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Floating solar PV to reduce water evaporation in water stressed regions and powering water pumping: Case study Jordan

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ABSTRACT

Water resources are essential for human consumption and food production. The extraction and delivery of water resources are highly dependent on energy. Hence water, energy and food security are inextricably linked, and this nexus constitutes a major global societal challenge. Furthermore, globally, irrigation constitutes around 70% of our freshwater resources, rising to 90% in developing countries. There are over 300 million drinking water and irrigation ponds globally where 90% of the world's standing irrigation water resides. There is a need to conserve such resources, considering more than two thirds of the world's population are currently experiencing water stress. Hence, this work tackles the conservation of such resources addressing two important issues related to energy and water, thereby addressing elements of the UN Sustainable Development Goals. Its considered approach is the use of floating solar photovoltaic (FPV) technology implemented on irrigation reservoirs to conserve water by reducing evaporation losses whilst providing sustainable electricity at enhanced yield that can be utilised locally. For the study, we selected an arid and water stressed region of Jordan where real-world water and energy consumption data were available. Various floating PV (FPV) system configurations were modelled for installation on an irrigation reservoir where currently no FPV exists. A fixed tilt 300 kWp FPV system was found to be the optimum design in terms of water savings, energy yield, economics, and reductions in CO_2 emissions. Standard floating PV was deemed the preferred option compared to ground-mounted PV and FPV with tracking and/or active cooling. System payback period for the recommended design was 8.4 years with an annual greenhouse gas emission reduction of $\sim$ 141TCO$_2$. For the considered site, around 12,700 m^3 of water can be saved annually or 42% savings when compared to the uncovered reservoir. This research has wider applicability to other arid regions such as Africa, Middle East, and the Indian Subcontinent.

1. Introduction

Water scarcity has become a major issue during the 21st century, with more than two thirds of the world's population under water stress for at least one month of the year and half a billion people experiencing severe water shortages daily [1]. Furthermore, water resources are not only needed for human consumption but also for agriculture and hence food. In many regions around the world extraction and delivery of water resources is highly dependent on energy. Hence the Food and Agriculture Organisation of the United Nations (FAO), has established the "water, energy and food security nexus" inextricable linkage meaning actions in any one particular area often can have effects in one or both of the other areas [2]. Hence, guaranteeing food supply is interlinked to water conservation and availability as well as energy and thus constituting a major challenge for global society [3]. A recent study indicated that globally irrigation is the largest consumer of fresh water representing around 70% of our water resources. In developing countries 90% of available water resources are used for irrigation as compared with 60% in developed countries [4]. Hence, in a developing country context, any approaches that can conserve and extend water availability, especially in hot, arid, and semi-arid climates will be highly appropriate not only from the point of view of food security but also in terms of economic development.

Water ponds has been used for centuries for both drinking water and crop irrigation. Globally, there are estimated 277,400,000 small scale (<10,000 m^2) and 24,120,000 large scale (10,000–100,000 m^2) irrigation ponds, representing more than 90% of the world's standing

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Nomenclature

A	Footprint of PV installation, m^2
CF_t	Cashflow in year t, $USD
D	Vapour pressure deficit, kPa
e	Vapour pressure, kPa
E	Open-water evaporation, mm/day
f	Inflation rate
f_u	Wind function
G_i	Carbon dioxide equivalent emissions, $kgCO_2e/kWh$
G_{PV}	Embodied greenhouse gases emissions, $kgCO_2e/m^2$
h	Height above ground, m
i	Real discount rate
i'	Nominal discount rate
K_d	Diffuse fraction of the global horizontal irradiation
K_t	Cloudiness index
LW	Long wavelength radiation, $MJ/m^2/day$
n	Project lifetime, years
R	Solar radiation at the surface
SW	Short wavelength radiation, $MJ/m^2/day$
T	Temperature, °C
U	Wind speed, m/s

Greek letters

α	Absorptivity of atmosphere
β	Energy losses associated with electricity transmission and distribution
Γ	Psychrometric coefficient, kPa/°C
Δ	Slope of the saturation vapour pressure curve, kPa/°C
λ	Latent heat of vapourisation, MJ/kg
σ	Stefan-Boltzmann Constant, W/m^2K^4

Subscripts

a	Actual
b	Beam
d	Diffuse
Free	Free water surface
LF	Large footprint Floating Photovoltaic
Max	Maximum
Min	Minimum
n	Net
s	Saturation
SF	Small Footprint Floating Photovoltaic
T	Total
W	Water

Acronyms

CAPEX	Capital Expenditure
FAO	Food and Agriculture Organisation for the United Nations
FIT	Feed-in Tariff
FPV	Floating Photovoltaics
GHG	Greenhouse Gas
HAT	Horizontal Axis Tracking
HDPE	High Density Polyethylene
HOMER	Hybrid Optimisation of Multiple Energy Resources
LCOE	Levelised Cost of Electricity
NOCT	Nominal Operating Cell Temperature
NPC	Net Present Cost
NPV	Net Present Value
OPEX	Operational Expenditure
SPIS	Solar-Powered irrigation system
VAT	Vertical Axis Tracking

Table 1
FPV Advantages and drawbacks compared to ground-mounted PV [7 10 11 12].

FPV advantages	FPV challenges
• Higher conversion efficiencies due to the cooling nature of water and in many cases the absence of dust. • FPV installations can reduce surface water evaporation. Particular importance in arid regions. • FPV requires no land, so does not compete with other land-users such as agriculture, mining or tourism. • FPV limits algae growth thus improving water quality. • Risk of theft and vandalism is reduced.	• Higher initial investment, operation & maintenance costs. • Uncertainty of long-term environmental impacts. • Electrical safety challenges when building and operating PV in water. • Metallic structures are more prone to corrosion, hence FPV has a shorter lifetime than ground-mounted PV. • Lack of separate regulations for permitting and licensing FPV projects.

irrigation water [5]. The use of these ponds is expanding considerably.

An approach to the challenges of the energy–water–food nexus particularly for water conservation and energy, is the use of solar photovoltaic (PV) modules (panels) to cover water bodies such as the ponds mentioned above. This results in multiple benefits for both water conservation and energy delivery from a particular site. Placing solar PV panels over water ponds using, for example, floating solar systems not only conserves water by reducing evaporation losses through effects on incident solar radiation and surface wind speed, but enhances the energy yield (hence economics) of the PV systems through the cooling effect [6]. An additional benefit of locating solar PV systems over such ponds reduces the need for land which can exploited for other benefits.

Despite the potential advantages mentioned above, the overall economic, environmental, social and technical benefits for utilising floating PV on irrigation ponds for the purposes of water conservation and pumping are unknown. To our knowledge practical examples of such utilisation has not been considered in the literature. Hence this body of work is unique as it models floating PV technology for a specific irrigation reservoir in an arid region for the dual purpose of reducing water evaporation and providing low carbon electricity at enhanced yield that can be utilised locally for groundwater pumping. The work also compares two categories of fixed tilt floating to ground-mounted PV designs coupled with tracking and active cooling systems. Furthermore, to address this critical knowledge gap, we quantified the evaporation savings, emissions, and economics based on real-world data of a reservoir in an arid and water stressed region of Jordan. The outcomes of this case study are important due to the nature of such regions where water stress is likely to be exasperated by the changing climate. Hence, the work provides opportunities to be exploited not only regionally but also globally where over 300 million water ponds exit. In essence, the approach presented here can be generalised to provide global assessment under different weather conditions.

1.1. Floating solar PV

Solar photovoltaics systems that float on a body of water were first developed in the 2000–2010 decade, with the first small scale system built in Japan in 2007, and the first commercial system was built in California in 2008 [7]. It was not until 2013 that installations larger than 1 MWp were developed. By the end of 2019, the total installed capacity of FPV exceeded 2 GWp [8]. By 2030, there will be an estimated 62 GWp of FPV globally. Today, Asia dominates the FPV market, with 87% of global capacity is situated [9]. To date, there are no FPV installations in Jordan.

As shown in Table 1, floating photovoltaics (FPV) have many advantages and drawbacks compared to ground-mounted PV installations [7 10 11 12].

There is a wealth of floating solar designs, thus indicating the nascent stage of the industry. However, researchers tend to classify them in three categories [13]:

1. **Free standing (Type 1):** Modules are high above the water surface with excellent convective cooling and a minimal footprint on the water. However, this type does not reduce surface water evaporation significantly.
2. **Small footprint on water (Type 2)**: Similar to Type 1 but modules are closer to the water surface and relatively small water surface coverage.
3. **Large footprint on water (Type 3)**: Water surface almost entirely blocked by floating structure with low convective cooling capability compared with Types 1 and 2. Usually consist of high-density Polyethylene (HDPE) rafts or pontoons. This type is likely to exhibit excellent water evaporation reduction capability.

Due to the similarities between Type 1 and Type 2, these can be grouped together into one category. Hence, these will be referred to as Small Footprint structures herein. As indicated above, it is apparent that a trade-off exists between evaporation reduction due to the high footprint on water and the increase in electricity production from the convective cooling effect. The Small Footprint FPV has good convective cooling effect and a poor evaporation reduction, whilst Large Footprint FPV is more than likely to have the opposite in both categories i.e., poor convective cooling effect and a good evaporation reduction [13].

Novel FPV technologies, aimed at improving the overall energy capture, include tracking (vertical, horizontal and dual-axis), active cooling mechanisms in the form of a water veil or sprinklers, concentrated FPV and submerged FPV (where the modules sit slightly below the surface of the water). Some installations incorporate multiple such facets. All of these technologies incur higher investment and maintenance costs compared to the standard fixed-tilt FPV design.

One of the main attractions of floating PV is the increased efficiency of the PV modules due to the evaporative cooling effect of the water body. To quantify the cooling effect the heat loss coefficient or U-value is used. H. Liu et al. [13] found that a Small Footprint structure has an average U-value of 46 W/m^{2}K, whereas a Large Footprint type has a U-value of 31 W/m^{2}K. By comparison, ground-mounted or rooftop PV systems have a U-value of 15–29 W/m^{2}K depending on the degree of ventilation. Oliveira-Pinto and Stokkermans [14] used Liu's U-values to simulate the energy production of FPV systems in three locations using PVSyst® [15]. It was found that a Large Footprint FPV installation has an increase in production of 0.31–0.46% while a Small Footprint installation has an increase in production of 1.81–2.59% compared to a ground-mounted PV system. In another study performed by Yadav et al. [16] where the power of a system based on a single module of capacity 250 W FPV installed on a high density HDPE floats (large footprint typology) was compared to a 250 W ground-mounted system. They found the power of the FPV system was 2.24% higher than the ground-mounted system. Simulations by L. Liu et al. [17] show similar results, where a power gain of 1.58–2.00% was presented. It is noted that these increases in performance are less than other literature sources which suggest very optimistic power gains, ca. 10% compared to ground-mounted PV [18 19].

Over the last decade several studies have reported the beneficial effect FPV can have on reducing evaporation from water bodies. This is achieved by (a) the floating structure provides shading and hence reduces the incident solar radiation on the water surface and (b) the free surface of water is covered and is subject less to the effects of wind. Santafé *et al.* published the earliest articles discussing FPV and evaporation [20 21]. Initially a 20 kWp prototype was installed on an irrigation reservoir prior to their consideration of a 300 kWp of FPV system covering the entire 4490 m^2 reservoir. A unique feature of their design was the flexible couplings between each platform which allowed the system to adapt to different water levels. Over the test period, it was estimated that 5,000 m^3 of water was saved from reducing evaporation, while producing 425 MWh of electricity annually. Rosa-Clot and Tina [22] performed simulations of FPV plants on wastewater basins in Bolivar, South Australia. Fixed and vertical axis tracking (VAT) systems, with and without cooling, were compared based on energy performance and water saving potential. It was concluded that a fixed system would allow greater coverage of the basins thus producing more energy and saving more water. Water cooling enhanced the energy yield by 10%. The authors quote that for every MWp of installed PV, between 15,000 and 25,000 m^3 of water would be saved. Other studies, investigating FPV and evaporation reduction include Durkovíc and Durišíc [23], Melvin [24], and Taboada *et al.* [25]. Other studies include those by Zhou *et al.* [26], which addressed the assessment for long term complementary operation between floating photovoltaic power and hydropower generation linked to average annual food production and Qasem Abdelal [27] which considered lab-scale, very small area (4 m^2) FPV which is more concerned with key water quality parameters such as nitrate and chlorophyll concentrations. The majority of studies relied on simulations of FPV plants, and there is a gap in knowledge for fully-fledged large-scale commercial projects and their role in reducing evaporation. Except for the work by Santafé *et al.* [20], there are no examples augmenting FPV with agricultural irrigation systems at scale in the literature.

Given that FPV installations are not as prevalent as ground-mounted PV, there is a degree of uncertainty surrounding cost data, both in terms of capital (CAPEX) and operating (OPEX) expenditure. Site location can also influence costs of FPV significantly with factors such as bathymetry, water-level variation and wind characteristics all playing a role. Here, the literature surrounding the economics of FPV systems is discussed. At present the CAPEX of FPV is greater than that of ground-mounted PV due to the floating support structure, the associated mooring and anchoring system and the underwater DC cabling. Reindl *et al.* [7] states that the total CAPEX for FPV projects in 2018 was $800–1200 per kWp, having fallen from $2000–3000 per kWp in 2015–2016. This is broadly consistent with other literature sources. For instance, Rosa-Clot [22] quotes $1100/kWp for FPV plant in Australia while Goswami *et al.* [28] suggest a 10 MW FPV plant in India would cost $940/kWp. As with other renewable energy technologies, economies of scale are likely to bring the cost of FPV down significantly over the coming years, especially the cost of the floating support structures. In terms of operation and maintenance costs, Reindl [7] suggests a value of $11/kWp/year, exactly the same as for ground-mounted PV. Goswami [28], on the other hand, suggests $19.7/kWp/year. For FPV systems incorporating tracking and/or cooling technology both Giuseppe [29] and Durkovíc [23] propose OPEX costs in the region of $20/kWp/year. The Levelised Cost of Electricity (LCOE) for FPV installed in a desert climate was estimated to be around $54 per MWh [7]. A corresponding ground-mounted PV system has an LCOE 8–9% lower than that of FPV. This difference will likely be narrowed as the FPV technology scales up.

Solar-powered irrigation systems (SPIS) are also a technology becoming ever more common. A number of studies have shown the benefits of deploying this technology in Jordan [30 31]. The growth of both FPV and SPIS is likely to be accelerated by the reduction in cost of photovoltaic systems. However, to our knowledge, there have been no studies examining the potential to combine FPV and SPIS in a Middle East context. This is at the core of this research which aims to investigate and design an FPV-SPIS system on a known site in Jordan where there is a requirement for such a combination. The work considers two distinct classes of FPV installations to be compared and assessed, namely, Large Footprint FPV and Small Footprint FPV. The economics and environmental implications of the scheme in a Jordanian context will be assessed. The work has wider applicability where remote, enhanced sustainable power and water evaporation reduction are needed.

Fig. 1. Overhead Image of Farm 'A' with irrigation reservoir highlighted [41].

2. Case study approach

One of the worst affected countries is the Kingdom of Jordan. According to the World Resource Institute, Jordan is ranked fifth place in terms of countries suffering from water scarcity issues [32], with an annual water resource is 145 m^3 per capita [33], far lower than the United Nation's 500 m^3 threshold that indicates absolute water scarcity. This problem is getting worse due to a growing population and the impact of climate change. Climate change is leading to unpredictable rainfall while increasing temperatures are causing surface water evaporation and a more arid landscape. For Jordan, more than 90% of annual precipitation is lost through evaporation [34]. Hence, finding ways to reduce surface water evaporation can become a major step towards improving the nation's ground and surface water resource.

Jordan also lacks natural resources but is blessed with a lot of sunshine. It relies heavily on imported fossil fuels to meet its electricity demands (ca. 90%) costing 10% of the country's GDP [35]. This not only poses an energy security problem but also makes the country vulnerable to fluctuations in fuel prices. Recently there has been a push to install solar photovoltaics (PV), with more than 800 MW solar PV capacity currently installed and a goal of 2.2 GW by 2021 is in place [36]. This is part of a wider goal to reach 10% of the country's electricity needs from renewables by 2020 [37]. Jordan has the potential to become a sustainable energy hub of the Middle East as it is one of the most economical and politically stable nations in the region. Jordan's PV industry has significant room for growth, especially considering its solar resource which averages at 5.6 kWh/m^2/day and 310 sunny days per year [35]. In Jordan, a 100% tax exemption for ten years for renewable energy investments in certain regions of the country is in place, particularly those where socio-economic developments are required [35]. Another financial incentive was the 0.17 $/kWh feed-in-tariff (FIT) from 2012 [38] which was revised downwards to $0.148 per kWh for 2016 and 2017 [39]. It is due to be revised yet again to $0.0705 per kWh thereafter [40].

The aim of this research is to investigate and design an FPV-SPIS system on a known site in the Jordan where there is a requirement for such a combination. The case study site is 'Farm A' [41], a 54 ha farm located in the Mafraq governate of Northern Jordan where irrigation is supported by pumped ground water into a large reservoir. The four systems selected for modelling and comparison are given in Section 3.2 with definitions explained under Section 1.1. The system design is based on real operation data from the farm and will have the dual purpose of saving water evaporation from an irrigation pond and providing electricity to two pumps for irrigation.

Established in 2003, the farm cultivates four crops, namely olives, stone fruit, pomegranates, and grapes. Water for irrigation is provided from groundwater using a submerged 83 kW pump in a private well. Water from the well is stored in an irrigation reservoir of area 13,500 m^2 and depth 7 m. A 37 kW booster pump from the reservoir to the irrigation pipelines is also installed. At present, the two AC pumps are powered by grid electricity at a price of $0.12 per kWh.

Fig. 1, below, depicts an overhead image of Farm 'A'.

3. Methodology

This section describes the methodology undertaken in this research. It involves a PV system design using HOMER Pro®, estimations of surface water evaporation rates, economics, and estimations of carbon dioxide equivalent emissions.

3.1. System design

HOMER Pro® microgrid software was used to design the PV system capable of satisfying the well and booster pumps at Farm 'A'. HOMER (Hybrid Optimisation Model for Multiple Energy Resources) is the global standard for designing and optimising microgrids. It works by choosing the system with the lowest total Net Present Cost (NPC) from a set of variables and constraints.

The total NPC (or life-cycle cost) of a system is defined as the present value of all costs the system incurs over the project lifetime, minus the present value of all revenues it makes over the project lifetime [42]. It is calculated using Discounted Cash Flow (DCF) analysis. The costs include installation costs, operation and maintenance costs, and replacement fees. Revenues, on the other hand, include sales of electricity to the grid and the salvage value once the project is completed. The NPC is a convenient method to compare different options, with the lowest NPC scenario being the most economically favourable one. NPC can also be referred to as Net Present Value (NPV) which is identical except multiplied by negative one. For financial analysts, NPC or NPV is the most common tool when comparing the feasibility of different projects.

Net Present Cost is presented mathematically in Equation (1) below:

$$NPC = \sum_{t=1}^{n} \frac{CF_t}{(1+i)^t} \tag{1}$$

Where CF_t is the cashflow in year t i.e. the sum of all costs minus the sum of all revenues, n is the project lifetime and i is the real discount rate (or interest rate), calculated as:

$$i = \frac{i^{'} - f}{1 + f} \tag{2}$$

Where i' is the nominal discount rate and f is the expected inflation rate [43]. Hence, the time value of money is incorporated into Net Present Cost.

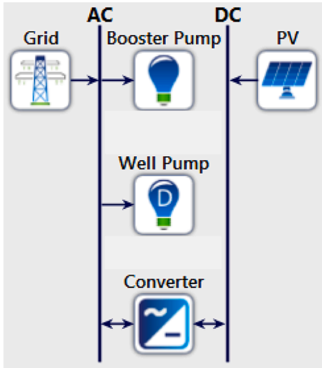

Fig. 2. HOMER Pro® system schematic.

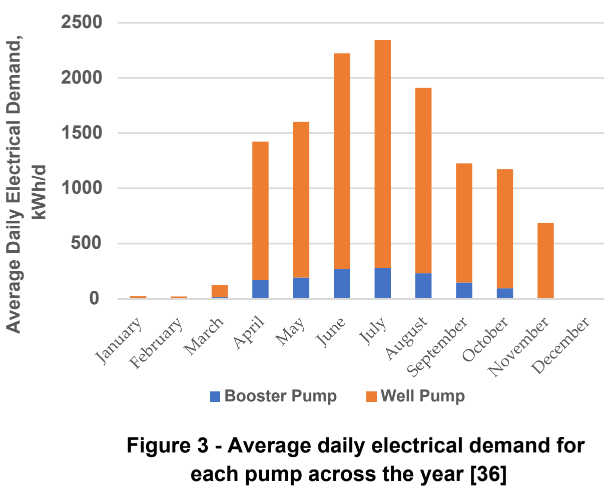

Fig. 3. Average daily electrical demand for each pump across the year [36].

The system consists of six elements – PV array, DC to AC converter, grid electricity, booster pump load, well pump load and the irrigation reservoir. Fig. 2 shows the HOMER Pro® schematic of the system. A detailed list of specifications for the system design can be found in Appendix A.

From analysis of the energy consumption used in the farm, it is estimated that for every m^3 of water pumped by the irrigation system, 1.55 kWh of electrical power was required. Fig. 3 shows the average daily electrical demand of the well and booster pump in each month of the year based on farm operational data [44]. Resource data for global horizontal irradiation and average daily ambient temperature were imported to HOMER Pro® from NASA Surface Meteorology and Solar Energy Database [45] as shown in Fig. 4.

3.2. PV systems analyses

A scenarios analyses approach was undertaken to determine and understand the PV system requirements for the farm based on electrical demand of the farm and solar resource. Initially, a business-as-usual scenario using grid electricity to power both pumps (i.e., no PV) was modelled to determine the NPC of the required system at Farm 'A' where no changes are made to the irrigation system. In this scenario, grid electricity was purchased at a rate of $0.12/kWh. As such, there is no capital expenditure associated with this scenario and operational costs arise purely from purchasing grid electricity.

Next, the FPV scenarios were modelled with input parameters shown in Table 2. This was done for both a small footprint and large footprint type floating structure. Finally, a system with ground-mounted PV was simulated. In all the scenarios incorporating PV, grid electricity providing backup power was modelled. Any excess energy captured from the PV systems was sold to the grid at $0.0705/kWh.

PV system analyses using HOMER Pro® were undertaken for the following scenarios:

1. Reservoir with no PV; power from Jordanian national grid.
2. Small Footprint FPV.
3. Large Footprint FPV.
4. Ground-mounted PV.

Table 2
Parameters used as inputs to simulation model for all PV scenarios.

Load	
Well Pump Average Load (kWh/d)	121.6
Deferrable Load Storage Capacity (kWh)	10,000
Booster Pump Average Load (kWh/d)	851.9
Random day-to-day variability for booster pump	5%
Random hourly variability for booster pump	5%
PV system	
Grid Interconnection Charge	$100 per kWp [46]
Efficiency	18% [47]
Derating Factor	80%
Temperature Effects on Power	−0.4 %/°C [47]
Annual Performance Degradation	0.7 %/year [48]
Inverter	
CAPEX	Cost Curve generated from [49]
Replacement Cost	90% of CAPEX
OPEX	5% of CAPEX
Efficiency	95%
Lifetime	15 years
Grid Tariffs	
Purchasing Price	$0.12/kWh [41]
Selling Price	$0.0705/kWh [40]
Financials [50,51]	
Nominal Discount Rate	8%
Expected Inflation Rate	2%
Project Lifetime	20 years
Max. Annual Capacity Shortage	2%

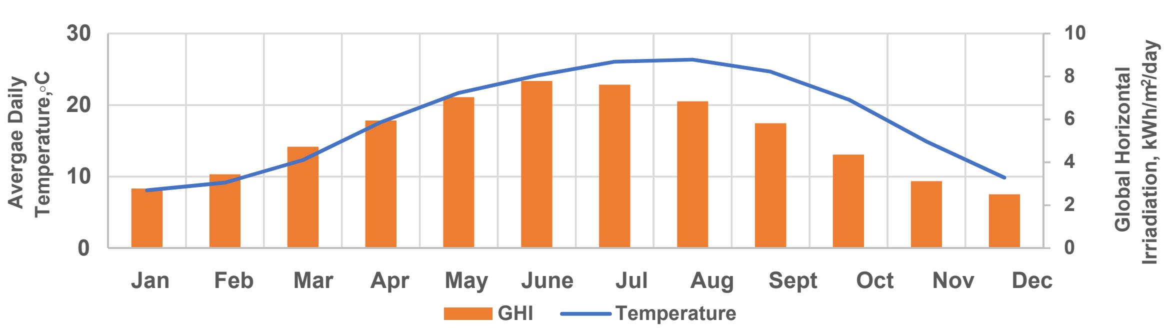

Fig. 4. Average Global Horizontal Irradiation and ambient temperatures at 32.5° N, 36.5° E for each month of the year.

Table 3
Comparison between HOMER Pro® inputs for FPV and ground-mounted PV.

	Floating PV (Scenario 2 & 3)	Ground-mounted PV (Scenario 4)	Notes
PV CAPEX ($USD/kWp)	1000	900	CAPEX of FPV tends to be $100/kWp more than ground-mounted PV [7]
PV OPEX ($USD/kWp/year)	11	11	[7]
Nominal Operating Cell Temperature (°C)	40 for Small Footprint [13] 44 for Large Footprint [13]	48 [47]	To account for evaporative cooling effect
Ground Reflectance	6% [13]	20%	20% is the default value for HOMER Pro® for ground-mounted PV.
Panel Inclination (°)	10	32	32° is the optimum tilt angle for Farm 'A'. FPV inclination typically between 10° & 15°. Once initial modelling was complete the FPV inclination angle was optimised based on NPC and renewable energy yield.

Table 4
Cost comparison between advanced energy capture technologies for FPV.

	Horizontal Axis Tracking	Vertical Axis Tracking	Active Cooling	HAT + Cooling	VAT + Cooling
CAPEX ($USD)	1200	1200	1063	1263	1263
OPEX ($USD/year)	20	20	25	25	25

A comparison between the floating PV and ground-mounted PV specifications are shown in Table 3.

The impact of incorporating advanced technologies to improve the energy capture of FPV were then assessed. This was done for both small footprint and large footprint FPV. The technologies assessed were:

- Horizontal axis tracking (HAT)
- Vertical axis tracking (VAT)
- Active cooling mechanism
- HAT and active cooling
- VAT and active cooling

FPV systems which use tracking technology have a higher capital investment and higher operation and maintenance costs, but improved energy capture. Hence, it was assumed the CAPEX and OPEX for a system incorporating single axis tracking technology $1,200 per kWp and $20/kWp/year respectively.

As with tracking technology, the use of active cooling technologies incurs additional CAPEX and OPEX requirements. Dizier [52] estimates that deploying a sprinkling type cooling system adds $63/kWp of CAPEX and the FPV with cooling has an OPEX of $25/kWp/year while improving the energy capture of the system by 6.6%. The cost specification comparison for these options is summarised in Table 4. Submerged PV, FPV with concentrators and bi-facial FPV were not analysed as part of this study due to the nascent stage of these technologies.

3.3. Estimation of surface water evaporation

In this section, the methods used to estimate the surface water evaporation with and without floating PV are described.

3.3.1. Method for open water surface

Water evaporation from the irrigation reservoir was estimated using the well-established Penman Equation (3), [53].

$$E = \frac{\Delta}{\Delta+\gamma}\cdot\frac{R_n}{\lambda} + \frac{\gamma}{\Delta+\gamma}\cdot\frac{6.43\,(f_u)D}{\lambda} (\textit{SEQ Equation} \backslash * \textit{ARABIC}\,3).$$

Where E is the open-water evaporation in mm/day, R_n is the net radiation at the surface in MJ/m^2/day, Δ is the slope of the saturation vapour pressure curve in kPa/°C, γ is the psychrometric coefficient in kPa/°C, λ is the latent heat of vapourisation in MJ/kg, f_U is the wind function and D is the vapour pressure deficit in kPa.

The term, Rn, in Equation (3) was calculated using the following equations:

$$SW_n = (1-\alpha)(R_d + R_b) \tag{4}$$

$$LW_n = \sigma T_w^4 (0.56 - 0.0092\sqrt{e_a})(0.1 + 0.9C) \tag{5}$$

$$R_n = SW_n + LW_n \tag{6}$$

Where R_d is the diffuse irradiation in MJ/m^2/day, R_b is the direct beam radiation in MJ/m^2/day, α is the absorptivity of the Earth's atmosphere, taken to be 0.3, SW_n is the net incoming short wavelength radiation in MJ/m^2/day, LW_n is the net incoming long wavelength radiation in MJ/m^2/day, σ is the Stefan-Boltzmann constant, 5.67x10^{-8} W/m^2/°C^4 and C is the cloudiness index. For simplification, the summation of R_d and R_b in Equation (4) was taken to be equivalent to the global horizontal irradiation, R_{GHI}. This assumption has limited impacts on the results of the calculation [54].

3.3.2. Evaporation estimation incorporating FPV

To incorporate FPV into the evaporation model, the method described by Scavo et al. was deployed [55]. Below is the consideration for undertaken for the two floating PV cases.

A) Small Footprint FPV:

Small Footprint FPV systems are not completely in contact with the water surface, so they protect the water surface from direct beam radiation but not diffuse radiation. Hence, Equation (4) is modified to only include the diffuse component of the solar radiation as shown in Equation (7).

$$SW_{nSF} = (1-\alpha)R_d \tag{7}$$

R_d is the diffuse horizontal radiation in MJ/m^2/day, which is determined as from Equation (8).

$$R_d = K_d R_{GHI} \tag{8}$$

Where K_d is the diffuse fraction of the global horizontal radiation, R_{GHI}. It is calculated from the following empirical Equation for Amman, Jordan [56] which uses the cloudiness index, C defined in Equation (9).

$$K_d = 0.847 - 0.985C \tag{9}$$

The net longwave radiation is calculated using Equation (10).

$$LW_{nSF} = \sigma T_w^4 (0.56 - 0.0092\sqrt{e_a})(0.1 + 0.9\times 0.3) \tag{10}$$

To determine the evaporation rate from the entire irrigation reservoir, E_{FPV}, we incorporate the fraction of the water's surface covered by the FPV structure, x, determined from Equation (11).

$$E_{FPV} = E_{free}(1-x) + xE_{nSF} \tag{11}$$

Where E_{Free} is the evaporation from the free surface not covered by the FPV structure.

B) Large Footprint FPV.

For Large Footprint FPV systems, negligible solar radiation hits the

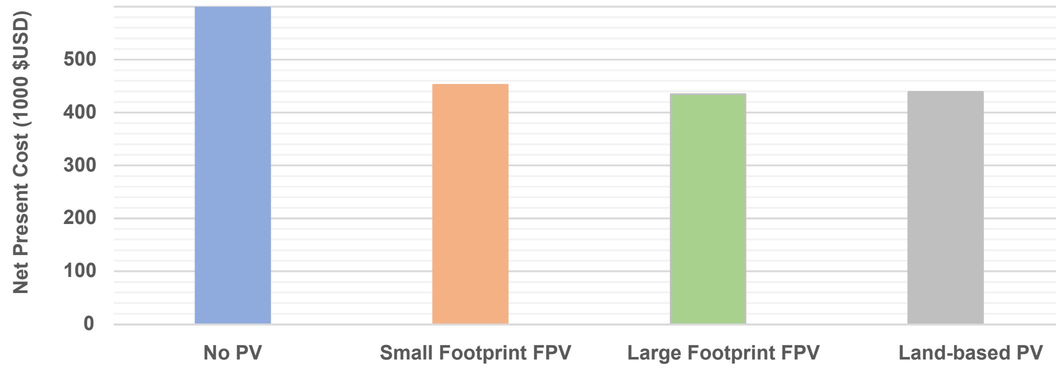

Fig. 5. NPC comparison between No PV, small footprint FPV, large footprint FPV and ground-mounted PV.

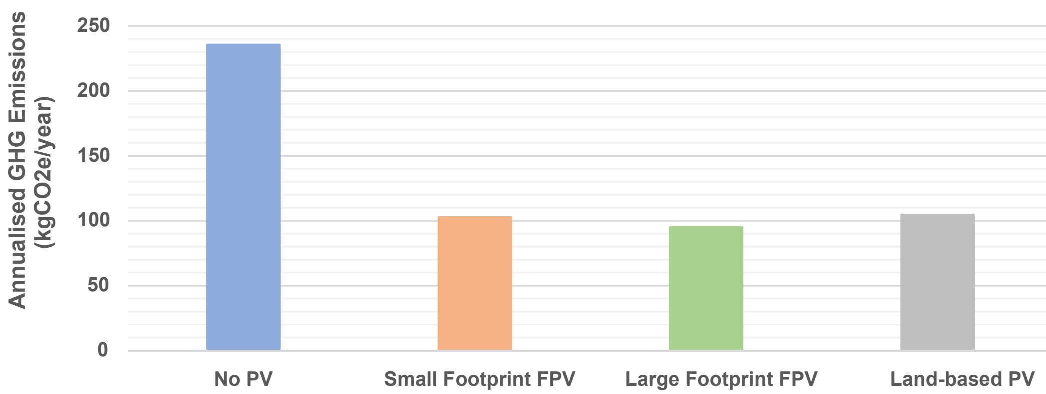

Fig. 6. Annual GHG emission comparison between no PV, small footprint FPV, large footprint FPV and ground-mounted PV.

surface of reservoir. As a result, the equations are modified to:

$$SW_{nLF} = 0 \tag{12}$$

$$LW_{nLF} = \sigma T_w^4(0.56 - 0.0092\sqrt{e_a})(0.1) \tag{13}$$

$$R_n = R_{free}(1 - x) + xR_{LF} \tag{14}$$

$$E_{FPV} = (1 - x)E_{free}' \tag{15}$$

Where R_{Free} is the net radiation on a free water surface and E_{Free}' is the evaporation rate when R_n is calculated using Equation (3).

3.4. Estimation of greenhouse gas emissions

The total greenhouse gas emissions, G_T, for the 'no PV' or business-as-usual scenario was estimated using Equation (16).

$$G_T = \sum_i^n G_i{}^*E_S{}^*(1+\beta) \tag{16}$$

Where G_i is the carbon dioxide equivalent emissions per unit grid electricity produced in Jordan in $kgCO_2e/kWh$ in year i, E_S is the annual energy consumption by the system in year i, β is the energy losses associated with electricity transmission and distribution taken to be 12% [57], n is the project lifetime taken to be 20 years.

While the FPV system itself does not emit any greenhouse gases, there are emissions associated with manufacturing, transportation, and installation. For the PV scenarios, some grid electricity had to be purchased to provide power during high demands or during periods of low solar resource. The greenhouse gas emissions for the PV scenarios were estimated using Equation (17).

$$G_T = A^*G_{PV} + \sum_i^n G_i{}^*E_g{}^*(1+\beta) \tag{17}$$

Where A is the footprint of the FPV installation in m^2, E_g is the annual grid electricity purchased from the grid in kWh, G_{PV} is the embodied greenhouse gases emissions of the PV system in $kgCO_2e/m^2$. For a ground-mounted PV system, the embodied carbon emissions are 115 $kgCO_2e/m^2$ [20]. For floating PV, Santafé *et al.* [20] estimates embodied emissions of 137.73 $kgCO_2e/m^2$. To be on the conservative side, a value of 150 $kgCO_2e/m^2$ was used for this analysis.

4. Results

This section provides a summary of the results for the various scenarios modelled and their implications to water evaporation, economics and emissions.

4.1. Comparison of modelled PV systems

Based on the input data, including operational data for the farm, the simulations indicated that a 300 kWp PV system and 200 kW inverter as the cost optimum solution for the FPV scenarios. To make a fair comparison between FPV and ground-mounted PV, the same PV and inverter capacity were chosen for the ground-mounted PV scenario. Figs. 5-7 below compare the four scenarios based on NPC, annual evaporation, and annualised greenhouse gas emissions. A complete list of the overall modelling results can be found in Appendix A and recommended system designs are in Appendix B.

Fig. 5 shows that large footprint FPV is the most economically attractive option. Meanwhile the business-as-usual scenario is the least attractive from an NPC standpoint. Fig. 7 shows the Large Footprint FPV reduces surface water evaporation dramatically while the Small

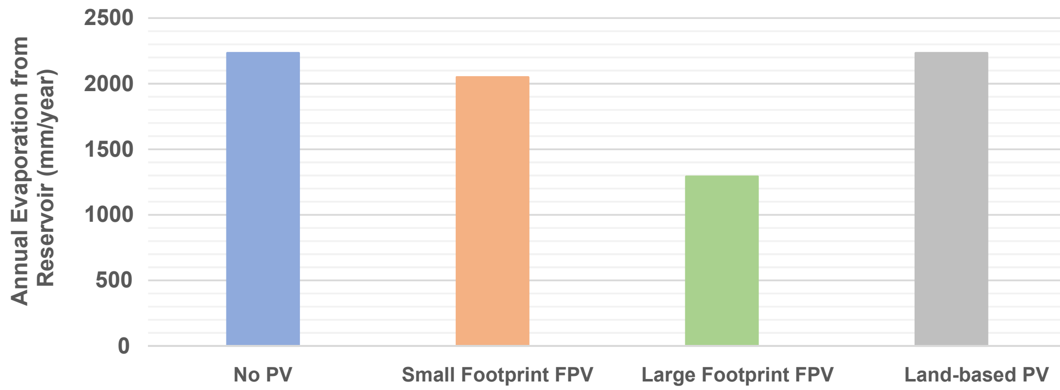

Fig. 7. Annual evaporation comparison between no PV, small footprint FPV, large footprint FPV and ground-mounted PV.

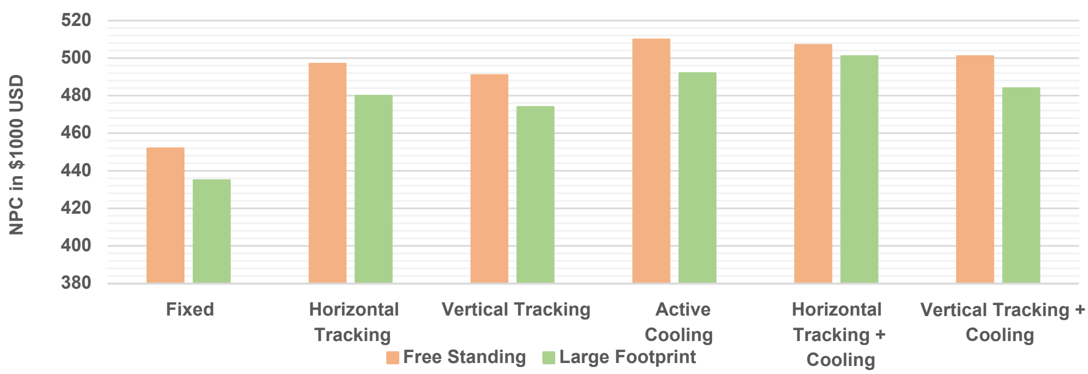

Fig. 8. Net Present Cost comparison between fixed FPV and FPV with advanced energy capture technologies.

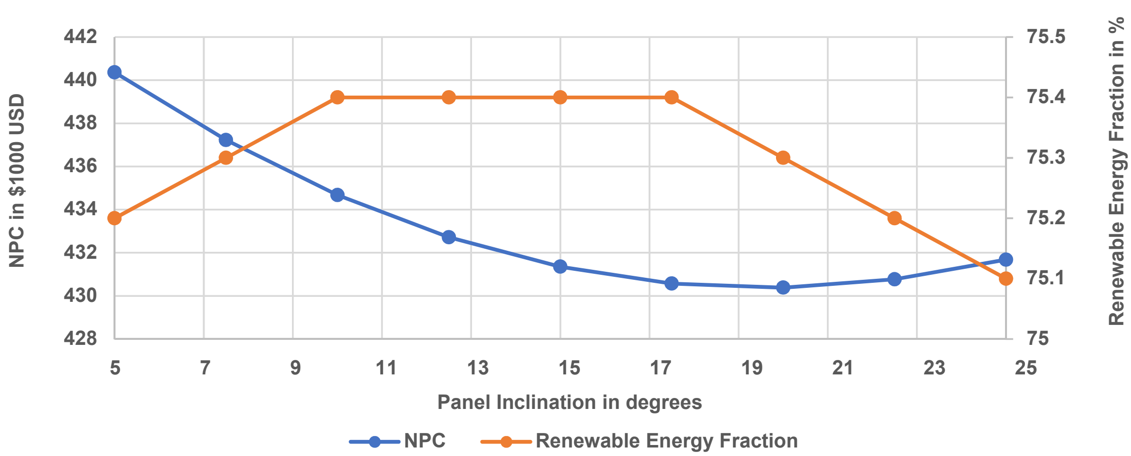

Fig. 9. Impact of panel inclination on NPC and renewable energy fraction.

Footprint FPV installation only reduces evaporation by around 200 mm per year. Fig. 6 shows all PV options reduce greenhouse gas emissions substantially, with the Large Footprint FPV reducing emissions the most compared to ground-mounted PV and Small Footprint FPV. The Large Footprint design was estimated to save 141 tCO_2e per year compared to the 'No PV' scenario.

From the results shown in the Figs. 5 – 7 it is evident that the 'No PV' or business-as-usual scenario is the least attractive option given it has the highest NPC, highest GHG emissions, and highest annual evaporation from the irrigation reservoir. Its only advantage is the zero-capital expenditure compared to the other options.

The ground-mounted PV option has an NPC competitive with the two FPV options. On the basis that it has higher annualised GHG emissions and does not reduce evaporation from the reservoir, it was deemed unfavourable compared to the FPV scenarios.

The best option is the Large Footprint FPV since it saves a large amount of water from evaporation (Fig. 7) and has the lowest GHG emissions (Fig. 6). Its NPC is also slightly lower than the small footprint type FPV option (Fig. 5). The Large Footprint design was estimated to have a simple payback of 8.4 years.

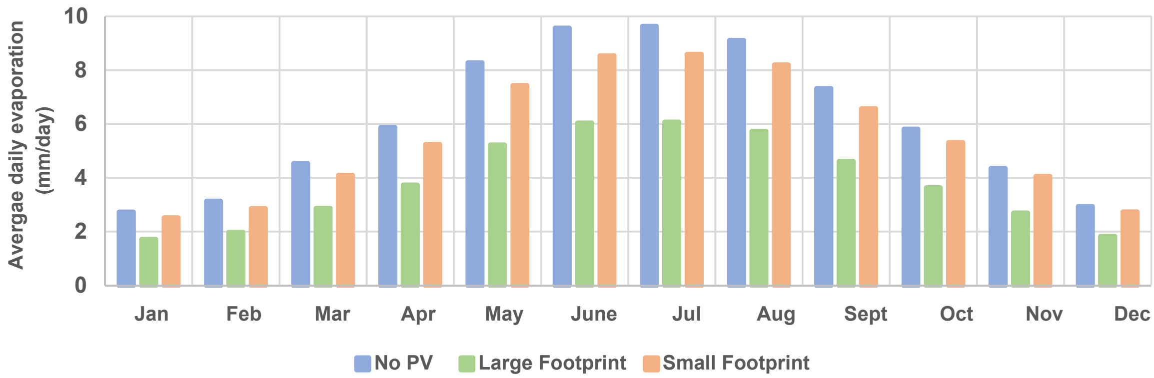

Fig. 10. Average daily evaporation in each month of year for the No PV and FPV scenarios.

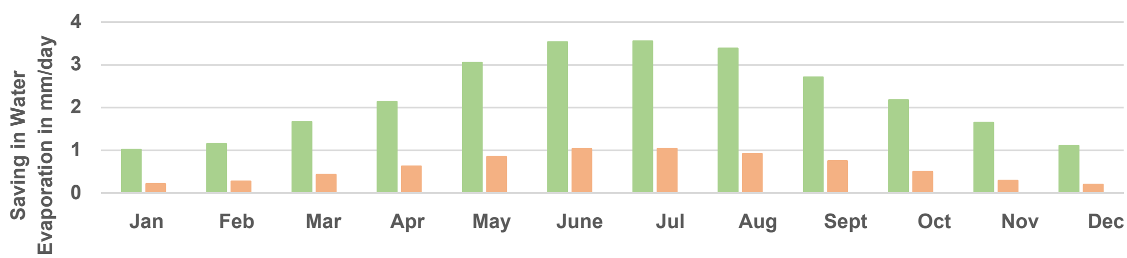

Fig. 11. Average daily savings in evaporation in each month of the year for large footprint and small footprint FPV.

Table 5
Enhanced energy capture of FPV compared to ground-mounted PV model.

FPV Typology	Operating Cell Temperature in °C (reduced from the 48 °C standard)	Annual electricity production in MWh for 300 kWp FPV System	Annual electricity production in MWh for equivalent 300 kWp ground-mounted System	% increase in energy production
Large Footprint	44	462	456	1.3%
Small Footprint	40	467	456	2.4%

Table 6
Water saved in terms of m^3/MWh, m^3/MWp and percentage savings compared to literature.

	300 kW Large Footprint FPV	300 kW Small Footprint FPV	Published Literature Data
Water saved (m^3/MWh)	27.5	3.2	0.8–30
Water saved (m^3/MWp)	42,000	7,500	1,200–60,000
Percentage saving compared to equivalent area of free surface	75%	43%	60–90%
Percentage saving compared to entire reservoir uncovered	42%	8.3%	–

4.2. Impact of using advanced energy capture technologies

Based on HOMER Pro® the best system design chosen to simulate advanced technologies, such as tracking and cooling, has a PV capacity of 200 kWp and a 150 kW inverter.

Fig. 8 compares the NPC of these scenarios to the standard fixed tilt FPV scenarios. The figure shows that a standard fixed tilt FPV without active cooling system is superior in terms of its NPC than FPV with tracking and/or active cooling when designing a FPV solution to satisfy the requirements of Farm A's water pumping.

At present, the additional costs of these technologies in terms of CAPEX and OPEX outweigh the advanced energy capturing properties. If the costs of tracking and cooling decline, then these technologies may become competitive in the future. There is also the added practical problem associated with maintenance. Farm 'A' is in a rural location so access to suitably qualified maintenance staff is problematic. Tracking and active cooling both require a more intensive maintenance schedule compared to standard FPV. Hence, this further justifies why standard fixed tilt FPV without active cooling is preferable for Farm 'A'.

4.3. Impact of PV module inclination

Compared to all other scenarios, including business-as-usual, ground-mounted PV, Small Footprint FPV and FPV with tracking and/or cooling, a fixed tilt FPV with a Large Footprint type structure was deemed best across all three criteria as discussed in Sections 4.1 - 4.2. The impact of altering the panel inclination angle on the Net Present Cost and fraction of renewable energy consumed by the project was investigated next as shown in Fig. 9. It is clear from the results that the optimum tilt angle in terms of NPC is 20°. However, commercial FPV installations rarely exceed an angle of 15° so that they can withstand wind loads. A tilt of 15° corresponded to the highest renewable energy fraction, hence reducing greenhouse gas emissions. On these bases, an inclination angle of 15° was selected for the recommended system design.

4.4. Evaporation and cost savings

Based on the model, described by Scavo *et al.* [55], to estimate the evaporation rates with and without floating PV, it is apparent that the Large Footprint FPV structure reduces evaporation the most. Fig. 10 shows the average daily evaporation in each month of year for the 'No PV' and FPV scenarios. Fig. 11 shows the average daily savings in evaporation in each month of the year for Large Footprint and Small Footprint FPV. As can be seen from the figures, the Large Footprint PV provides the maximum reduction in evaporation and hence water savings as compared with the other scenarios.

The marked difference in evaporation rates between the Large Footprint and Small Footprint FPV is due to the fact that the former blocks almost all incoming short wavelength radiation while the latter blocks only direct beam radiation while diffuse radiation is still subjected to the water surface.

In addition, the water savings from deploying FPV will also result in a reduced electrical demand since less water is required to be pumped to the irrigation reservoir. There is, hence, a cost saving associated with the water saving for each type of FPV design. For the Large Footprint design, this cost saving is estimated to be $1,360 per year while the Small Footprint FPV saves around $280 per year. This cost saving was estimated using Equation (18) with the values for the large footprint design given as an example.

$$CostSaving = 1.55\frac{kWh}{m^3} \times 12,700\frac{m^3}{year} \times \frac{\$68.1}{MWh} = \$1,360 peryear \tag{18}$$

Where 1.55 kWh/m^3 is the energy requirement of the two water pumps mentioned earlier, $68.1/MWh is the Levelised Cost of Electricity (LCOE).

5. Discussion

5.1. Enhanced energy capture due to evaporative cooling effect

As stated in Table 3, section 3.2, the evaporative cooling effect of water on the PV modules was modelled by reducing the nominal operating cell temperature from the standard 48 °C to values given in Table 3. To check this assumption was correct, the annual electricity production from the PV was compared as shown in Table 5. This is broadly consistent with the findings by Oliviera-Pinto [14], Yadav [58] and L. Liu [17]. Hence, the assumptions were deemed appropriate.

5.2. Water evaporation reductions

The model used to estimate the evaporation under the 'No PV' scenario yielded a total of 2235 mm/year (see Appendix C). This is consistent with literature values which stated that, in Northwest Jordan, the annual surface water evaporation is 1900 mm [59].

In terms of the evaporation under the FPV scenarios, the Large Footprint FPV saves 42% of water compared to an uncovered reservoir whereas the small footprint FPV saves 8% of water compared to an uncovered reservoir. These values are consistent with literature, hence the model used can be deemed appropriate.

The water savings in terms of m^3/MWh and m^3/MWp are shown in Table 6 below. Hence, the model used is consistent with the literature.

5.3. Limitations of FPV in Jordan

The significant up-front cost of floating PV is one of the main drawbacks for implementing the technology in Jordan. The proposed system has a capital expenditure of $USD 344,000. This level of investment is unviable unless the farm owner has access to finance or can receive support through a water-energy-food saving scheme that may be required in the future.

Another drawback is maintenance, although Jordan has capable engineering capacity, rural locations may present a challenge to provide urgent support when needed. Nevertheless Farm 'A' is accessible by road and is 1 h and 15-minute drive from the capital city, Amman, so accessing maintenance should not be problematic.

5.4. Recommendations to increase uptake of FPV in Jordan

The Feed-in Tariff (FIT) for the project was taken to be $0.0705 per kWh, the most up to date value for grid-connected PV projects in Jordan, which is less than half what it was in 2012 ($0.148 per kWh). It is unclear whether the FIT will reduce again but should the value change, the modelling and the Net Present Cost of the FPV system would need to be updated to reflect this.

Other countries have specific FITs for floating PV such as Vietnam where the FPV Feed-in Tariff is 8.5% higher than that of ground-mounted PV [60]. Taiwan, has a generous FIT for FPV, set at $0.14/kWh in 2019 compared to $0.13/kWh for ground-mounted PV [61]. It is therefore, recommended that Jordan adopts a similar policy whereby the financial incentives for FPV are greater than ground-mounted PV to encourage uptake over the coming years.

Another financial incentive that could be applicable for FPV in Jordan include a Renewable Energy Certificates (REC) scheme whereby FPV has a higher weighting than other forms of electricity generation such as the scheme in South Korea [62]. At present, Jordan does not have such as scheme, but it is being considered for the future [63].

Should Jordan want to deploy multi-MW FPV projects, it is recommended that the tendering process is separated from ground-mounted PV as is the case in Taiwan and India [7]. Jordan has several large water bodies, such as King Talal Dam and Sharhabeel Dam which may be suitable for housing large scale FPV installations. Deployment of large-scale FPV would improve Jordan's energy security, by reducing its reliance on fossil fuel imports from neighbouring countries.

In essence, this study has wider applicability, not just at Farm 'A', but at many such farms in Jordan where irrigation reservoirs are present. Where farms are not connected to the national grid, floating PV would be a particularly attractive option for irrigation pumping compared to pumps powered by diesel generators.

5.5. Global recommendation for utilising FPV on irrigation reservoirs

Water resources are essential for both drinking water and crop irrigation, most of this is derived from freshwater reservoirs or ponds. Globally, these reservoirs represent a very large surface area for deployment of floating PV reducing the impact on valuable land whilst providing clean power for pumping at enhanced energy yield. In a development setting and in addition to their role in providing water, these reservoirs present a resource that can be exploited for power generation whilst reducing evaporation of scares water. The generated power could be used for the required pumping but also as an anchor load for remote communities' power supply systems.

In developing countries where 90% of irrigation stems from such reservoirs, which are mainly located in remote areas where the national grid supply is either not available or is weak and unreliable. Hence, it can be envisaged that the FPV system could also represent the power plant for a community mini grid supplying energy to services such as schools, health clinics, other surrounding buildings [64–67] Furthermore, it is clear from our analyses that the presented approach can alleviate some of the challenges of the energy–water–food nexus, particularly for water conservation and the displacement of fossil fuel utilisation. Hence, the local and global benefits from deploying FPV on reservoirs are vast not only from the point of view displacing carbon but also in addressing such a nexus whilst providing a nucleus for development in remote off grid areas.

Our recommendation, which is part of our future work, is to map these reservoirs and their surrounding demographics in a selected representative sample of developing countries to scope the potential for community power generation and how this can be linked to reducing water evaporation through the installation of PV on these reservoirs. The work will also need to address policy and economic implications taking into account the added benefit of power supply to the community. The work will culminate in providing a road map for such deployment backed up with evidence for policy makers and financial institutions, such as the World Bank.

6. Conclusions

Water resources are central to human and are essential for biodiversity. Water, energy, and food security are inextricably linked and, as such, this nexus is a major global societal challenge. There are over 300 million drinking water and irrigation ponds (reservoirs) globally where 90% of the world's standing irrigation water resides and their use is expanding considerably. Hence, this work tackles two important issues related to energy and water in such reservoirs, thereby addressing elements of the UN Sustainable Development Goals.

Floating solar photovoltaics (FPV) is a developing technology normally generating electricity from systems deployed on water bodies thus eliminating the need for utilising valuable land. The feasibility of a floating photovoltaic system, that can be deployed on irrigation reservoirs was investigated. The case study selected was Jordan, a country with a harsh environment and scarce water resources. The systems investigated have the dual purpose of (a) providing power to two irrigation pumps at the case study farm and (b) reducing water evaporation from the reservoir. Three main criteria were used to establish the best option: water savings, economics, and greenhouse gas emissions. An optimisation tool was used to select the best system design based on Net Present Cost. Water evaporation rates were estimated using the Penman Equation. The method outlined by Scavo et al. [55] was deployed, to account for the presence of FPV, in the evaporation rate modelling.

It was found that a 300 kWp large footprint type FPV structure with a tilt of 15° connected to a 200 kW inverter was the best solution across all three criteria. Augmenting advanced energy capture technologies to the system, such as tracking and cooling, were deemed economically unfavourable by comparison to the fixed FPV options. Hence, a standard fixed tilt design without active cooling was adopted. The proposed FPV design was also deemed favourable economically compared to an equivalent ground-mounted PV system.

In terms of water evaporation benefits, the FPV installation was estimated to save 12,700 m^3 of water per year. This is equivalent to a saving of 42% of water as compared to the business-as-usual scenario (without PV cover). The financial impact of reducing evaporation was estimated to be a saving of $1,360 per year for the farm.

The proposed system was estimated to save 141 tonnes of carbon dioxide equivalent emissions per year. A simple payback time of 8.4 years and an NPC $170,000 less than the current regime of pumping irrigation water was identified for the best solution. Our results show that FPV on agricultural irrigation reservoirs is a suitable technology that can contribute to the goal of increasing the water conservation in Jordan. As such, policies to encourage widespread uptake of the technology should be considered, such as introducing a separate FIT for FPV compared to ground-mounted PV.

In the approach presented to alleviate some of the challenges of the energy–water–food nexus, particularly for water conservation and the displacement of fossil fuel utilisation, it is clear from our results that the use of floating photovoltaics (FPV) to cover irrigation reservoirs provides such benefits. Such systems do not only conserve water by reducing evaporation losses but results in enhancement of the energy yield (hence economics) of the deployed PV systems. As indicated earlier, in developing countries 90% of irrigation use water from such reservoirs, some of these are in remote off-grid regions. Hence deployment of FPV will also aid in providing energy access not only for water pumping but also for community utilisation. Hence, the global benefits from such deployment are huge, and through the presented case study, this work provides key knowledge to support such needed development including those represented in the water-energy-food nexus.

This work has shown that floating PV can provide both economic and environmental benefits when used on irrigation reservoirs not only in the case study country but also beyond. There is no body of knowledge that is available to mobilise these ponds for power generation as well as conserving water through FPV and this work is providing initial seminal evidence of such potential. Furthermore, the presented research is generalisable which can address some of the global challenges faced in the water-energy-food nexus. The novel combination presented here in not only important from the point of view of sustainable power generations but is also linked to water scarcity and the energy-water-food nexus. Water scarcity is becoming worse due to climate change and the proposed multifunctional solution of floating solar PV mitigates such impacts. To our knowledge no previous studies have been conducted to investigate this combination whilst providing impactful results in terms of scientific outcome, evidence, and direction to policy as well as sustainability.

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.

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Appendix A:. Modelling results

The overall modelling results are summarised in Tables A.1-A.3, below, for the four main scenarios (No PV, small footprint FPV, large footprint FPV and ground-mounted PV) as well as the best scenario from the analysis of FPV incorporating advanced energy capture technologies, namely vertical axis tracking with large footprint FPV. The recommended system design, which proved best across all three criteria (economics, water savings and greenhouse gas emissions), is highlighted in green. The decision for the recommended system design was based on the data presented in Figs. 5-8 in Sections 4.1 and 4.2.

Table A1
Overall Modelling Results: System Design.

	No PV (Business as Usual)	Fixed Tilt Small Footprint FPV	Fixed Tilt Large Footprint FPV	Vertical Axis Tracking Large Footprint FPV	Fixed Tilt Ground-mounted PV
PV Capacity(kW)	–	300	300	200	300
PV Capacity Factor (%)	–	17.4	17.6	19.9	17.6
Annual PV Generation (MWh)	–	456	462	349	462
Footprint on Water (m^2)	–	3000	4285	2860	–
Inverter Capacity (kW)	–	200	200	150	200
Inverter Capacity Factor (%)	–	24.6	24.8	25.2	24.7
Grid Purchases (MWh)	369	142	130	133	151
Grid Sales (MWh)	–	207	213	111	216

Table A2
Overall Modelling Results: Economics.

	No PV (Business as Usual)	Fixed Tilt Small Footprint FPV	Fixed Tilt Large Footprint FPV	Vertical Axis Tracking Large Footprint FPV	Fixed Tilt Ground-mounted PV
NPC ($USD)	600,000	492,000	431,000	457,000	439,000
LCOE ($/MWh)	140	71.0	68.1	87.3	66.9
CAPEX ($USD)	0	344,000	344,000	270,000	314,000
OPEX ($/kWp/year)	53,800	12,100	9900	18,000	12,800
Simple Payback Time (Years)	–	8.8	8.4	8.0	8.0
Discounted Payback Time (Years)	–	12.5	11.75	11.25	11.25

Table A3
Overall Modelling Results: Environmental Implications.

	No PV (Business as Usual)	Fixed Tilt Small Footprint FPV	Fixed Tilt Large Footprint FPV	Vertical Axis Tracking Large Footprint FPV	Fixed Tilt Ground-mounted PV
Absolute Evaporation Reduction (m^3)	–	2490	12,700	11,200	–
Percentage Reduction (%)	–	8.3	42.1	37.0	–
Value of Water Saved ($USD/year)	–	274	1360	1520	–
GHG Emissions (tCO_2e/year)	235.8	102.7	95.0	106.2	107.7

Appendix B:. Energy balance for recommended system design and cash flow analysis

The recommended system design is the 300 kW fixed tilt large footprint floating PV design, as informed by Figs. 5-8 in Sections 4.1 and 4.2. Here, plots depicting key attributes of this system are presented in Figs. B.1-B.4.

It is apparent from Fig. B.1 and Fig. B.2 that the maximum and most consistent power output from the PV and inverter occurs during the summer months while the lowest and least reliable power output occurs in the winter months. Fig. B.3 clearly shows that backup power is needed during the night time of summer months where there is no solar resource yet a high demand to power the two pumps. Fig. B.4 shows that excess electricity is produced from the PV during the daylight hours from December to March when the electrical demand from the two pumps is low but there is still a reasonable solar resource. This excess electricity is sold to the grid. Fig. B.5 shows export and import form the grid to the selected PV system.

Fig. B.6 and Fig. B.7 show the high capital expenditure of $344,000 in year 0, which mainly derives from the floating PV system (modules, moorings, floating structure etc). As the years progress, the costs incurred are mainly associated with operating expenses i.e. purchasing grid electricity to provide backup power. In year 15, the inverter needs replaced, hence the added cost in that year. In the final year, when the system is decommissioned, the positive cash flow in this year arises from the salvage value of the PV system and inverter. Fig. B.8, below, shows the cumulative cash flow for the recommended system design:

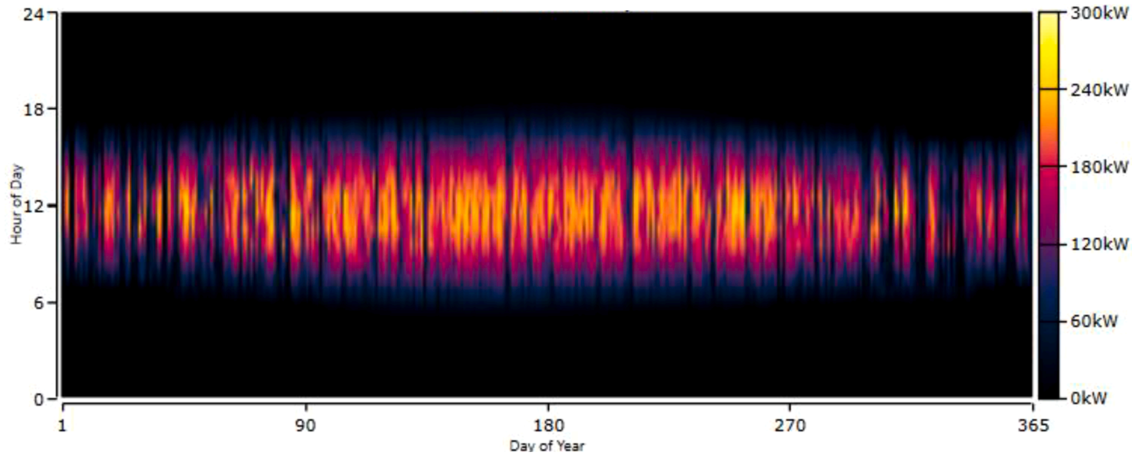

Fig. B1. Hourly power output from 300 kW large footprint FPV array during the first year of the project.

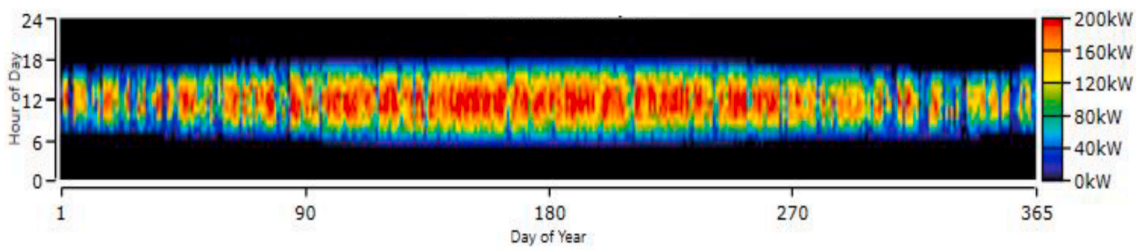

Fig. B2. Hourly inverter output from 200 kW inverter during the first year of the project.

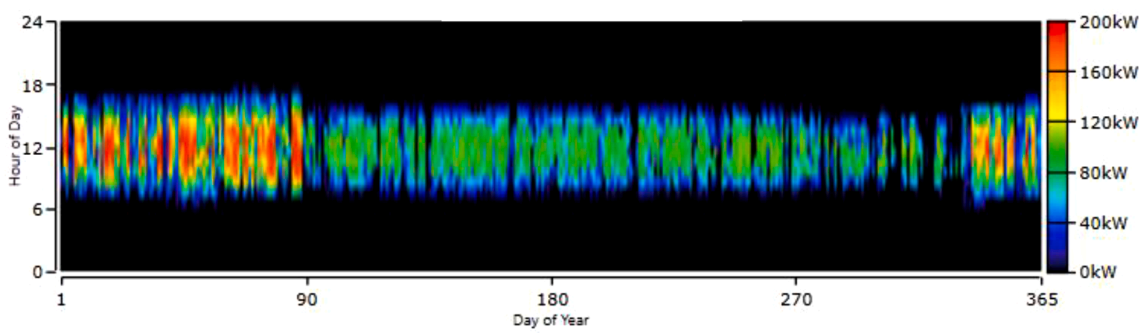

Fig. B3. Hourly electricity purchased from grid to provide backup power for the pumps during the first year of the project.

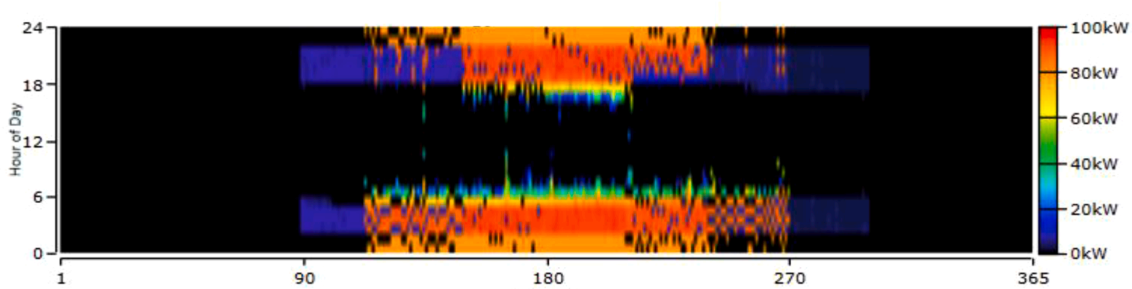

Fig. B4. Hourly electricity sold to grid during periods of excess electricity production by the FPV array during the first year of the project.

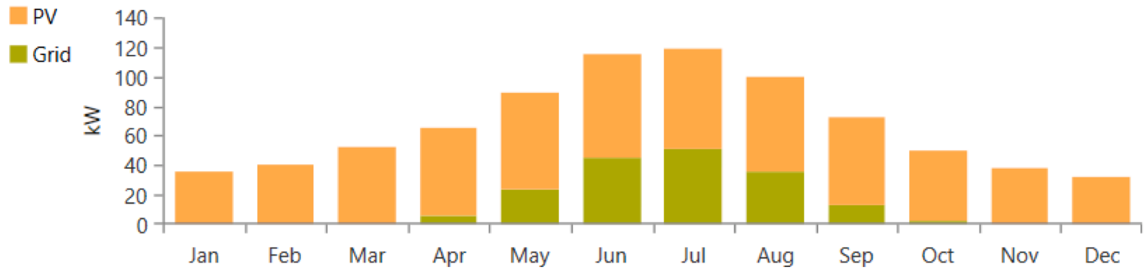

Fig. B5. Average monthly electrical production per month from FPV array (orange) and average electricity purchased per month from the grid (green).

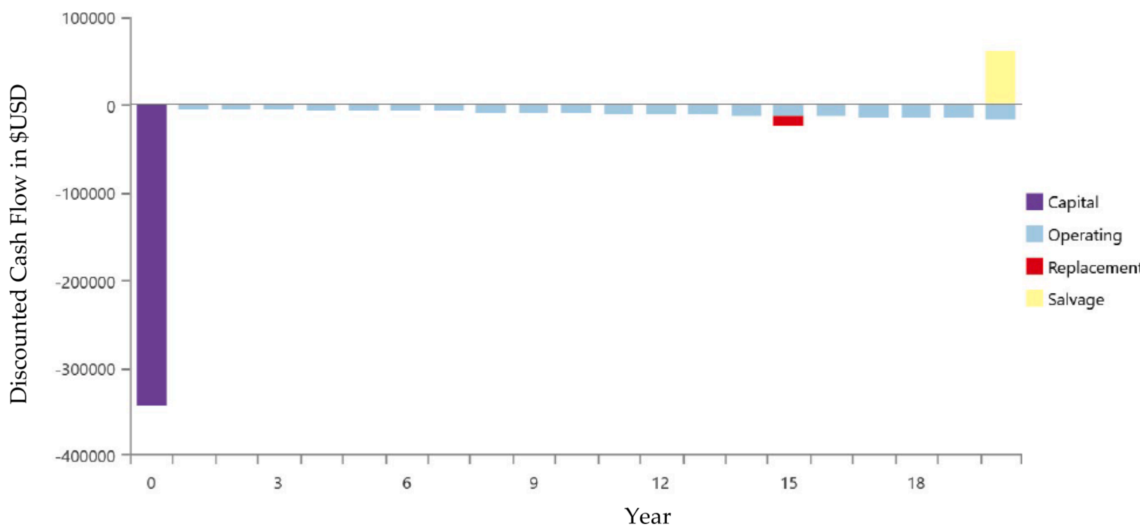

Fig. B6. Annual discounted cash flow on cost type basis over project lifetime.

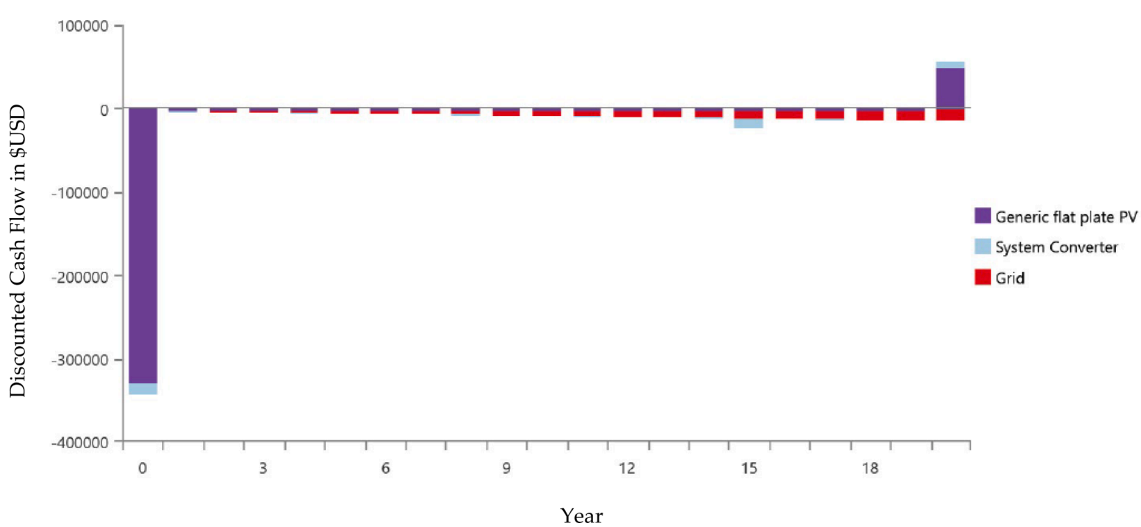

Fig. B7. Annual discounted cash flow on system component basis over project lifetime.

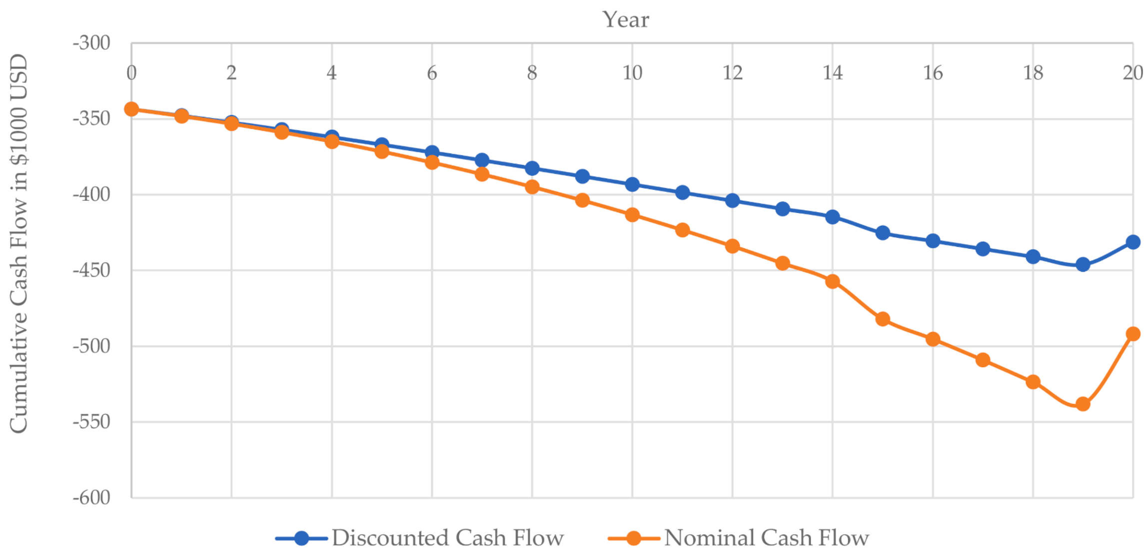

Fig. B8. Cumulative cash flow for recommended system design showing both discounted and nominal cash flows.

Appendix C:. Evaporation rate data

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Table C1
Evaporation data with and without FPV for each month of the year.

Scenario	Evaporation (mm) Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
No PV	85	88	141	176	257	287	298	282	220	180	130	91	2235
Large footprint FPV	49	51	81	102	148	166	173	163	127	104	76	53	1293
Small footprint FPV	78	89	127	163	230	265	266	254	204	165	126	85	2051

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