Sadeghi, Hesami Naghshbandy, & Bahramara, 2020), and appropriate PV-ESS integration can save up to 50% (Leone, Peretti, Paris, & Longo, 2022).

It can be said that different peak demand periods of electric vehicle charging stations (EVCS) have not been evaluated except for the researchers in (Long et al., 2021). Moreover, the possible variations in radiation and PV capacity have not been evaluated in detail for prosumers on technical, economic, and environmental aspects. This study conducts a detailed feasibility analysis for these load profiles depending on possible solar radiation and PV capacity variations. In addition, optimum threshold points are determined for demand profiles with different peak times, considering the power quality impacts on self-consumption potentials. Also, the possible HPS outputs in the morning, midday, and night peak demand profiles are comparatively evaluated. The main contributions of this study are as follows:

- Potential increases in solar radiation could shorten the payback period by up to 5.4 years.

- Potential increases in PV capacity could raise the share of renewable energy by up to 61.7% and reduce unit energy costs by up to 83.9%.
- A hybrid increase in PV capacity and solar radiation could raise HPS opportunities for investors by up to 31.1%.
- PV capacity of 800 kW and above and solar radiation of 5.5 kWh/m^2/day and above cause power quality problems except for midday peaks.
- It is recommended that investors consider power quality issues at the distribution busbar for maximum HPS capacities.

This paper is organized as follows. Section 1 introduces the literature review and contributions. Section 2 describes the methodology, mathematical modeling, and assumptions. Section 3 compares and evaluates the optimization ve feasibility results. Finally, Section 4 concludes and provides recommendations for future work.

MATERIAL AND METHODOLOGY

PV and grid integration has been considered for potential EVCS installations in Antalya. In line with climate targets, load demand is primarily met by PV. If the demand cannot be met, energy is purchased from the grid. To determine the optimal HPSs, the primary objective in this study is net present cost (NPC) and CO_2 minimization, and the secondary objective is low COE values. Therefore, ESSs are not used in optimal HPSs due to high ESS investment costs and lower energy prices in Türkiye.

Considering several parameters such as radiation, temperature, and depreciation factor, the PV output power is calculated by Equation (1). The cell temperature is given in Equation (2) and the PV efficiency is indicated in Equation (3).

$$P_{PV}(t) = Y_{PV}.f_{PV}.\left(\frac{G_T(t)}{G_{T,STC}}\right).\left[1+\alpha_P.\left(T_C(t)-T_{C,STC}\right)\right] \quad (1)$$

$$T_C(t) = T_a(t) + \frac{G_T(t)}{800}.(T_{NOCT}-20) \quad (2)$$

$$\eta_{mp,STC} = \frac{Y_{PV}}{A_{PV}\,.\,G_{T,STC}} \quad (3)$$

Converters operating in inverter and rectifier modes are used for energy conversion in AC and DC busbars. Inverter output power is calculated in Equation (4), rectifier output power in Equation (5), and converter efficiency in Equation (6).

$$P_{inv}(t) = \eta_{inv}\,.P_{DC}(t) \quad (4)$$

$$P_{rec}(t) = \eta_{rec}\,.P_{AC}(t) \quad (5)$$

$$\eta_{DC/AC} = \frac{P_{PV}}{P_{Converter}} \quad (6)$$

The capital, replacement, and operation and maintenance costs in Table 1 are used for the optimum HPS capacities to be evaluated in the feasibility analyses.

Table 1. *HPS Cost*

	PV	Converter
Capital Cost	1000 $/kW	300 $/kW
Replacement Cost	900 $/kW	300 $/kW
O&M Cost	10 $/kW/year	0.02 $/kW/year

EVCS peak demand periods can vary depending on the consumption in the operational areas to be installed. Mathematical modeling such as EV charging time, EV charging power, and total demand are needed to create an EV charging demand profile. EV charging time is calculated in Equation (7), EV charging power in Equation (8), and total charging demand in Equation (9).

$$\tau_{e,j} = \left[st_{e,j} + \frac{ER_e}{P_{EV(max)}} \right] \tag{7}$$

$$P_{EV(j)}(t) = \begin{cases} P_{EV(max)}, & if\ t \in \tau_{e,j} \\ 0, & if\ t \notin \tau_{e,j} \end{cases} \tag{8}$$

$$P_{EV}^{t} = \sum_{j=1}^{N_{EV}} P_{EV(j)}(t) \tag{9}$$

PV to load ratios and energy demands for morning, midday, and night peak demands are summarized in Table 2.

Table 2. *EVCS demand profiles*

	Peak Time Range (hour)	PV to Load Ratio (%)	Energy Demand (kWh/day)
Morning	07.00-09.00	38	2479
Midday	11.00-13.00	48	2505
Night	17.00-19.00	32	2496

Minimization of potential EVCS costs is the third critical issue after CO_2, NPC, and COE objectives. In this context, the cumulative cost minimization objective of the investment and operation costs of EV charging stations is determined by Equation (10). The upper and lower limits of the possible number of EVs that can visit the charging station are given by Equation (11).

$$min_{C_{EVCS}} = \sum_{i=1}^{N_{CS}} \left(C_{cap,EV}^{i} + C_{op,EV}^{i} \right) \tag{10}$$

$$0 < N_{CS} \leq N_{CS}^{max} \tag{11}$$

Hybrid Optimization of Multiple Energy Resources (HOMER) was used for optimization and the HPS model explaining the scope of the study is shown in Figure 1. Considering the EVCS installation area constraints, possible PV capacities are included in the system via switches. The included PV capacities were also evaluated at solar radiation in the 2.5-6.5 kWh/m^2/day range. In the EVCS, 10 high and low charging units are considered, and the daily EV charging session is taken as 200.

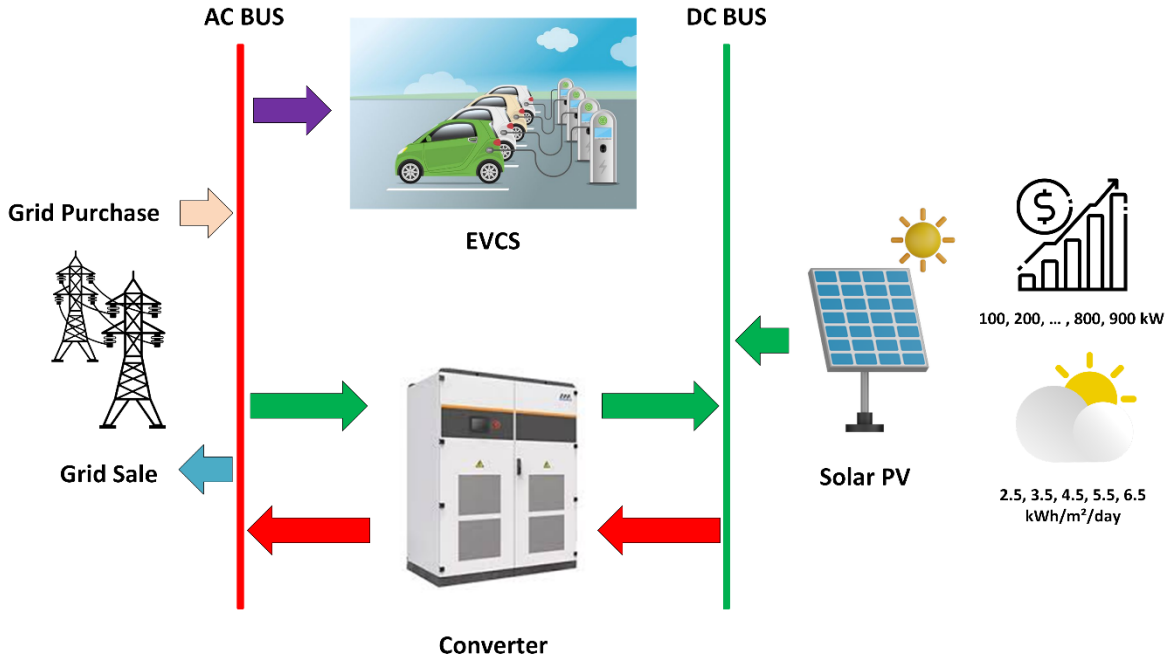


Figure 1. HPS models

Equation (12) is used to determine the NPC minimization for optimal HPSs. The capital recovery factor is calculated in Equation (13) to be used in Equation (12). The real discount rate is calculated in Equation (14).

$$NPC = \frac{C_{ann,tot}}{CRF(i,N)} \tag{12}$$

$$CRF(i,N) = \frac{i\,.\,(1+i)^n}{i\,.\,(1+i)-1} \tag{13}$$

$$i = \frac{i' - f}{1+f} \tag{14}$$

The total annual HPS cost per energy served is called COE and is calculated by Equation (15).

$$COE = \frac{C_{ann,tot}}{E_{served}} \tag{15}$$

Considering the share of conventional generation in supplied energy, the RF is determined in Equation (16).

$$RF = 1 - \frac{E_{nonren}}{E_{served}} \tag{16}$$

The ratio of PV energy transferred directly to demand to total PV energy production is called the self-consumption ratio (SCR) and is calculated by Equation (17). The share of PV energy transferred directly from demand to total demand is called the self-supply ratio (SCR) and is calculated by Equation (18).

$$SCR = \frac{\sum E_{PV}^{cons}}{\sum E_{PV}^{gen}} \quad (17)$$

$$SSR = \frac{\sum E_{PV}^{cons}}{\sum E_{load}} \quad (18)$$

OPTIMIZATION RESULTS

The variation in COE, SCR, and SSR for the morning, midday, and night peaks depending on solar horizontal radiation and PV capacities is evaluated in Figure 2, while the variation in RF, discounted payback period (DP) and DC/AC converter efficiency is evaluated in Figure 3. COE generally decreases up to 12% for lower PV capacities with increasing radiation. The self-consumption outputs show close results (<5%) at different peaks, while the effect of radiation is higher at night peaks. A possible increase in radiation could reduce the SCR by up to 8% during the night peak, and increase the SSR and RF by up to 12.5%. The DP can be shortened by up to 5.4 years and DC/AC converter efficiency reduced by up to 61%, with benefits dominating the cost-benefit relationship. Although most decision criteria give close results, the night peak is more attractive due to the short payback period.

On the other hand, higher PV capacities at lower radiation can increase the RF by up to 48.9% and the SSR by up to 42.2%. Moreover, a decrease of up to 36.7% in COE increases investment attractiveness, while the SCR decreases by up to 48.3%. The increase in capacity installations will raise investment costs and extend the amortization period up to 2.57 years. A possible rise in radiation would further increase the RF by up to 12.8% and the SSR by up to 1.65%. It would also further reduce SCR by up to 18.4% and COE by up to 47.2%. Moreover, the payback period disadvantage of 2.57 years increases by 0.85 years to 3.42 years. Under lower solar radiation, night peaks generally have the highest payback period, while midday peaks have the highest RF and SSR potential. The worst conditions in terms of the payback period happen during morning peaks at higher radiations, while midday peaks perform similarly at lower radiations.

A possible increase in PV capacity combined with radiation could raise the reduction in COE by up to 66.2%. The possible similar results in self-consumption outputs in radiation differ if the increase in PV capacity is included. In general, SCR decreases between 25.1-37.25%, SSR increases between 12-14.1% and RF rises around 25%. SSR and RF results are close to each other, although the highest SCR decrease and SSR increase are observed during the midday peak and RF increase during the morning peak. Assuming a payback period of 3.72 to 4.71 years after increased PV capacities, investors' interest in HPS increases by 31.1%. The potential DC/AC converter efficiency lost due to radiation can be recovered by 6.7% with increased PV capacity. The high advantage that midday peak HPSs can offer compared to other peak times shortens the DP by up to 1 year.

SCR values of 30% and below are stated in (Demirci, Ozturk, Tercan, & Nakir, 2022) to cause overvoltage problems. Although values of 55% and above increase power losses, values up to 70% can reduce the maximum voltage peaks on critical buses by up to 18%.SCR values of 70% and above should be managed appropriately depending on the busbars to be connected.

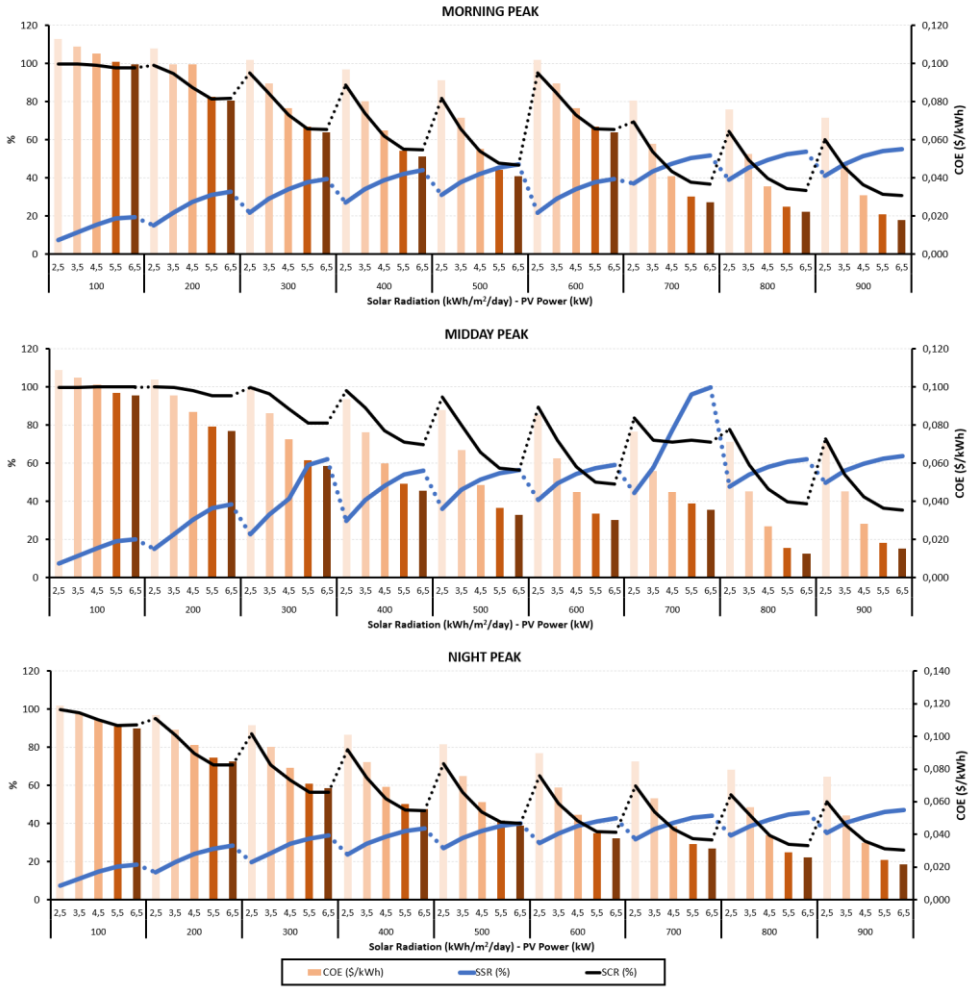


Figure 2. Effects of solar radiation and PV capacities on COE, SSR, and SCR

In this study, the SCR for morning peaks above 800 kW PV capacity, and 5.5 kWh/m^2/day solar radiation is not below 30% but very close to the limit. For the night peaks, 800 kW PV capacity and 4.5 kWh/m^2/day radiation, and 700 kW PV capacity and 5.5 and 6.5 kWh/m^2/day radiation are close to the limits. Even worse, for PV capacities of 800 kW and above and solar radiation of 5.5 kWh/m^2/day and above, SCR drops below the 30% limit during the night peak. Due to the higher supply-demand matching of PV power generation and midday peaks, there is no problem with SCR limits. While the potential benefit of HPS at higher PV capacities is attractive, it is recommended that investors with different consumption profiles should comprehensively evaluate power quality issues, especially at critical nodes in the distribution grid.

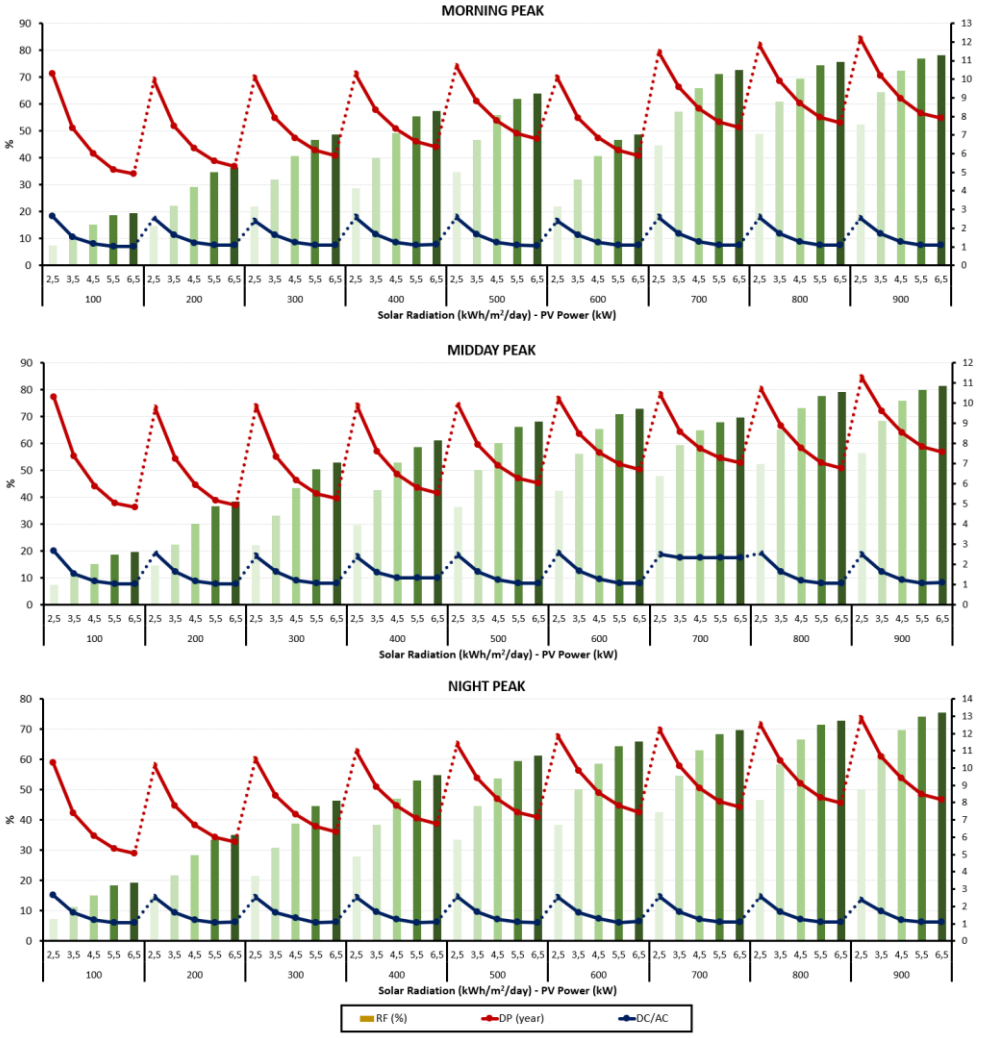


Figure 3. Effects of solar radiation and PV capacities on RF, DP, and DC/AC converter efficiency

CONCLUSION AND DISCUSSION

This study analyzes the HPS potential at various PV capacities and solar radiation for possible EVCS installations in Antalya in-depth on technical, economic, and environmental aspects. Moreover, the HPS outputs are comparatively evaluated for load profiles with different peak demand times. In addition, non-beneficial thresholds for PV capacity and solar horizontal radiation are determined for each consumption profile based on the SCR. The results show that possible increases in horizontal solar radiation can shorten the payback period by up to 5.4 years. Although evening peaks are more attractive in terms of the payback period, the potential for RF, SSR, and SCR is higher during midday peaks. Although increased PV capacities can extend the payback period up to 3.42 years, it can raise the RF by up to 61.7% and reduce the COE by up to 83.9%. The related disadvantages in the payback period can be eliminated by the possible increase in solar radiation and investors' interest in HPS can increase up to 31.1%. On the other hand, PV capacity of 800 kW and above and solar radiation of 5.5 kWh/m2/day and above for morning and night peaks can cause power quality issues at critical bus nodes due to close

SCR limits. There is no negative impact on the midday peak. Although it is assumed that higher PV capacity and solar radiation will increase the HPS benefit, it is suggested to elaborate the analysis based on SCR limits at critical bus nodes. The outputs of this study can be extended and evaluated in the future for various subsidy and incentive policies and different economic actions of countries.

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