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Research paper

Techno-economic and environmental evaluation of a campus-scale floating photovoltaic system in Burdur, Türkiye

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ABSTRACT

This study presents a techno-economic and environmental evaluation of a campus-scale floating photovoltaic (FPV) system proposed for the campus lake of Burdur Mehmet Akif Ersoy University in Burdur, Türkiye. The assessment integrates lake-surface utilization, site-specific solar-resource conditions, actual campus electricity demand, discounted life-cycle economic analysis, environmental assessment, deterministic sensitivity analysis, and multi-parameter Monte Carlo uncertainty analysis. The contribution of the study lies in integrating site-specific FPV sizing and actual campus electricity-demand matching with discounted life-cycle economic analysis, environmental assessment, deterministic sensitivity analysis, and multi-parameter Monte Carlo uncertainty analysis within a single assessment framework. A total lake area of 12,000 m^2 is considered, with 40% allocated to FPV deployment. Using 580 W crystalline-silicon modules, 3000 h/year of solar duration, and a performance ratio of 0.80, the proposed 1.08 MW system is estimated to generate approximately 2592 MWh/year, corresponding to nearly 30% of annual campus electricity demand. Under the harmonized 25-year life-cycle assumptions, including 0.5% annual energy degradation, 2% annual O&M escalation, an inverter replacement in year 15, and an 8% discount rate, the discounted LCOE is approximately 0.0745 USD/kWh, the NPV is approximately 0.68 million USD, the IRR is approximately 12.91%, and the discounted payback period is approximately 10.97 years. A 10,000-run Monte Carlo analysis yields a positive NPV in approximately 97.5% of simulations. The system could also avoid approximately 1166 tCO_2/year under the adopted grid-emission factor. The results support FPV as a promising campus-scale option while emphasizing that detailed PV simulation, engineering design, and site-specific ecological monitoring are required before implementation.

List of Abbreviations

Abbreviation	Full Name
BESS	Battery Energy Storage System
CAPEX	Capital Expenditure
CO_2	Carbon Dioxide
DO	Dissolved Oxygen
FPV	Floating Photovoltaic
GEPA	Turkish Solar Energy Potential Atlas
GHG	Greenhouse Gas
GIS	Geographic Information System
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
NPV	Net Present Value
O&M	Operation and Maintenance
PR	Performance Ratio
PV	Photovoltaic
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus

1. Introduction

Global warming and climate change have intensified the need to

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decarbonize electricity generation and accelerate the deployment of renewable energy technologies [1,2]. Photovoltaic (PV) systems play an important role in this transition because they can generate electricity without direct greenhouse-gas emissions during operation [3]. However, conventional ground-mounted renewable energy projects require land and may create competition with agricultural, ecological, or future infrastructure uses [4–6].

Floating photovoltaic (FPV) systems provide an alternative by deploying PV modules on lakes, reservoirs, and other water bodies, thereby using surfaces that are otherwise underutilized for electricity generation [7,8]. In addition to avoiding land-use conflicts, FPV systems may benefit from water-induced cooling, lower soiling, and reduced evaporation; however, their technical, economic, and environmental performance remains strongly site-specific.

1.1. Background and development of floating photovoltaic systems

FPV technology emerged with an early prototype installed in Aichi, Japan, in 2007 and subsequently expanded through commercial projects in reservoirs and other inland water bodies. Compared with conventional land-based PV, FPV installations can reduce land occupation while the underlying water body may lower module operating temperatures and improve energy yield. Reported benefits also include reduced evaporation and, under appropriate coverage conditions, suppression of excessive algal growth [9,10].

A typical FPV plant consists of PV modules, floating structures or pontoons, anchoring and mooring systems, inverters, transformers, and electrical transmission components [9]. The selection of floating and anchoring configurations is site-specific and depends on factors such as water depth, water-level fluctuation, wind and wave exposure, corrosion risk, maintenance access, and environmental constraints [11,12]. For the purposes of the present study, these design elements are treated as implementation constraints rather than as the primary focus of the analysis.

1.2. Techno-Economic assessment of FPV systems

One of the main technical advantages of FPV is the natural cooling effect of the water surface. Lower module temperatures can reduce thermal losses and increase energy yield relative to land-based PV under comparable irradiance conditions. Previous studies have reported FPV module temperatures approximately 2.74–14.5 °C lower than terrestrial modules and corresponding efficiency improvements that depend on local climate and system design [7,9]. Field-based evidence from different climatic zones similarly indicates that the magnitude of the cooling benefit varies substantially with environmental conditions.

Techno-economic feasibility is determined not only by energy yield but also by the additional structural and installation requirements of FPV systems. Capital expenditure can be higher than for ground-mounted PV because of floats, mooring, anchoring, corrosion-resistant components, and water-based installation requirements, while land acquisition costs may be reduced or avoided [13]. Consequently, indicators such as capital expenditure (CAPEX), operation and maintenance (O&M) cost, levelized cost of electricity (LCOE), net present value (NPV), internal rate of return (IRR), and payback period should be evaluated using site-specific assumptions.

Empirical and case-specific studies demonstrate a wide range of techno-economic outcomes. Ravichandran et al [14] reported a 5.18 megawatts (MW) reservoir-based configuration producing approximately 9.72 gigawatt-hours (GWh)/year, whereas Nguyen et al [15] evaluated a 47.5 MW hydropower-reservoir FPV project and reported an IRR of about 11.14% and a payback period of 14.4 years under base financial conditions. Islam et al [16] assessed a 10 MW FPV system at UMP Lake in Malaysia and reported 17,960 MWh/year, a CAPEX of approximately 8.94 million United States dollars (USD), an LCOE of USD 0.052/kWh, and a payback period of 9.5 years. These differences emphasize the influence of system scale, solar resource, electricity prices, financing assumptions, and local project conditions on FPV economics.

Lake-surface irradiance conditions may also differ from those of fixed terrestrial systems. Water generally has a relatively low albedo, while wave-induced changes in module orientation can create small irradiance non-uniformities and mismatch losses. Conversely, open-water locations may experience lower shading than campus rooftop or ground-mounted systems ([17,18]; H [19]).

1.3. Environmental assessment of FPV systems

The environmental performance of FPV systems extends beyond avoided land occupation and carbon-emission reduction. Partial coverage of water surfaces can reduce evaporation and solar-radiation penetration, but it can also influence water temperature, dissolved oxygen, thermal stratification, light availability, and aquatic ecological processes. Therefore, environmental benefits should be considered together with potential site-specific impacts rather than treated as universally positive outcomes.

Empirical studies illustrate this site dependence. Santos et al [20] estimated substantial evaporation reduction for FPV coverage at the Passaúna Reservoir in Brazil. Yang et al [21], using field monitoring and three-dimensional hydrodynamic/ecological modelling at Tengeh Reservoir, observed changes in surface-water temperature, dissolved oxygen, stratification, and water-quality indicators beneath FPV coverage. More recent field and whole-lake investigations have likewise reported measurable changes in lake thermal regimes and local surface-energy balance (Z [22,23]). These findings indicate that FPV coverage ratios and layouts should be selected together with site-specific ecological assessment and monitoring.

Reliability and environmental performance are also linked to the aquatic operating environment. Although reduced dust accumulation may lower cleaning requirements, high humidity, corrosion, biofouling, mechanical loading, and cable-related ecological concerns require appropriate materials, robust anchoring, and regular inspection [24–26].

1.4. FPV integration with hybrid renewable energy systems

FPV can also be integrated with other renewable energy and storage technologies to improve system flexibility and infrastructure utilization. FPV–hydropower configurations are among the most mature options because existing reservoirs, transmission lines, and substations can be shared, while dispatchable hydropower can help compensate for solar intermittency [27,28].

Energy-storage technologies such as battery energy storage systems (BESS) and hydrogen can shift surplus solar generation to periods of higher demand and improve grid resilience. Recent FPV-hydrogen studies demonstrate the technical relevance of this pathway. Al Saadi and Ghosh [29] coupled a 26.57 MWp FPV plant in Oman with a PEM electrolyser, hydrogen tank, and fuel cell, showing that hydrogen can provide long-duration balancing for solar intermittency, although the resulting hydrogen-storage configuration substantially increased the levelized energy cost. Hussain and Ghosh [30] further compared FPV-powered green-hydrogen production across different Köppen climate zones and showed that climate, soiling, inflation, and solar-resource conditions materially affect electricity and hydrogen economics. In Türkiye, Güven [31] assessed FPV-powered green hydrogen for inland ferry operation and found substantial life-cycle emission benefits, while also showing that economic feasibility remains sensitive to policy support and financial incentives. These studies indicate that hydrogen is a technically credible extension of FPV systems, particularly where long-duration storage, mobility, or sector coupling is required.

Storage is not explicitly sized in the present study because the proposed campus FPV plant is modelled as a grid-connected, behind-the-meter generation asset rather than an autonomous microgrid. The campus remains connected to the national grid, which supplies the residual demand whenever FPV generation is insufficient; conversely, the present feasibility model does not assume that surplus electricity must be stored to ensure supply adequacy. Adding BESS or hydrogen storage would therefore introduce a separate optimization problem involving hourly PV production, state-of-charge or hydrogen inventory, power-conversion efficiencies, replacement schedules, and additional CAPEX/O&M. Because the available data set does not contain a full measured hourly PV-production series and the objective of this paper is to establish the feasibility of the FPV generation asset itself, storage optimization is outside the present scope. Nevertheless, BESS and FPV-hydrogen configurations are identified as priority extensions for future work, especially for peak shaving, evening demand support, resilience, and increased on-site self-consumption.

Other hybrid configurations, including FPV-wind and FPV-hydropower systems, can exploit temporal complementarity between renewable resources and shared grid connections [27,28,32]. In the present study, hybridization and storage are therefore treated as future integration pathways rather than being explicitly sized or optimized; the principal analysis focuses on the technical, economic, and environmental feasibility of the campus-lake FPV system itself.

1.5. Comparative assessment of empirical FPV studies

To position the present study within the empirical literature, Table 1 summarizes representative FPV studies with emphasis on their methodological approaches, system scales, techno-economic indicators, environmental parameters, and principal findings. The current campus-lake case is included in the same table to facilitate direct comparison.

A critical comparison of the empirical literature reveals several methodological limitations that remain insufficiently addressed. First, a substantial proportion of previous FPV studies focus on large reservoirs, hydropower-associated installations, or utility-scale systems, which limits the direct transferability of their findings to relatively small institutional water bodies. Second, techno-economic and environmental dimensions are frequently evaluated separately; studies reporting detailed economic indicators such as CAPEX, LCOE, NPV, IRR, and payback period do not always provide a corresponding environmental assessment, whereas field-based environmental studies often focus on parameters such as evaporation, water temperature, dissolved oxygen, or water quality without integrating investment feasibility. Third, sensitivity to site-specific economic and resource assumptions is not consistently examined across previous studies, making direct comparison of reported feasibility indicators difficult. These limitations indicate the need for an integrated, site-specific assessment framework that simultaneously considers energy performance, economic feasibility, environmental benefits, actual electricity-demand matching, and uncertainty in key input parameters, particularly for campus-scale FPV applications. In addition, surface-albedo effects and tilt-angle optimization were not explicitly modeled; therefore, future work should quantify plane-of-array irradiance and determine the site-specific optimum tilt using detailed PV simulation and field validation.

1.6. Research gap, novelty, and contributions

The focused comparison indicates that empirical FPV research has largely developed along separate streams. Technical studies have examined cooling and energy-yield effects, environmental studies have assessed evaporation, water temperature, stratification, dissolved oxygen, and water quality, and techno-economic studies have predominantly focused on medium- and large-scale reservoir or hydropower applications. In contrast, integrated assessments of relatively small institutional water bodies that directly link FPV sizing to an actual institutional electricity-demand profile while simultaneously evaluating economic feasibility, carbon mitigation, and parameter sensitivity remain limited.

The principal contribution of this study lies in the integrated, site-specific assessment of a campus-scale FPV application in Burdur, Türkiye. Rather than attributing novelty to the campus-lake setting itself, the framework combines FPV system sizing, actual campus electricity-demand matching, techno-economic and environmental evaluations, and multi-parameter sensitivity and uncertainty analyses within a single assessment. This integrated framework demonstrates how lake-area utilization, energy generation, demand coverage, CAPEX, LCOE, NPV, IRR, payback period, and potential CO_2-emission reduction can be evaluated consistently for an institutional-scale FPV application.

More specifically, the study directly links available lake area and FPV sizing to actual campus electricity demand and evaluates technical performance, discounted life-cycle economics, carbon-emission mitigation, and uncertainty under a harmonized set of assumptions. The contribution therefore derives from the integration and consistency of these assessment dimensions in a site-specific campus-scale framework, rather than from the campus-lake application alone.

2. Analysis of a FPV system on the campus lake of Burdur mehmet Akif Ersoy university

The study area is located within the campus of Burdur Mehmet Akif Ersoy University, situated in the northeastern part of the Mediterranean region of Türkiye at a latitude of 37.7144° N and a longitude of 30.2715° E [38]. More specifically, the geographical coordinates of the campus are 37° 42′ 51.9948″ N and 30° 16′ 17.7132″ E. The campus accommodates approximately 32,000 students, representing a significant and consistent energy demand profile [39]. A satellite representation of the campus layout is provided in Fig. 1, and the variation of load demand in a day is presented in Fig. 2a.

The electrical energy requirements of the campus are currently met entirely through the national grid. The energy consumption data utilized in this study were obtained from CK Akdeniz Electricity Distribution Company [41]. An analysis of the load demand profile reveals that the peak load reaches 2189.53 kW, whereas the minimum load is approximately 798.21 kW. The total daily electricity consumption is around 34 MWh, indicating a substantial and continuous demand for electrical energy. The variation of load demand throughout a typical day is illustrated in Fig. 3.

Campus annual demand is based on the electricity-consumption data used in this study; FPV values are scenario calculations. Fig. 2b complements the representative daily profile with an annual energy perspective. The 8640 MWh/year campus value is the annual consumption used in the present assessment, whereas the FPV bars are modeled generation scenarios rather than measured production. This distinction is important because the available utility data support annual demand matching, but not a complete 12-month FPV operating record for a system that has not yet been installed.

A temporal assessment of the load profile indicates that the lowest energy consumption occurs between 06:00 and 07:00, primarily due to the deactivation of outdoor lighting systems. In contrast, peak demand is observed between 17:00 and 20:00, which corresponds to increased campus activity, including academic and social engagements during evening hours [41]. The presence of a campus lake offers a strategic opportunity for the deployment of floating photovoltaic (FPV) systems to support on-site renewable energy generation. The integration of FPV systems on university campus lakes presents a promising approach for enhancing renewable energy adoption while efficiently utilizing otherwise underutilized water surfaces. In this study, a medium-scale FPV system is conceptually evaluated based on site-specific parameters, including solar irradiance levels as seen in Fig. 3, available lake surface area, and proximity to existing electrical infrastructure. University campuses provide an advantageous environment for such applications due to their relatively stable energy demand patterns and institutional

Table 1
Comparative assessment of empirical techno-economic and environmental FPV studies.

Study	Location / Application	Methodology	FPV Scale	Key techno-economic parameters	Environmental parameters	Main findings
[33]	Netherlands & Singapore	Field measurements, FPV–land/rooftop comparison, PVsyst	Experimental FPV systems	Specific yield, module temperature	Water-cooling effect	FPV temperatures were up to 3.2 °C lower in the Netherlands and 14.5 °C lower in Singapore; estimated yield gain reached about 3% and 6%, respectively
[14]	High Dam & Aswan Reservoir, Egypt	Site-specific performance/case-study analysis	5.18 MW selected configuration	Energy yield, module technology, tilt/ tracking	Water-surface utilization	The selected configuration produced approximately 9.72 GWh/year, demonstrating substantial reservoir FPV potential
[34]	Lake/reservoir environment, UK modelling context	Lake thermal modelling	Scenario-based FPV coverage	—	Water temperature and stratification	Demonstrated that FPV coverage can materially modify lake thermal processes and potentially mitigate some climate-related changes
[20]	Passaúna Reservoir, Brazil	Meteorological data + evaporation models + FPV coverage scenarios	Existing 1265.14 m^2 FPV + expansion scenarios	1–5 MWp scenarios	Evaporation reduction	Existing FPV coverage was estimated to reduce evaporation by 60.2%; full-reservoir scenarios indicated substantial water-saving potential
[21]	Tengeh Reservoir, Singapore	Field monitoring + 3-D hydrodynamic/ecological modelling	1 ha demonstration; 42 ha scenario (~50 MW)	—	Temperature, dissolved oxygen (DO), chlorophyll-a, total nitrogen (TN), total phosphorus (TP), total organic carbon (TOC)	Field measurements showed roughly 0.5 °C higher surface-water temperature and lower dissolved oxygen beneath panels; modelling demonstrated effects on stratification and several water-quality indicators
[15]	Da Mi hydropower reservoir, Vietnam	Operational/case-study financial assessment	47.5 MW	NPV, IRR, B/C, payback, energy generation	Renewable-energy displacement	Approx. 69.99 GWh/year generation; reported financial IRR of about 11.14% and payback of 14.4 years under the base financial conditions, improving substantially under the national-economic scenario
[16]	UMP Lake, Malaysia	PVsyst 7.3, techno-economic and carbon analysis	10 MW	CAPEX, LCOE, payback	CO_2 reduction	17,960 MWh/year, CAPEX USD 8.94 M, LCOE USD 0.052/kWh, payback 9.5 years, and 11,135 tCO_2/ year avoided

(continued on next page)

Table 1 (*continued*)

Study	Location / Application	Methodology	FPV Scale	Key techno-economic parameters	Environmental parameters	Main findings
[35]	Cirata Reservoir, Indonesia	RETScreen, scenario-based techno-economic assessment	145 MW	LCOE, payback, energy price, financing	greenhouse gas (GHG) reduction	Demonstrated techno-economic feasibility while showing strong dependence on financing, energy-price, and carbon assumptions
[36]	Battery-integrated FPV application	PVsyst + MATLAB/Simulink + economic optimization	Site-specific FPV/ BESS	LCOE, discounted payback	CO_2 reduction	Optimized case reported LCOE ≈ USD 0.261/kWh, discounted payback 9.5 years, and approximately 731 tCO_2/year avoided
[22]	Operational FPV water body	3-D empirical monitoring / energy-balance assessment	Existing FPV	—	Water temperature, energy balance, microclimate	Demonstrated measurable FPV-induced changes in water temperature and local surface-energy balance, providing field-based evidence of environmental effects
[37]	Irrigation pond, Alicante, Spain	Actual operating data + regional extrapolation	Operational pond FPV	Self-consumption, investment, cost saving	Land/water-energy sustainability	Operating installation achieved 31% self-consumption and approximately 27% reduction in energy costs; regional deployment was estimated at EUR 130 M investment with EUR 23 M/ year savings
[23]	Whole-lake FPV experiment	Whole-lake experimental environmental assessment	Lake-scale experiment	—	Water temperature/ ecological response	Provided rare whole-lake empirical evidence that FPV can significantly alter water temperature, strengthening the evidence base on aquatic environmental impacts
Current study	**Burdur Mehmet Akif Ersoy University campus lake, Türkiye**	**Site-specific technical + economic + environmental + sensitivity/ scenario analysis**	**1.08 MW**	CAPEX USD 1.62 M; LCOE 0.0745 USD/ kWh; NPV +USD 0.89 M; IRR 12.91%; payback period ≈7 yr	**1166 tCO_2/year reduction; limited lake coverage**	**2592 MWh/year; ≈30% of campus electricity demand using 40% of lake surface**

commitments to sustainability and carbon neutrality. Previous studies in the literature highlight that campus-based FPV systems can serve not only as energy generation units but also as experimental platforms for education and research in renewable energy technologies [42,43].

From a technical standpoint, the feasibility of installing FPV systems depends on several critical factors, including anchoring mechanisms, floating platform design, and environmental compatibility. The cooling effect of water bodies can significantly improve photovoltaic efficiency, resulting in higher energy yields compared to conventional ground-mounted systems under similar solar irradiance conditions. Furthermore, integrating FPV systems into campus microgrids enhances energy management capabilities and reduces transmission losses. Simulation studies suggest that covering approximately 30–40% of the lake surface can generate a considerable proportion of the campus's electricity demand without disrupting ecological balance [42]. Additionally, the modular structure of FPV systems allows for phased deployment and scalability in accordance with financial and technical constraints.

From an economic perspective, FPV systems offer cost advantages by eliminating land acquisition requirements and enabling the use of shared infrastructure. When combined with energy storage technologies, such as battery storage systems or hydrogen production units, the overall reliability and resilience of the campus energy system can be further improved. Environmentally, FPV installations contribute to reducing water evaporation and suppressing algal growth, thereby improving water quality. However, comprehensive environmental impact assessments are essential to ensure that aquatic ecosystems are

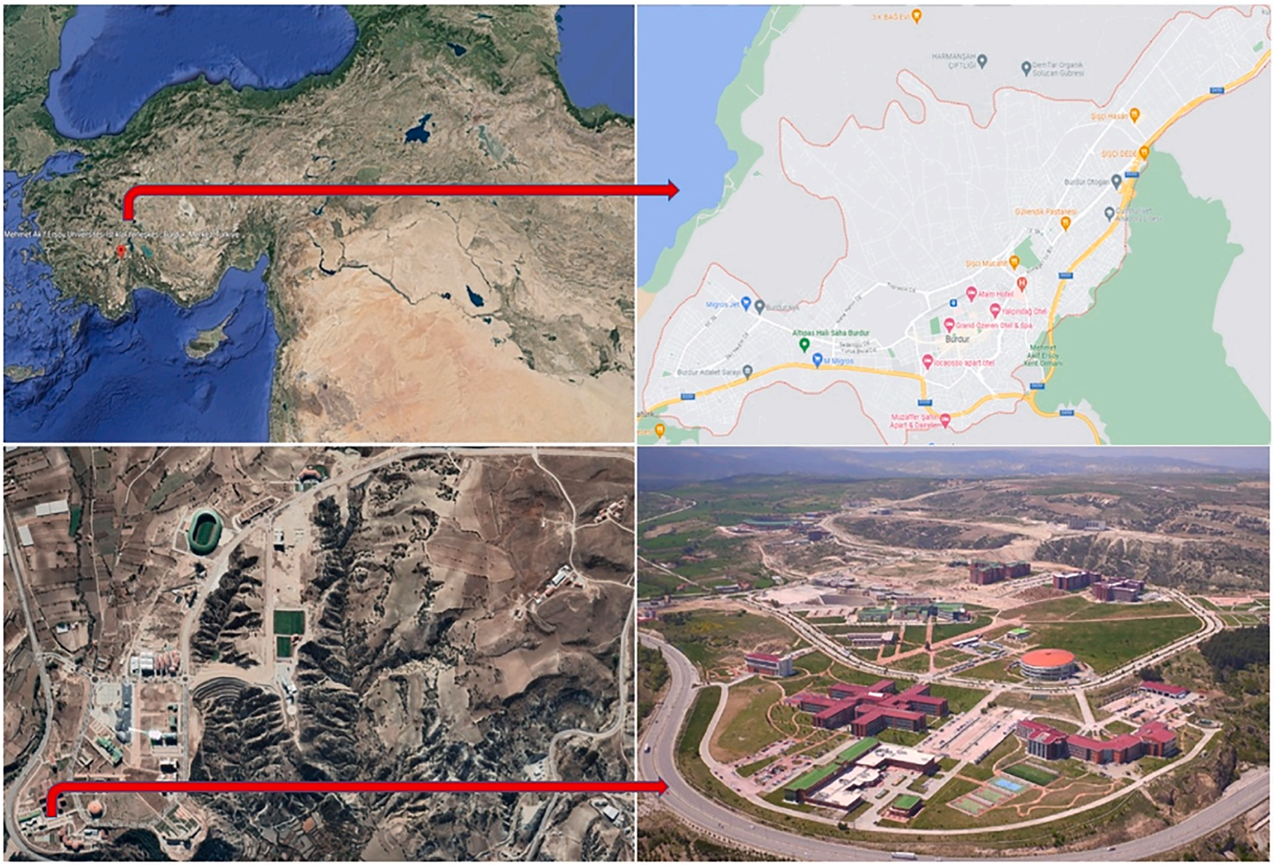

Fig. 1. A satellite representation of the campus layout [40].

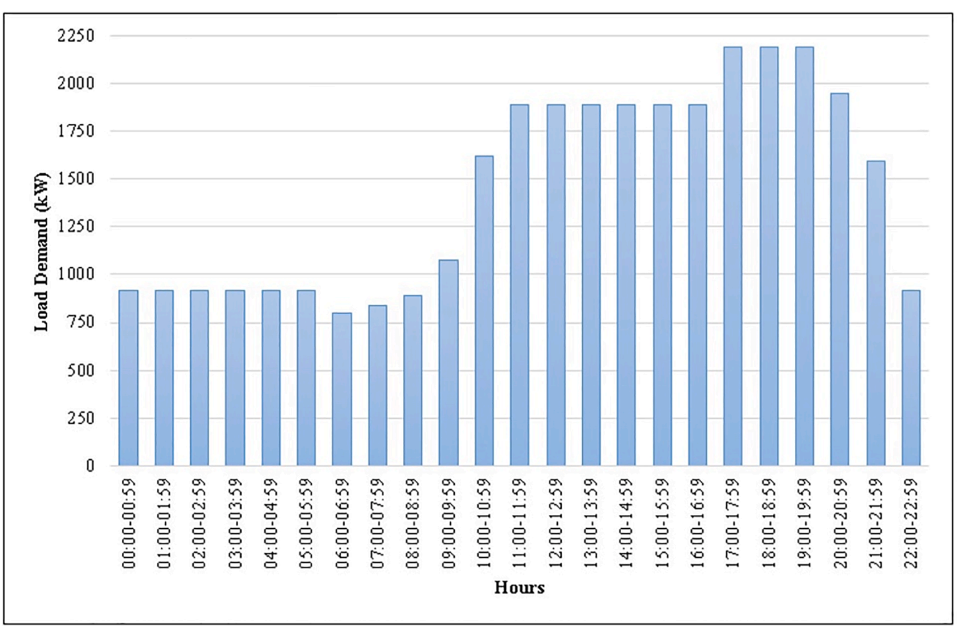

Fig. 2a. The variation of load demand throughout a typical day [41].

not adversely affected by factors such as reduced light penetration or physical disturbances. Overall, this case study demonstrates that FPV systems deployed on university campus lakes represent a technically feasible, economically viable, and environmentally sustainable solution for advancing institutional energy transitions [27,44].

2.1. The calculation of the FPV system on the Campus lake of Burdur Mehmet Akif Ersoy university

The technical analysis of a FPV system on a campus lake requires the evaluation of available water surface area, usable PV coverage ratio,

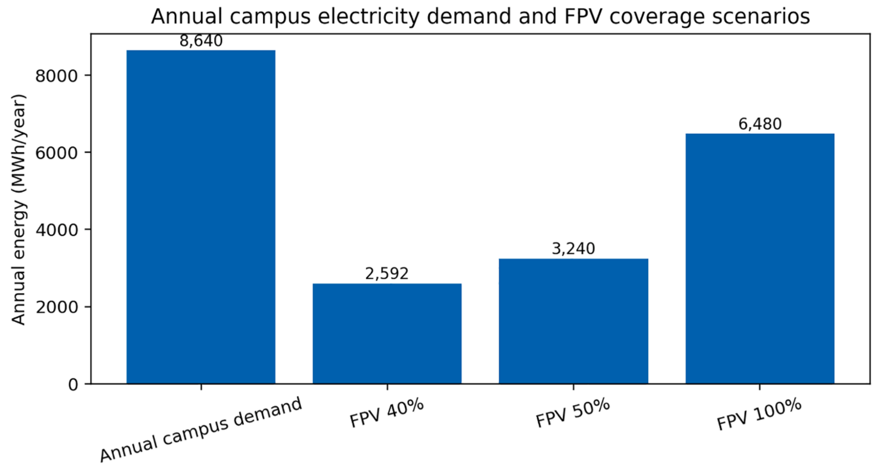

Fig. 2b. Annual campus electricity demand compared with modeled FPV generation under 40%, 50%, and 100% lake-surface coverage scenarios.

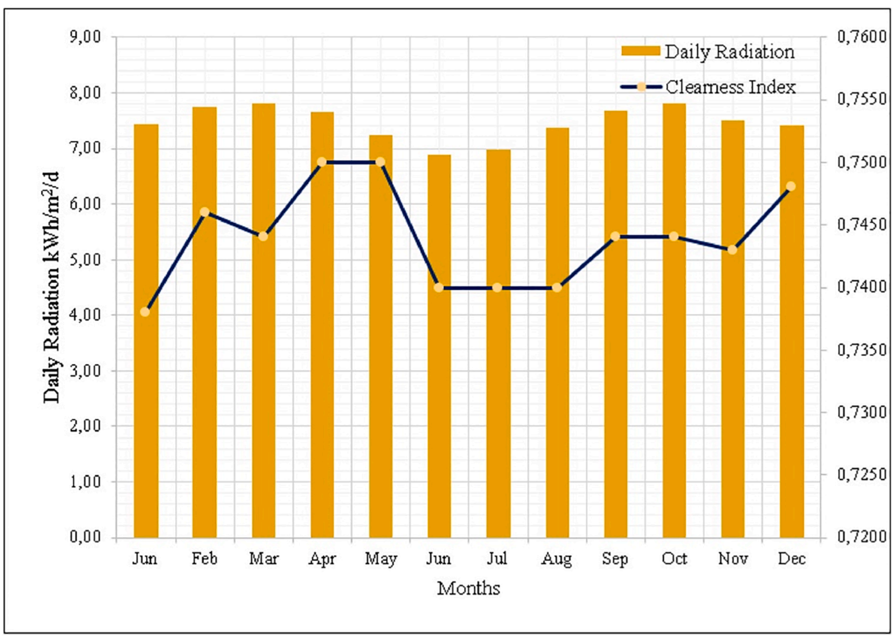

Fig. 3. Density of solar energy and clearness index for the campus [40].

installed capacity, annual energy generation, performance ratio, and contribution to campus electricity demand. The first step is to determine the total surface area of the lake using satellite imagery, Geographic Information System (GIS)-based measurement tools, or field surveys. The picture of the campus lake is shown in Fig. 4.

Since full coverage of the lake may negatively affect the aquatic ecosystem, oxygen exchange, sunlight penetration, and visual landscape, only a limited portion of the lake surface should be allocated for FPV installation. Accordingly, the approximate surface area of the lake, with 200 m length and 60 m width, can be estimated using a simplified rectangular approximation:

$$A = L \cdot W \tag{1}$$

where A is the total lake area (m^2), L is the length of the lake (m), and W is the width of the lake (m). The usable FPV area can be calculated as:

$$A_{FPV} = A_{lake} \cdot C_r \tag{2}$$

The 40% base-case coverage is adopted as a planning scenario rather than as a universal ecological threshold. It preserves 60% of the lake as open water while providing a sufficiently large area for a campus-scale FPV array, maintenance access, shoreline setbacks, and future layout adjustment. International guidance emphasizes that FPV coverage should be determined case by case because water quality, thermal response, anchoring, wind exposure, and competing water uses vary substantially among sites [45]. Empirical studies likewise show that water-temperature, dissolved-oxygen, stratification, and ecological responses depend on coverage and local limnology [21,23]. Accordingly, 40% is used here as a feasibility-level compromise and is explicitly tested against 50% and 100% theoretical coverage scenarios below. The 100% case is included only as an upper-bound energy benchmark and is not proposed for implementation.

The regulatory context also supports a site-specific rather than purely area-maximizing approach. Türkiye's 2024 legislative change opened the way for renewable-energy facilities on seas, dam reservoirs, artificial lakes, and natural lakes, while excluding drinking-water reservoirs, wetlands, and protected coastal/shoreline areas from this general provision [46]. This legal framework does not establish 40% as a statutory coverage limit. Therefore, prior to implementation at the Burdur campus lake, the lake's legal status, water-use function,

Fig. 4. Campus lake and indicative 40% FPV planning zone (conceptual; not a final engineering/GIS layout).

environmental permitting requirements, and applicable shoreline and ecological constraints must be confirmed with the competent authorities. The present 40% value should consequently be interpreted as a scenario assumption subject to environmental and regulatory approval, not as a government-prescribed threshold.

$$N = \frac{A_{FPV}}{A_{module}} \tag{3}$$

where is the number of PV modules and is the effective area occupied by one module. The total installed capacity of the system is then calculated as:

$$P_{installed} = N \cdot P_{module} \tag{4}$$

where is the total installed capacity and is the rated power of a single PV module. Assuming that each PV module requires approximately 2.58 m^2 [47] of effective area and has a rated power of 580 W, the number of modules and installed capacity are calculated as 1860 pieces and 1.08 MW respectively. The annual electricity generation of the FPV system can be estimated using the following expression:

$$E_{annual} = P_{installed} \cdot H_{annual} \cdot PR \tag{5}$$

where represents the annual energy output, is the annual equivalent solar irradiation or peak sun hours and is the performance ratio of the system. The performance ratio accounts for losses caused by temperature, inverter efficiency, cable losses, soiling, mismatch, shading, and system downtime.

The influence of module temperature on PV power can be expressed using the standard temperature-coefficient relationship:

$$P(Tc) = PSTC[1 + \gamma(Tc - 25)] \tag{6}$$

where P(Tc) is the module power at cell temperature Tc (°C), PSTC is the rated power under standard test conditions (STC, 25 °C cell temperature), and γ is the module power temperature coefficient ($°C^{-1}$). For crystalline-silicon PV modules, γ is typically negative; therefore, a reduction in cell temperature increases the instantaneous power output relative to operation at a higher cell temperature under otherwise comparable irradiance conditions. In an FPV system, heat exchange with the water surface and the associated microclimate may reduce module operating temperature and can therefore provide a potential performance benefit.

However, no site-specific module-temperature, ambient-temperature, or water-temperature measurements were available for the Burdur campus lake. Consequently, the temperature relationship is included to explain the physical mechanism, but no additional cooling-related power or energy gain is imposed on the base-case results. The actual temperature benefit should be quantified in future work using measured cell and water temperatures or a validated thermal/PV simulation model.

In FPV systems, the cooling effect of the water surface may reduce module operating temperature and improve energy yield compared to conventional land-based PV systems; however, the magnitude of this benefit is site- and design-dependent and is not treated as a measured gain for the Burdur campus lake. A performance ratio (PR) of 0.80 was adopted as a conservative feasibility-level base-case assumption. This value is lower than the PR = 0.87 used in the FPV performance modelling framework of Kichou et al [48] and is explicitly tested over a 0.75–0.85 range in the Monte Carlo uncertainty analysis. Therefore, PR = 0.80 is treated as an uncertain modelling assumption rather than a site-measured parameter. The annual average sunshine duration in Burdur province is approximately between 2800 and 3000 h, corresponding to an average daily sunshine duration of about 7.5–8.2 h. These values are derived from national solar radiation datasets provided by the Turkish Solar Energy Potential Atlas (GEPA) [49]. Assuming an annual solar duration of 3000 h and a performance ratio of 0.80, the annual energy generation of the FPV system is estimated to be approximately 2592 MWh. Considering an annual campus electricity demand of 8640 MWh, the proposed system is capable of supplying approximately 30% of the total energy consumption. This result indicates that a 1.08 MW FPV system installed on the campus lake could generate approximately 2592 MWh of electricity annually. The contribution of the FPV system to the campus electricity demand can be calculated as:

$$Contribution(\%) = \frac{E_{annual}}{E_{campus}} \cdot 100 \tag{7}$$

where is the annual electricity consumption of the campus. For instance, if the campus consumes 8640 MWh of electricity per year, the FPV system could supply 30% of the energy consumption. The main technical specifications and estimated energy-production results of the proposed FPV systems are summarized in Table 2.

Considering an annual campus electricity demand of 8640 MWh, the proposed FPV system, with an estimated annual generation of 2592 MWh, can supply approximately 30% of the total electricity consumption. This demonstrates that even with a relatively limited usable water surface, FPV systems can provide a substantial contribution to institutional energy demand. Therefore, under the assumed conditions,

Table 2
All results of the FPV system for the campus lake of Burdur Mehmet Akif Ersoy University.

Parameter	Value
Total lake area (m^2)	12,000
Usable FPV area (40%) (m^2)	4800
Panel area (m^2)	2.58
Number of panels (amount)	1860
Panel power (W)	580
Installed capacity (MW)	1.08
Solar duration (h/year)	3000
Performance ratio (PR)	0.80
Annual energy generation (MWh/year)	2592
Campus demand (assumed) (MWh/year)	8640
Energy coverage (%)	30

the FPV system could meet approximately 30% of the campus annual electricity demand. This demonstrates that partial utilization of a campus lake for FPV installation can provide a significant contribution to renewable energy generation, reduce dependency on grid electricity, and support institutional sustainability targets. However, before implementation, detailed feasibility studies should also include structural design, anchoring system analysis, wind load assessment, environmental impact evaluation, grid connection capacity, economic analysis, and long-term operation and maintenance planning.

Accordingly, the technical assessment presented in this study should be interpreted as a preliminary feasibility analysis rather than a detailed engineering design. Detailed structural design, anchoring and mooring analysis, electrical configuration, wind and wave load assessment, and grid-integration studies are beyond the scope of the present study and should be addressed prior to actual implementation.

To test the reviewer-relevant question of whether greater lake utilization could materially increase campus-demand coverage, two additional theoretical surface-coverage cases were evaluated using the same module density, 580 W module rating, 3000 h/year solar-duration assumption, and PR = 0.80. Because the model is area-proportional at this feasibility stage, installed capacity and annual generation scale linearly with usable FPV area. The resulting comparison is summarized in Table 3.

The scenario comparison shows that increasing coverage from 40% to 50% raises modeled annual generation from 2592 to 3240 MWh and campus-demand coverage from 30.0% to 37.5%. Even the purely theoretical 100% coverage case would supply approximately 6480 MWh/year, or 75% of annual campus demand under the same assumptions; it would therefore not provide annual energy autonomy. More importantly, full coverage would eliminate open-water area and could intensify ecological, thermal, oxygen-exchange, maintenance, and landscape constraints. The 40% base case is thus retained not because it maximizes electricity production, but because it represents a more balanced feasibility scenario. Final coverage should be optimized only after bathymetric, ecological, water-quality, wind/wave, anchoring, and permitting studies.

Table 3
Theoretical lake-surface coverage scenarios and campus-demand contribution.

Lake coverage	Usable area (m^2)	Approx. modules	Installed capacity (MW)	Annual generation (MWh/year)	Campus demand coverage (%)
40% (base case)	4800	1860	1.08	2592	30.0
50%	6000	≈2326	≈1.35	3240	37.5
100% (upper bound)	12,000	≈4651	≈2.70	6480	75.0

2.2. Proposed FPV configuration for the campus lake

Based on the characteristics of the proposed campus application and the technical alternatives reviewed above, the conceptual configuration adopted in this study consists of a modular pontoon-based floating platform equipped with crystalline-silicon photovoltaic modules. This configuration is considered appropriate for a relatively small, enclosed institutional water body because modular pontoons provide layout flexibility, facilitate staged installation and maintenance, and allow the planned 40% surface coverage to be implemented without occupying the entire lake. For the conceptual mooring and anchoring arrangement, a near-shore/shore-based system is proposed rather than a deep-water anchoring configuration. The limited dimensions and enclosed nature of the campus lake make shoreline-based anchoring conceptually suitable for reducing installation complexity and improving accessibility for inspection and maintenance. Mooring lines would maintain the position of the floating array while accommodating normal variations in water level and environmental loading. Crystalline-silicon modules are selected as the reference module technology because they represent a mature and widely deployed PV option with established performance characteristics and compatibility with commercial modular FPV platforms. The proposed configuration should nevertheless be interpreted as a conceptual system selection for preliminary feasibility assessment rather than a final engineering design. Prior to implementation, the final pontoon geometry, module arrangement, anchoring locations, mooring-line specifications, structural loads, electrical string/inverter configuration, cable routing, earthing and protection, and grid-connection requirements must be determined through a detailed site-specific engineering study considering bathymetry, shoreline conditions, water-level variation, wind and wave loading, corrosion exposure, operational safety, and applicable electrical standards. The performance improvements reported for FPV systems in the literature should not be interpreted as site-specific measured benefits for the Burdur campus lake. Cooling-related efficiency gains, energy-yield improvements, and CAPEX differences depend strongly on local climatic conditions, water temperature, wind regime, array geometry, floating-platform design, project scale, procurement conditions, and installation characteristics. Accordingly, literature-derived values are used in this study only as contextual benchmarks and reference ranges rather than as directly transferable performance gains. No additional site-specific energy-yield increment attributable solely to the water-induced cooling effect was applied to the base-case energy calculation. Similarly, the adopted CAPEX represents a feasibility-level assumption that is examined through sensitivity and Monte Carlo uncertainty analyses rather than a site-specific contractor quotation. The actual magnitude of cooling benefits, efficiency gains, investment costs, and energy-yield improvements at the investigated site should therefore be validated through site measurements, detailed engineering design, or established PV simulation tools prior to implementation. Water-surface albedo and module tilt can influence plane-of-array irradiance and, consequently, FPV energy yield. However, the present study does not perform a site-specific optical/albedo model or tilt-angle optimization. The base-case energy estimate therefore uses the stated solar-resource and performance-ratio assumptions without claiming an additional gain from water-reflected irradiance or an optimized tilt angle. For implementation-stage design, the optimum tilt and plane-of-array irradiance should be determined using site-specific meteorological data, water-surface reflection characteristics, array geometry, and an established PV simulation environment such as PVsyst or SAM, followed where possible by validation against measured operating data.

3. Techno-economic assessment of the FPV system

3.1. Economic analysis of the FPV system

FPV systems generally require higher initial investment costs compared to conventional ground-mounted photovoltaic installations due to additional engineering, material, and installation complexities. According to the literature, the average capital expenditure (CAPEX) of FPV systems typically ranges between 1200 and 1800 USD/kW, although this range can vary depending on site-specific conditions, system scale, and technological configurations. Assuming an average capital cost of 1500 USD/kW for the FPV system, the total initial investment cost can be considered to be approximately 1.62 million USD.

The annual operation and maintenance cost is typically estimated as 1%–2% of the initial investment. The annual operation and maintenance (O&M) cost is assumed to be 1.5% of the total capital investment, which corresponds to approximately 24,300 USD per year. For Türkiye, the average electricity tariff applicable to institutional or commercial consumers can reasonably be assumed to be around 0.10 USD/kWh [50], based on recent market observations and tariff structures. Under this assumption, the FPV system is expected to generate a substantial annual revenue stream. Considering the projected annual energy production of the system, the total yearly revenue can be estimated to be on the order of approximately 259,200 USD. This revenue estimation reflects a conservative pricing scenario and does not account for potential future increases in electricity prices, time-of-use tariffs, or additional incentives such as feed-in tariffs or renewable energy support mechanisms. Therefore, in real market conditions, the actual revenue could be higher, further enhancing the financial attractiveness of the FPV investment. Based on the estimated annual revenue and the assumed operation and maintenance (O&M) costs, the system is expected to generate a net annual profit of approximately 234,900 USD. This value represents the remaining income after deducting the yearly O&M expenses from the total electricity sales revenue, reflecting the effective cash inflow generated by the FPV system on an annual basis. When this net annual profit is evaluated in relation to the initial capital investment, the payback period—defined as the time required for the project to recover its initial cost—can be estimated to be approximately 7 years. This indicates that, under the given assumptions, the investment can return its upfront cost within a relatively moderate timeframe.

The LCOE represents one of the most widely used indicators for evaluating the economic performance of energy generation systems. It expresses the average cost of producing one unit of electricity over the entire lifetime of a project, considering the total investment and the cumulative energy generation.

$$\mathrm{LCOE} = \sum\nolimits_{t=0^n} \left[(\mathrm{CAPEX}_t + \mathrm{O\&M}_t + \mathrm{R}_t) / (1+\mathrm{r})^t \right] \Big/ \sum\nolimits_{t=1^n} \left[\mathrm{E}_t / (1+\mathrm{r})^t \right] \tag{8}$$

In this study, the LCOE was recalculated using a standard discounted life-cycle cost approach. The LCOE is defined as the ratio of the present value of all project costs to the present value of electricity generated over the project lifetime:

$$\mathrm{LCOE} = \sum \left[(\mathrm{CAPEX}_t + \mathrm{O\&M}_t + \mathrm{R}_t) / (1+\mathrm{r})^t \right] \Big/ \sum \left[\mathrm{E}_t / (1+\mathrm{r})^t \right] \tag{9}$$

where $CAPEX_t$ represents capital expenditure, $O\&M_t$ represents operation and maintenance expenditure, R_t represents replacement costs, r is the discount rate, and E_t is the electricity generated in year t. A 25-year project lifetime and an 8% discount rate were retained. Annual energy production was assumed to degrade by 0.5% per year, consistent with typical crystalline-silicon PV degradation assumptions reported by IEA PVPS [51]. Annual O&M expenditure was assumed to begin at 24,300 USD in year 1 and escalate by 2% per year to represent inflationary and variable maintenance effects. In addition, an inverter replacement cost equal to 10% of the initial system investment was included in year 15, consistent with the replacement interval and cost scenarios examined in the NREL inverter cost study [52]. Using these assumptions, the present value of total life-cycle costs is approximately 1.98 million USD and the present value of lifetime electricity generation is approximately 26.57 GWh, resulting in a discounted LCOE of approximately 0.0745 USD/kWh. This value is therefore used as the principal LCOE indicator in the revised techno-economic assessment.

Based on the explicit cash-flow model described below, the Net Present Value (NPV) is approximately +0.68 million USD at an 8% discount rate over a 25-year project life.

$$NPV = \sum_{t=1}^{25} \frac{Cashflow}{(1+r)^t} - \mathrm{CAPEX} \tag{10}$$

The Internal Rate of Return (IRR), defined as the discount rate at which NPV equals zero, is approximately 12.91%. Since this value exceeds the assumed discount rate of 8%, the base-case investment remains economically attractive under the stated assumptions. The discounted payback period is approximately 10.97 years, calculated as the point at which the cumulative discounted net cash flow becomes non-negative. Given the assumed 25-year project lifetime, the system provides a substantial operating period after discounted capital recovery.

3.1.1. *Cash flow model and calculation of financial indicators*

To ensure transparency, reproducibility, and consistency with the discounted LCOE calculation, the financial indicators were recalculated using the same 25-year life-cycle cash-flow assumptions. The initial investment is represented by a cash outflow of 1620,000 USD at year 0. Year-1 electricity revenue is 259,200 USD and then declines with 0.5% annual energy degradation, while year-1 O&M expenditure is 24,300 USD and escalates by 2% annually. An inverter replacement equal to 10% of the initial CAPEX is included in year 15. No residual value, tax, debt financing, electricity-price escalation, or additional incentives are included in the base case. The discount rate is 8% and the project lifetime is 25 years.

$$\mathrm{NPV} = -\mathrm{I_o} + \sum [t = 1 \text{ to } \mathrm{n}] \mathrm{CF_t} / (1+r)^t \tag{11}$$

where I_o is the initial investment, CF_t is the year-specific net cash flow after degradation, O&M escalation, and replacement costs, r is the discount rate, and n is the project lifetime. Using the harmonized assumptions, NPV is approximately +0.68 million USD.

IRR is calculated as the value of r that satisfies $0 = -I_o + \Sigma[t = 1 \text{ to } n]\, CF_t/(1+r)^t$. For the harmonized base-case cash-flow series, the IRR is approximately 12.91%.

The discounted payback period is determined from the cumulative discounted cash flow and is reached when the cumulative present value of annual net cash flows equals the initial investment. Under the harmonized base-case assumptions, this occurs after approximately 10.97 years. The representative cash-flow values used for the NPV, IRR and discounted payback calculations are presented in Table 4.

The resulting harmonized base-case indicators are: NPV = +0.68 million USD, IRR = 12.91%, simple payback period = 7.06 years, and discounted payback period = 10.97 years. These values are calculated using the same degradation, O&M escalation, replacement, project-life, and discount-rate assumptions used in the standard LCOE assessment. A summary of the principal technical and economic parameters of the proposed FPV system is provided in Table 5.

Table 4
Base-case cash flow model used for NPV, IRR, and discounted payback calculations.

Year (s)	Revenue (USD/year)	O&M (USD/year)	Replacement (USD)	Net Cash Flow / Treatment
0	0	0	0	−1620,000 initial investment
1	259,200	24,300	0	234,900
15	241,634	32,063	162,000	47,571
25	229,821	39,085	0	190,736

Table 5
All economic parameters of the Campus Lake of Burdur Mehmet Akif Ersoy university.

Parameter	Value
Installed capacity (MW)	1.08
Total investment (CAPEX) (million USD)	1.62
Annual O&M cost (USD)	24,300
Annual revenue (USD)	259,200
Net annual profit (USD)	234,900
Payback period (years)	7.06
LCOE (USD/kWh)	0.0745
NPV (million USD)	+0.68
IRR (%)	12.91
Discount payback period (years)	10.97

The economic feasibility of the proposed FPV system was evaluated based on a total installed capacity of 1.08 MW. Assuming an average investment cost of 1500 USD/kW, the total capital expenditure is estimated at approximately 1.62 million USD. The annual operation and maintenance cost is considered as 1.5% of the initial investment, corresponding to 24,300 USD/year. With an assumed electricity price of 0.10 USD/kWh, the system generates an annual revenue of approximately 259,200 USD.

After deducting O&M costs, the net annual profit is estimated at 234,900 USD. Accordingly, the payback period of the system is calculated to be approximately 7 years. Furthermore, the discounted levelized cost of electricity (LCOE) is estimated to be approximately 0.0745 USD/kWh, indicating strong economic viability.

3.2. Sensitivity analysis of the FPV system

A sensitivity analysis was conducted to evaluate the impact of varying electricity prices on the financial performance of the FPV system. The effects of electricity-price variations on annual revenue and the simple payback period are presented in Table 6.

The harmonized results demonstrate that project economics remain sensitive to electricity value. At 0.08 USD/kWh, the annual year-1 revenue is 207,360 USD and the simple payback period is approximately 9.16 years. At the 0.10 USD/kWh base case, year-1 revenue is 259,200 USD and simple payback is approximately 7.06 years. At 0.12 USD/kWh, year-1 revenue reaches 311,040 USD and simple payback falls to approximately 5.75 years. Using the full discounted life-cycle model, NPV remains positive across these three tariff cases, ranging from approximately 0.15 to 1.21 million USD.

Another sensitivity analysis was also performed to examine the effect of variations in CAPEX on the overall economic performance of the FPV system. The results, presented in Table 7, indicate that the initial investment cost has a direct and significant impact on the payback period of the project.

Under the 1200 USD/kW CAPEX case, total investment is approximately 1.30 million USD and the harmonized simple payback period is 5.49 years. At the 1500 USD/kW base case, total investment is 1.62 million USD and simple payback is 7.06 years. At 1800 USD/kW, total investment rises to approximately 1.94 million USD and simple payback extends to 8.73 years. The corresponding discounted NPVs remain positive, but decline substantially as CAPEX increases, confirming that upfront investment is a major determinant of project feasibility.

The findings, summarized in Table 8, clearly indicate that solar duration is a critical parameter influencing both the technical and economic performance of the system. In the scenario where the annual solar duration is assumed to be 1500 h, the system is expected to generate approximately 1296 MWh of electricity annually, corresponding to about 15% of the total energy demand of the campus. This represents a relatively low irradiation condition, under which the contribution of the FPV system remains limited. When the solar duration increases to 2000 h, the annual energy production rises to approximately 1728 MWh, allowing the system to meet nearly 20% of the total electricity demand. This scenario reflects moderate solar resource availability and demonstrates a noticeable improvement in system performance. In a high solar potential scenario, with an annual solar duration of 3000 h, the FPV system can generate up to 2592 MWh per year, covering approximately 30% of the campus electricity demand. This case highlights the significant benefits of favorable climatic conditions, where increased solar exposure directly enhances both energy output and system contribution to overall demand. Overall, the analysis demonstrates a strong positive relationship between solar duration and both annual energy generation and demand coverage. As solar irradiation increases, the system becomes more effective in meeting energy needs, thereby improving its overall feasibility and sustainability.

To further examine the robustness of the economic results, the influence of annual O&M expenditure was evaluated over a range of 1.0%–2.0% of CAPEX. This range brackets the 1.5% base-case assumption and represents plausible variation in routine inspection, cleaning, component replacement, and water-based maintenance requirements, Table 9.

Reasonable variations in annual O&M expenditure have a moderate but measurable effect on capital recovery. Increasing the year-1 O&M rate from 1.0% to 2.0% of CAPEX extends the harmonized simple payback period from approximately 6.80 to 7.34 years. The project retains a positive NPV across this range under the other base-case assumptions. The influence of financing conditions was also assessed using discount rates of 6%, 8%, and 10%, consistent with the WACC scenarios reported in the World Bank Group, ESMAP, and SERIS [45] floating-solar assessment framework. For this sensitivity analysis, the same standard discounted LCOE methodology was applied, including 0.5% annual energy degradation, 2% annual O&M escalation, and the year-15 inverter replacement cost. The resulting changes in the present value of life-cycle costs, present value of lifetime energy generation, and standard discounted LCOE are summarized in Table 10, The minimum,

Table 6
Sensitivity Analysis of Annual Revenue and Payback Period with Respect to Electricity Price Variations.

Electricity Price (USD/kWh)	Annual Revenue (USD)	Payback (year)
0.08	207,360	9.16
0.10	259,200	7.06
0.12	311,040	5.75

Table 7
Sensitivity analysis of payback period with respect to CAPEX variations.

CAPEX (USD/kW)	Total Cost (M$)	Payback (year)
1200	1.30	5.49
1500	1.62	7.06
1800	1.94	8.73

Table 8
Impact of solar duration on annual energy production and demand coverage.

Solar Duration (h)	Annual Energy (MWh)	Coverage (%)
1500	1296	15
2000	1728	20
3000	2592	30

Table 9
Sensitivity of economic performance to annual O&M Cost.

Annual O&M (% of CAPEX)	Annual O&M (USD)	Net Annual Cash Flow (USD)	Simple Payback (years)
1.0%	16,200	243,000	6.80
1.5% (Base)	24,300	234,900	7.06
2.0%	32,400	226,800	7.34

Table 10
Sensitivity of Standard Discounted LCOE to Discount Rate.

Discount Rate	PV of Life-Cycle Costs (million USD)	PV of Lifetime Energy (GWh)	Discounted LCOE (USD/kWh)
6%	2.063	31.68	0.0651
8% (Base)	1.979	26.57	0.0745
10%	1.917	22.68	0.0845

most-likely, and maximum values assigned to the uncertain parameters are presented in Table 11, The percentile-based results for NPV, LCOE, simple payback period, and discounted payback period are reported inTable 12, A comparative summary of the solar-duration scenarios, annual energy generation, campus-demand coverage, annual revenue, and payback period is provided in Table 13.

As expected, higher discount rates increase the discounted LCOE because future energy generation is discounted more strongly relative to the initial capital cost. Across the 6%–10% range, the standard discounted LCOE increases from approximately 0.0651 to 0.0845 USD/kWh, with a base-case value of 0.0745 USD/kWh at an 8% discount rate.

3.2.1. Multi-parameter Monte Carlo uncertainty analysis

To complement the one-factor-at-a-time sensitivity analyses, a Monte Carlo uncertainty analysis was performed to evaluate the combined influence of multiple uncertain technical and economic parameters. A total of 10,000 simulations were generated using independent triangular distributions. Triangular distributions were selected because the available evidence supports defensible minimum, most-likely, and maximum values for the principal feasibility parameters, while site-specific probability distributions are not available at this preliminary project stage. The ranges were defined from the sensitivity bounds and site-specific assumptions used elsewhere in the manuscript. The analysis simultaneously varied CAPEX, electricity price, annual O&M rate, discount rate, annual solar duration, and performance ratio (PR), while the project lifetime (25 years), annual module degradation (0.5%), O&M escalation (2%), and year-15 inverter replacement assumption were retained from the standard LCOE model.

The probabilistic results indicate that the base-case conclusion remains robust under simultaneous parameter variation, although the uncertainty band is substantially wider than that implied by the deterministic analysis.

Across the 10,000 simulations, the median NPV is approximately 0.59 million USD and the 5th–95th percentile interval ranges from 0.09 to 1.14 million USD. The probability of obtaining a positive NPV is approximately 97.5%. The median discounted LCOE is 0.0769 USD/kWh, while the median simple and discounted payback periods are 7.15 and 11.57 years, respectively. Pearson correlation coefficients indicate that electricity price (0.66) is the strongest positive driver of NPV, whereas CAPEX (−0.52) and discount rate (−0.48) are the strongest negative drivers. The combined analysis therefore confirms that project robustness is governed primarily by market value, upfront investment, and financing conditions, while site-specific solar availability and PR introduce additional technical uncertainty.

Table 11
Input distributions used in the multi-parameter Monte Carlo analysis.

Parameter	Distribution	Minimum	Most likely	Maximum
CAPEX (USD/kW)	Triangular	1200	1500	1800
Electricity price (USD/kWh)	Triangular	0.08	0.10	0.12
Annual O&M (% of CAPEX)	Triangular	1.0%	1.5%	2.0%
Discount rate	Triangular	6%	8%	10%
Solar duration (h/year)	Triangular	2800	2900	3000
Performance ratio	Triangular	0.75	0.80	0.85

Table 12
Monte Carlo results for key economic indicators (10,000 Simulations).

Indicator	5th percentile	Median	95th percentile
NPV (million USD)	+0.68	0.591	1.136
LCOE (USD/kWh)	0.0643	0.0769	0.0914
Simple payback (years)	5.74	7.15	8.96
Discounted payback (years)	8.14	11.57	19.60

The distribution in Fig. 5 shows that most simulated outcomes remain on the positive side of the NPV threshold, but a small lower-tail probability remains. This result provides a more realistic measure of economic robustness than independent parameter variations because adverse and favorable assumptions can occur simultaneously. The relationship between electricity price and the NPV of the proposed FPV system is illustrated in Fig. 6.

The results indicate that the economic feasibility of the FPV system is highly dependent on electricity pricing, with NPV increasing significantly as the unit electricity price rises. The sensitivity analysis demonstrates a strong positive correlation between electricity price and NPV, with the project maintaining a positive NPV even at lower price levels (0.08 USD/kWh). This indicates that the proposed FPV system remains economically feasible under conservative market conditions. The economic performance of the proposed FPV system was further evaluated using Net Present Value (NPV), Internal Rate of Return (IRR), and sensitivity analysis. Assuming a project lifetime of 25 years and a discount rate of 8%, the NPV of the system is calculated to be approximately 0.68 million USD, indicating strong economic feasibility. The IRR is estimated to be approximately 12.91%, which is above typical investment thresholds for renewable energy projects. The discounted payback period is approximately 10.97 years. Sensitivity analysis demonstrates that the system profitability is highly dependent on electricity prices, capital investment costs, and solar irradiation levels. These results confirm that the FPV system is economically viable under a wide range of realistic operating conditions.

3.3. Scenario-Based comparative analysis of the FPV system

The coverage analysis adds a second design dimension to the solar-duration scenarios. At fixed solar-resource and PR assumptions, the 40%, 50%, and 100% surface cases yield 30.0%, 37.5%, and 75.0% annual demand coverage, respectively. This demonstrates that lake area alone cannot close the campus energy balance: even the theoretical full-coverage case leaves approximately 2160 MWh/year of annual demand to be supplied by the grid or other resources. Consequently, increasing FPV area has diminishing practical value once ecological, access, mooring, and permitting constraints are considered. For this campus, a more defensible pathway to higher renewable penetration is therefore a portfolio approach combining a moderate FPV footprint with additional rooftop/ground PV, demand-side management, and—where hourly data justify it—BESS or hydrogen storage rather than attempting to maximize lake occupation. A comprehensive scenario-based analysis was conducted to evaluate the technical and economic performance of the proposed FPV system under varying solar irradiation conditions. In this assessment, several key parameters were held constant, including an installed capacity of 1.08 MW, a performance ratio (PR) of 0.80, and an annual campus electricity demand of 8640 MWh.

The analysis considered three distinct solar duration scenarios—low, medium, and high—representing different levels of solar resource availability. Under the low solar scenario (1500 h/year), the FPV system is expected to generate approximately 1296 MWh of electricity annually, corresponding to about 15% of the total campus electricity demand. In the medium scenario (2000 h/year), annual energy production increases to 1728 MWh, enabling the system to cover roughly 20% of the demand. In the high solar scenario (3000 h/year), the system achieves a significantly higher output of 2592 MWh per year, meeting

Table 13
Solar duration-based scenarios with economic comparison (Based on 0.10 USD/kWh).

Scenario	Solar Duration (h/year)	Annual Energy Generation (MWh)	Energy Coverage (%)	Annual Revenue (USD)	Payback Period (years)
Low Scenario	1500	1296	15	129,600	18.79
Medium Scenario	2000	1728	20	172,800	11.46
High Scenario	3000	2592	30	259,200	7.06

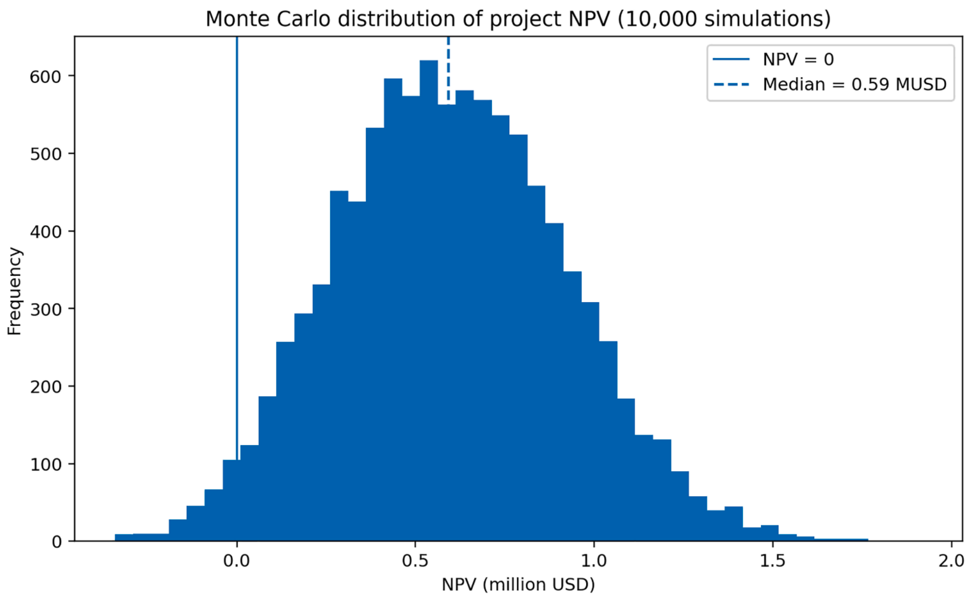

Fig. 5. Monte Carlo distribution of project NPV based on simultaneous parameter variation.

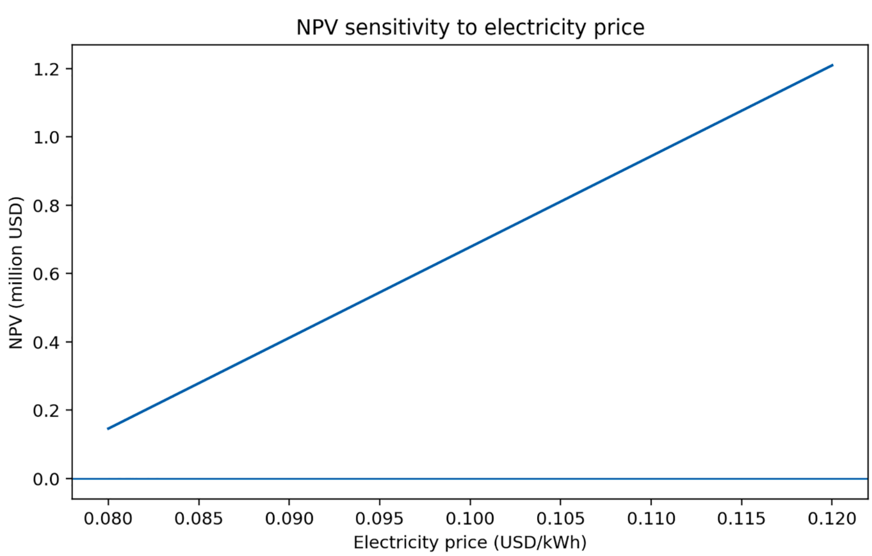

Fig. 6. Sensitivity analysis of NPV as a function of electricity price.

approximately 30% of the campus electricity requirement.

From an economic perspective, the same harmonized life-cycle assumptions were applied at an electricity price of 0.10 USD/kWh. The low solar scenario yields a simple payback period of approximately 18.79 years and a negative discounted NPV of approximately −0.65 million USD. Under the medium scenario, simple payback is approximately 11.46 years and NPV remains negative at approximately −0.21 million USD. Under the site-relevant high solar scenario, simple payback improves to approximately 7.06 years and NPV becomes positive at approximately 0.68 million USD. These results show that financial feasibility is not uniform across extreme solar-resource scenarios.

Overall, the scenario-based analysis demonstrates that FPV performance and investment attractiveness are strongly dependent on the assumed solar resource. The 1500 and 2000 h/year cases should be interpreted as stress-test conditions rather than representative Burdur resource values, since GEPA data used in the site assessment indicate approximately 2800–3000 h/year. The high/site-relevant scenario remains economically favorable, whereas the lower stress-test scenarios do not produce a positive discounted NPV under the harmonized life-cycle assumptions.

Fig. 7 illustrates the relationship between annual solar duration and the corresponding energy generation of the FPV system. As observed from the graph, there exists a clear and nearly linear correlation between solar irradiation duration and annual energy output. Specifically, as the solar duration increases from lower to higher values, the energy production rises proportionally, reflecting the direct dependence of photovoltaic performance on available solar resources. This trend confirms that longer sunshine durations significantly enhance the electricity generation capacity of the system. The linear behavior also indicates stable system performance under varying irradiation conditions, suggesting that the FPV system can reliably scale its output in response to changes in solar availability. Overall, the figure highlights the critical role of solar duration as a determining factor in maximizing both the technical efficiency and energy yield of FPV installations.

Fig. 8 presents the variation of the payback period as a function of solar duration, highlighting a clear inverse relationship between these two parameters. As observed from the graph, increasing solar irradiation leads to a substantial reduction in the payback period, indicating enhanced economic performance of the FPV system under higher solar resource conditions. In low solar duration scenarios, the payback period remains relatively long due to limited energy generation and consequently lower annual revenue. However, as the solar duration increases, the system produces more electricity, resulting in higher income and faster recovery of the initial investment. The trend depicted in the figure demonstrates a consistent and nonlinear decrease in payback time, emphasizing the strong sensitivity of financial outcomes to solar availability. Overall, this analysis underlines the critical importance of accurate solar resource assessment in FPV system planning and confirms that improved irradiation conditions significantly enhance both the technical efficiency and economic feasibility of such systems.

4. Environmental impacts, reliability, and maintenance of FPV systems in a campus lake context

4.1. Expanded environmental assessment

Because no field-based limnological or ecological measurements are currently available for the Burdur campus lake, the environmental assessment beyond avoided CO_2 emissions is expanded here using quantitative evidence from empirical FPV studies. These literature-derived values are not treated as site-specific predictions; rather, they define the range and direction of environmental responses that should be examined before implementation. Table 14 summarizes the principal evidence relevant to evaporation, water quality, aquatic ecosystem processes, and biodiversity.

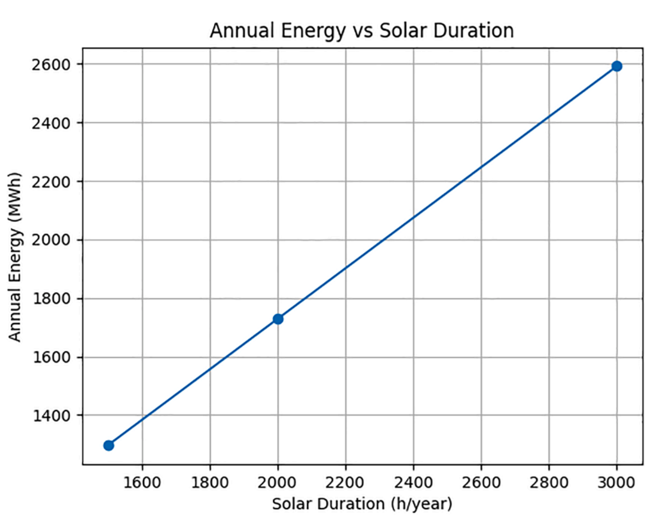

Fig. 7. Annual energy generation of the FPV system as a function of solar duration.

The evidence in Table 14 shows that FPV environmental effects cannot be characterized as uniformly beneficial. Evaporation reduction is consistently identified as a potential co-benefit, especially in dry climates, whereas shading and reduced air–water exchange can modify light availability, thermal structure, dissolved oxygen, nutrient cycling, and primary production. The magnitude and even direction of these responses vary with coverage ratio, water-body depth, trophic state, climate, FPV design, and season. Consequently, the environmental sustainability of the proposed campus-scale system should be interpreted as conditional on site-specific ecological verification rather than inferred from carbon reduction alone. For the Burdur campus lake, a future environmental monitoring program should include water temperature profiles, dissolved oxygen, pH, electrical conductivity, turbidity, chlorophyll-a, total nitrogen, total phosphorus, light penetration, and evaporation, together with seasonal biodiversity indicators. Measurements should be collected at representative locations beneath the FPV array, near the array boundary, and in an uncovered control area. Such a before–after/control–impact design would enable the environmental effects of the proposed 40% coverage to be quantified and would provide an evidence base for adaptive adjustment of array coverage if adverse ecological responses are detected.

The deployment of FPV systems on campus lakes presents a multidimensional impact framework that encompasses environmental sustainability, system reliability, and operational maintenance requirements. From an environmental perspective, FPV systems contribute significantly to reducing greenhouse gas emissions by displacing electricity generated from fossil fuel-based grid sources.

$$CO_2 Reduction = E_{annual} . EF \tag{12}$$

Based on the estimated annual energy generation of 2592 MWh, and using an assumed grid emission factor of 0.45 $kgCO_2/kWh$ for preliminary assessment, the system is capable of achieving an annual carbon emission reduction of approximately 1166 tons of CO_2. This substantial reduction highlights the role of FPV systems as an effective tool in supporting institutional carbon neutrality targets and broader climate change mitigation strategies.

FPV systems provide notable indirect environmental benefits beyond carbon emission reduction, particularly in terms of water conservation and ecosystem management. The partial coverage of water surfaces reduces solar radiation penetration, thereby limiting evaporation losses and suppressing excessive algal growth, which may contribute to improved water quality. However, careful optimization of system coverage and layout is essential to prevent adverse impacts on aquatic ecosystems, including alterations in dissolved oxygen levels and biological processes. Accordingly, comprehensive environmental impact assessments should be incorporated into the design phase.

From a reliability perspective, FPV systems benefit from the natural cooling effect of water bodies, which enhances module efficiency and mitigates thermal degradation, leading to improved energy yield and potentially extended component lifespan. Nevertheless, the aquatic environment introduces challenges such as high humidity, corrosion, biofouling, and mechanical stresses induced by wind and wave action. These factors necessitate the use of corrosion-resistant materials, robust anchoring solutions, and durable system components to ensure long-term operational stability.

In terms of operation and maintenance, FPV systems require tailored strategies compared to ground-mounted installations. Although reduced dust accumulation may lower cleaning frequency, regular inspection of floating structures, anchoring systems, and electrical components remains essential. Additionally, real-time monitoring systems should be employed to detect faults and performance deviations, while maintenance access considerations must be integrated into the system design.

Overall, FPV systems deployed on campus lakes represent a sustainable and efficient energy solution. Despite specific technical and environmental challenges, these systems can achieve high reliability and

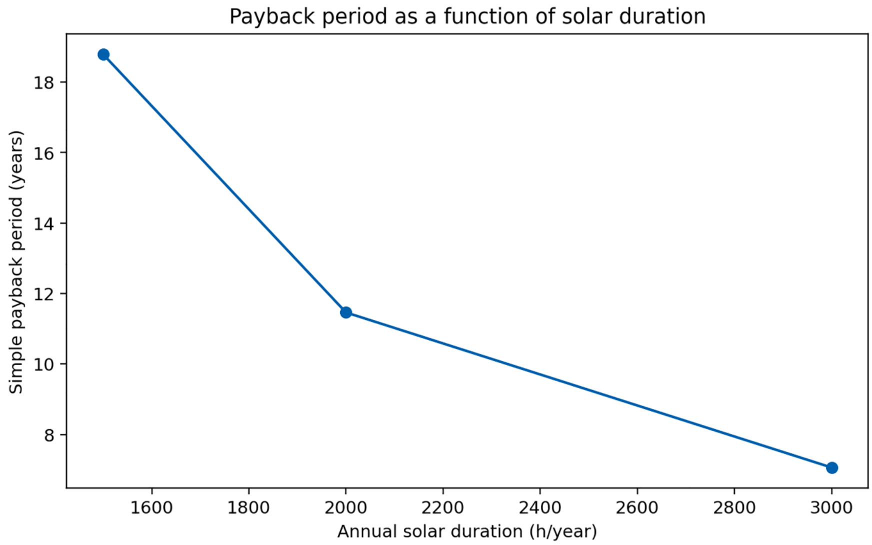

Fig. 8. Variation of payback period with respect to solar duration.

environmental compatibility through appropriate design, material selection, and proactive maintenance planning. Site-specific carbon-emission parameters of the proposed FPV system are summarized in Table 15.

Based on an annual electricity generation of 2592 MWh and an assumed grid emission factor of 0.45 $kgCO_2/kWh$, the proposed FPV system can reduce approximately 1166 tons of CO_2 emissions annually. Over a 25-year project lifetime, the cumulative emission reduction is estimated to be approximately 29,160 tons of CO_2. This demonstrates the significant environmental contribution of the proposed FPV system in supporting campus-level decarbonization and renewable energy transition goals.

This study aims to provide a comprehensive evaluation of FPV systems in a campus lake setting, combining technical, environmental, and hybrid energy perspectives to enrich the existing body of knowledge. Furthermore, it distinguishes itself from previous studies by emphasizing small-scale campus lake applications and incorporating techno-economic, environmental, and scenario-based analyses.

5. Discussion

The results of the present study demonstrate that the proposed 1.08 MW FPV system can provide a meaningful contribution to the electricity demand of the Burdur Mehmet Akif Ersoy University campus while maintaining favorable economic performance under the assumptions adopted in the analysis. With approximately 40% of the available lake surface allocated to FPV deployment, the system is estimated to generate 2592 MWh/year under the high solar-resource scenario, corresponding to approximately 30% of the annual campus electricity demand. These results indicate that relatively small institutional water bodies can support significant decentralized renewable electricity generation without requiring additional land occupation.

From a technical perspective, the estimated energy production is consistent with the broader empirical evidence demonstrating the performance potential of FPV systems, although direct comparison requires consideration of differences in system scale, climatic conditions, module technology, and modelling assumptions. For example, Ravichandran et al [14] evaluated a substantially larger reservoir-based FPV configuration in Egypt and reported an installed capacity of 5.18 MW with an annual electricity yield of 9.72 GWh for the selected polycrystalline configuration. In addition, Dörenkämper et al [33], using field data from the Netherlands and Singapore, demonstrated that water-induced cooling can increase annual FPV energy yield by up to approximately 6%, depending on climatic and system conditions. The present study does not explicitly model this additional cooling-related yield enhancement; therefore, its energy estimates should be interpreted primarily as site-specific feasibility estimates rather than as predictions incorporating all FPV-specific thermal effects.

The economic results support favorable preliminary feasibility under the harmonized base-case assumptions. With CAPEX of 1500 USD/kW, total investment is approximately USD 1.62 million, discounted LCOE is approximately 0.0745 USD/kWh, simple payback is approximately 7.06 years, NPV is approximately USD 0.68 million, IRR is approximately 12.91%, and discounted payback is approximately 10.97 years. A particularly relevant comparison is Islam et al [16], who assessed a 10 MW FPV system at UMP Lake in Malaysia and reported annual generation of 17,960 MWh, CAPEX of approximately USD 8.94 million, an LCOE of USD 0.052/kWh, and a payback period of approximately 9.5 years. The higher discounted LCOE obtained here reflects the inclusion of discounted life-cycle costs, annual degradation, O&M escalation, and inverter replacement, in addition to differences in scale, solar resource, and project assumptions.

The sensitivity analyses conducted in the present study reinforce this interpretation. Varying the electricity price between 0.08 and 0.12 USD/kWh changes the simple payback period from approximately 9.2 to 5.8 years, whereas changing CAPEX between 1200 and 1800 USD/kW results in payback periods ranging from approximately 5.5 to 8.3 years. Furthermore, the NPV remains positive even under the lower electricity-price scenario, indicating that the proposed investment retains economic feasibility under the range of conditions investigated. These results demonstrate that the economic attractiveness of the system is not determined solely by its technical energy potential but is strongly influenced by market and investment assumptions. Consequently, electricity price and initial capital expenditure should be considered key decision variables when assessing the feasibility of campus-scale FPV projects.

The environmental assessment indicates an additional potential benefit. Based on the electricity generated by the proposed system, annual avoided emissions are estimated at approximately 1166 tCO_2, demonstrating the potential contribution of FPV deployment to institutional decarbonization objectives. Islam et al [16], for comparison, estimated annual avoided carbon emissions of approximately 11,135 tCO_2 for their considerably larger 10 MW FPV installation in Malaysia. Although the absolute carbon reduction is substantially larger in that study, the difference primarily reflects system capacity, electricity generation, and the emission factor adopted in each assessment.

Table 14
Empirical evidence on environmental effects relevant to the proposed Campus-Lake FPV system.

Environmental aspect	Empirical evidence from FPV literature	Implication for the present study
Evaporation reduction	Abdelal [53] reported an average evaporation reduction of approximately 60% during a 9-month semi-arid pilot experiment. Al-Widyan et al [54] reported 31.2% water saving at 30% coverage and 54.5% at 50% coverage over a 30-day experiment.	The proposed 40% coverage could provide a water-conservation benefit, but site-specific evaporation reduction cannot be quantified without local meteorological and water-balance measurements.
Water quality and dissolved oxygen	Yang et al [21] predicted reductions beneath panels of up to 30% in chlorophyll-a, 15% in total organic carbon, and 50% in dissolved oxygen, while total nitrogen and total phosphorus increased by 10% and 30%, respectively. Bax et al [55] found 73–100% light reduction but only limited changes in water temperature and dissolved oxygen in a small pilot installation.	FPV effects are strongly site- and coverage-dependent. DO, temperature, pH, turbidity, nutrients, chlorophyll-a, and light penetration should therefore be monitored before and after deployment.
Aquatic ecosystem and biodiversity	Liu et al [56] found that at FPV coverage below 50%, changes in measured water-quality variables were generally of the same order as initial concentrations and did not significantly worsen trophic status, although dissolved oxygen was significantly reduced.	The 40% planning scenario is below the 50% threshold examined in that study, but this does not establish ecological safety for the campus lake; local ecosystem response must be verified empirically.
Plankton and bird biodiversity	A 2024 field survey of 26 water-surface PV systems in the Yangtze River basin found lower water temperature and dissolved-oxygen saturation and reductions in plankton species/individual density, together with an overall decrease in bird diversity and altered community composition.	Biodiversity impacts can extend beyond water chemistry. Baseline and post-installation surveys of plankton, aquatic vegetation, fish where present, and water-associated birds are recommended.

Table 15
Site-specific carbon-emission parameters of the proposed FPV system.

Parameter	Value
Annual energy generation (MWh/year)	2592
Emission factor (kgCO_2/kWh)	0.45
Annual CO_2 reduction (tonsCO_2/year)	1166
25-year CO_2 reduction (tonsCO_2)	29,160

Therefore, avoided emissions should be interpreted in relation to system size and the carbon intensity of the displaced electricity rather than through direct comparison of absolute values.

Nevertheless, carbon-emission reduction represents only one dimension of FPV environmental performance. Empirical studies demonstrate that covering a water surface can also alter evaporation, solar radiation penetration, water temperature, mixing processes, and water-quality characteristics. Al-Widyan et al [54], for example, experimentally reported an approximately 30% reduction in evaporation together with an average 2.7 °C decrease in PV module temperature. Similarly, Abdelal [53] experimentally investigated the effects of FPV coverage on evaporation and water quality under semi-arid conditions, highlighting the potential water-conservation function of FPV deployment. These findings suggest that the environmental value of campus-lake FPV may extend beyond carbon mitigation; however, such additional benefits cannot be quantitatively claimed for the present site without direct field measurements.

At the same time, the empirical literature indicates that environmental effects are strongly dependent on lake characteristics and FPV coverage. Yang et al [21], combining field observations with three-dimensional hydrodynamic–ecological modelling, found that FPV coverage can influence water temperature, water-column stability, dissolved oxygen, chlorophyll-a, and nutrient concentrations beneath the panels. Their field observations showed an average surface-water temperature increase of approximately 0.5 °C and a dissolved oxygen reduction of about 2 mg/L beneath a 1 ha demonstration FPV system. Conversely, Bax et al [55] observed a 73–100% reduction in underwater light availability beneath three pilot FPV designs but found comparatively limited effects on water temperature and dissolved oxygen at the investigated small scale. Ilgen et al [57] similarly measured a 73% reduction in irradiance and an average 23% reduction in near-surface wind speed beneath a commercial FPV installation, while observing relatively small changes in the thermal properties of the investigated lake under the measured conditions.

These contrasting empirical findings are particularly relevant to the proposed 40% surface-coverage assumption in the present study. While partial coverage was selected to balance electricity generation and preservation of the open-water surface, the present analysis does not include field-based hydrodynamic, water-quality, or ecological measurements. Therefore, the assumed 40% coverage should be interpreted as a technical planning scenario rather than an environmentally optimized coverage ratio. Before implementation, site-specific monitoring of water temperature, dissolved oxygen, light penetration, evaporation, aquatic ecology, and seasonal stratification would be required to determine whether this coverage level is environmentally appropriate for the campus lake. This interpretation is also consistent with Haas et al [58], who demonstrated that FPV coverage involves trade-offs between energy production, hydropower operation, and ecological conditions and that an optimal coverage range should therefore consider both energy and environmental objectives.

The scenario-based results also illustrate the importance of local solar-resource uncertainty. Under the low solar-duration scenario of 1500 h/year, annual electricity generation decreases to approximately 1296 MWh, covering around 15% of campus demand, whereas under the 3000 h/year scenario, generation reaches approximately 2592 MWh and demand coverage increases to approximately 30%. Thus, the contribution of FPV to campus energy autonomy varies substantially according to solar-resource assumptions. The use of multiple scenarios rather than a single deterministic estimate is therefore important when evaluating institutional FPV projects, particularly during the preliminary feasibility stage.

Taken together, comparison with the empirical literature indicates that the principal contribution of the present study is not the demonstration of individual FPV advantages, such as cooling, evaporation reduction, or avoidance of land use, since these effects have already been established in previous research. Instead, the contribution lies in applying an integrated technical, economic, environmental, and sensitivity-based assessment to a relatively small institutional water body and directly relating the resulting FPV generation to campus electricity demand. In this respect, the study complements the predominantly reservoir-scale and large-system literature by demonstrating how campus lakes can be evaluated as decentralized renewable-energy assets. The framework can potentially be transferred to other universities and institutional facilities possessing comparable underutilized water surfaces, provided that local climatic, economic, electrical, and ecological conditions are explicitly considered. These comparisons also underscore the boundaries of the present preliminary feasibility assessment. The principal methodological and implementation limitations are consolidated in Section 5.1 to avoid repetition.

From a decision-making perspective, the combined results reveal three trade-offs. First, energy coverage increases nearly linearly with occupied lake area in the simplified model, but environmental and permitting risks do not necessarily scale linearly; hence the technically maximum surface occupation is not the environmentally preferred design. Second, the grid-connected configuration makes storage unnecessary for basic annual energy accounting, but it does not resolve hourly mismatch: the daily profile peaks during the late afternoon/evening, when solar production is declining. Storage could therefore improve self-consumption and peak support even though it is not required to demonstrate annual FPV feasibility. Third, financial attractiveness is robust in the base case but remains exposed to CAPEX, electricity value, discount rate, and resource uncertainty. Taken together, these findings support a staged implementation strategy: validate the 40% concept with detailed bathymetry and environmental monitoring, obtain an hourly production-demand data set, and then optimize FPV coverage and storage jointly rather than treating lake area, storage, and economics as independent design decisions.

5.1. Limitations

The proposed FPV installation has not yet been implemented, and the technical assessment has not been validated against measured electricity-generation data or a detailed FPV simulation model. The analysis relies on feasibility-level assumptions for solar duration, PR, CAPEX, electricity value, and the grid-emission factor. Although the economic model now uses a consistent discounted life-cycle framework, future studies should replace these assumptions with project-specific quotations, tariffs, measured performance, and financing terms. Detailed structural and hydrodynamic design, bathymetry, anchoring and mooring loads, electrical string/inverter design, protection, cable routing, and grid-integration studies are outside the present scope. Surface-albedo effects and tilt-angle optimization are discussed but not explicitly modeled, and no site-specific cooling gain is imposed on the base-case energy output. The quantitative site-specific environmental result is limited primarily to avoided CO_2 emissions; evaporation, water quality, ecosystem, and biodiversity effects are supported by empirical literature rather than measurements from the Burdur campus lake. Future implementation-oriented research should therefore combine PVsyst/SAM/HOMER-type simulation, field performance monitoring, structural and electrical engineering, and before-after/control-impact limnological and biodiversity monitoring.

6. Conclusions

The principal scientific contribution of this study is the development and application of an integrated campus-scale FPV assessment framework for a relatively small institutional water body. Rather than treating technical performance, economics, environmental effects, and uncertainty as separate issues, the framework combines site-based system sizing and campus electricity-demand matching with a transparent cash-flow model, standard discounted LCOE methodology, environmental assessment, one-factor sensitivity analysis, and multi-parameter Monte Carlo uncertainty analysis. This integrated perspective extends the predominantly reservoir- and utility-scale FPV literature toward institutional and campus applications, where available water area, electricity demand, investment constraints, and environmental considerations must be evaluated jointly.

From a practical perspective, the study provides a feasibility-level decision-support approach for universities and other institutions considering the productive use of underutilized water surfaces. The proposed modular pontoon-based configuration, crystalline-silicon modules, and conceptual near-shore/shore-based anchoring arrangement provide a technically plausible starting point for the investigated campus lake. The economic and uncertainty analyses further demonstrate why investment decisions should not rely on a single deterministic scenario: project attractiveness is particularly sensitive to electricity value, CAPEX, financing conditions, O&M expenditure, and local solar-resource conditions. Accordingly, the framework can support early-stage screening and comparison of FPV alternatives before committing resources to detailed engineering design.

The findings should nevertheless be interpreted within the scope of a preliminary feasibility assessment. The proposed system has not yet been installed, and the technical analysis has not been validated against measured electricity-generation data or detailed PV simulation software. Site-specific structural, hydrodynamic, anchoring and mooring, electrical, and grid-integration designs are outside the present scope. Similarly, the quantitative environmental assessment is limited primarily to avoided CO2 emissions; literature-reported effects on evaporation, water quality, aquatic ecosystems, and biodiversity are used as contextual evidence and should not be interpreted as measured impacts for the Burdur campus lake. Literature-derived cooling, efficiency, energy-yield, and cost advantages are likewise treated as benchmarks rather than directly transferable site-specific benefits.

Future research should therefore prioritize implementation-oriented validation. A pilot or full-scale FPV installation should be monitored to obtain measured module temperature, energy yield, performance ratio, availability, and maintenance data and to benchmark the analytical model against established simulation tools such as PVsyst, SAM, or HOMER Pro. Detailed bathymetric, structural, wind and wave load, mooring and anchoring, electrical protection, cable-routing, and grid-connection studies are also required before construction. In parallel, long-term environmental monitoring should quantify water temperature, dissolved oxygen, pH, turbidity, chlorophyll-a, nutrient dynamics, evaporation, and biodiversity before and after FPV deployment. Such measurements would enable the technical, economic, and environmental assumptions used here to be replaced progressively by site-specific evidence.

Overall, the study demonstrates the value of evaluating campus-scale FPV through an integrated and uncertainty-aware framework rather than through isolated performance indicators. Its broader contribution is therefore methodological and practical: it establishes a reproducible pathway for translating the established potential of FPV technology into site-specific institutional feasibility assessments while clearly distinguishing preliminary evidence from the detailed engineering and environmental validation required for implementation.

CRediT authorship contribution statement

Bahtiyar Dursun: Investigation, Data curation, Conceptualization. **Ercan Aykut:** Writing – review & editing, Supervision, Formal analysis. **Sertaç Görgülü:** Software, Resources, Investigation. **Sibel Ülker Dursun:** Writing – original draft, Visualization, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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