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ANALYTICAL MODELING OF WATER CONSERVATION POTENTIAL AND THERMAL DYNAMICS IN FLOATING PV SYSTEMS

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Fresh water is a critical resource for sustaining life on Earth. This study explores the implementation of floating photovoltaic (FPV) systems on freshwater reservoirs, focusing on their potential for generating clean energy. A mathematical model is developed to estimate a reservoir's water evaporation, water loss, and dynamic volume using environmental data such as temperature, humidity, irradiance, and wind speed. These sensors collected data for 12 days, yielding an average error of 1.09% between the analytical and experimental processes. The analytical model applied to Karli Lake leads to an annual loss of 282 million liters of freshwater. Furthermore, the installation of FPVs at different lake coverage levels (10%, 30%, 50%, 70%, and 100%) has been assessed, revealing that around 48.14 billion liters of water could be conserved each year, sufficient to irrigate up to 10,000 hectares of land. Furthermore, installing FPV systems on the lake with diverse coverage could produce up to 900 GWh annually. This development could ease the pressure on the national grid and deliver clean energy to nearby communities.

1. INTRODUCTION

Due to the vast level of industrialization and economic growth worldwide in the past two decades, energy demand is increasing, which results in energy security challenges [1]. The major share of the energy requirement has been met by conventional sources that cannot fulfill the requirements and are unsuitable for the environment and climate [2]. In 2023, the total generation of renewable energy sources met 30.3% of worldwide demand. Wind and solar energy account for approximately 90% of all new renewable power additions [3]. Efforts from different countries will shift a significant portion of power generation, up to 45%, until 2045. Solar energy has enormous potential, particularly in nations located in high-capacity solar zones [4]. The cost of increased deployment of renewable energy sources is critical to meeting the demand for clean energy. Since the end of 2019, PV module costs have declined by more than 90%. Solar energy possesses significant potential, particularly in nations situated in regions with high solar capacity [5]. Along with that, other techniques that involve cooling of the PV modules recover 3-5% of the power output from losses. More advancements are in place to improve the collective performance of PV systems.

FPV systems have lately attracted attention as a novel solution to the constraints encountered by ground solar power plants, providing both spatial efficiency and improved energy output [6]. These systems provide several structural and operational benefits compared to terrestrial systems, especially with decreased land usage and enhanced energy production [7]. Floating photovoltaics have been recognized worldwide for their efficient use. Different studies have been performed to evaluate FPV's power generation, highlighting the substantial advantages that these systems provide while recognizing the technical barriers [8]. The first FPV installation was completed in 2007 in Aichi, Japan, with an installed capacity of 20 kW. From 2007 to 2014, globally installed capacity increased to 11 MW_p over seven years. Furthermore, research on extensive implementation, such as that conducted in industrialized regions, indicates that covering 30% of the world's water reservoirs with FPVs could produce 9434 TWh of power per year while conserving 106 Km^2 of water [9]. When evaluating FPV systems, it is important to estimate evaporation since it is a critical component of water management and conservation measures. Various empirical and physically based mathematical models have been created to measure evapotranspiration, which is closely connected to evaporation. Different analytical models have been adopted in previous years and include various variables that include temperature, luminosity, humidity, solar irradiance, and wind speed. The research study conducted by Penman, Monteith, Turc, and Hargreaves, Samani has significantly enhanced the fundamentals of water evaporation from lakes.

Recent studies have also evaluated the evaporation phenomena for FPV installations. TSEB-SM has enhanced precision in quantifying latent and sensible heat fluxes and provides greater differentiation of evapotranspiration [10]. Research on the Passauna Reservoir in Brazil reported that FPVs may decrease water evaporation, with an efficiency up to 60.2% across a covering area of 1265.14 m² [11]. All the above models demonstrate that the FPV performance is directly linked to geographical and meteorological factors, which affect both power generation and evaporation mitigation. Environmental variables, which include irradiance received from the Sun, temperature, wind speed, and humidity, vary by area, requiring location-specific investigations of FPV plants.

A unique combinatorial model was created to predict water surface evaporation under FPV. The model alters the aerodynamic term using wind speed, which is affected by the dimensions and configuration of pore water, and changes the radiation term according to energy balance and temperature. Experimental validation using floating setups validated its precision, providing efficient water conservation measures for dry and semi-arid areas [12]. FPVs are attracting interest as a sustainable energy alternative in light of land use limitations and climate change. Worldwide research indicates that the coverage of 10% of over one million water bodies may provide 14,906 TWh annually. This highlights FPV's capacity to fulfill power demand and facilitate decarbonization [13]. Another study found a thorough

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national evaluation of Chile's FPV potential, indicating a capacity of 6.3-16.6 GWp in the central regions. It also estimates enhanced benefits, including avoiding over 118 million m³ of yearly water evaporation and competitive energy prices between 51 and 55 USD/MWh in the latest years [14].

Most recent research studies consider the ecological effects and climatic conditions. Another study presents an FPV-PHES (floating photovoltaic pumped hydro energy storage) hybrid system accompanied by a comprehensive evaluation approach, emphasizing its energy, environmental, and economic advantages, especially in the context of China's extensive PHES structure [15]. FPV systems have advantages for climate and land use; however, their ecological effects, especially on water birds. This study highlights major factors and interactions between FPVs and water bird populations, stressing the need for ecological research and water conservation. Conventional generation systems often neglect systemic inefficiencies, leading to overly optimistic forecasts. An enhanced evaluation approach for FPVs in China rectifies these deficiencies, uncovering more accurate energy, environmental, and economic advantages and facilitating worldwide implementation plans [16]

The literature study indicates that FPV systems have gathered interest in their land conservation and climate mitigation capabilities. This study seeks to fill existing research gaps by using a sophisticated mathematical model to assess the energy and environmental effects of FPV systems. The mathematical model will assist policymakers, energy planners, and environmentalists in enhancing water conservation in underdeveloped countries, and it can also be utilized to find potential water conservation studies. In this paper, Section 2 presents the methodology, including the mathematical model and experimental chamber used to measure water evaporation from a water reservoir; Section 3 discusses the study results. Specifically, Section 2 presents the model implementation on the lake and the mathematical model, and Section 4 presents the conclusion from the research study.

2. **METHODOLOGY**

FPVs are among the fastest-growing offshore energy-generation setups for harnessing clean, green energy. The research uses a systematic methodology to estimate lake evaporation by developing a mathematical model. The model has been created to estimate evaporation based on FPV installation on a water reservoir. An experimental chamber is constructed to simulate environmental conditions under controlled settings. In this chamber, essential environmental parameters were recorded to furnish empirical data for mathematical model validation. The model is then validated by comparing its outputs with the experimental results to ensure reliability. The validated model is subsequently implemented under lake-specific conditions, enabling precise estimation of evaporation from the lake. The methodology section comprises the mathematical model and a discussion of chamber development for the experimental work. Figure 1 depicts the complete research methodology to evaluate the impact of FPV on evaporation from water reservoirs.

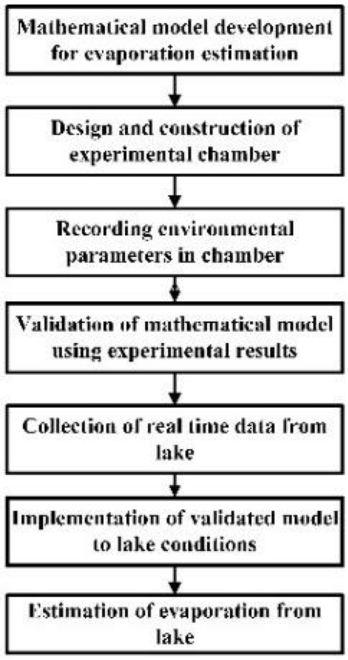

Fig. 1 – Methodology for research study

2.1. MATHEMATICAL MODEL

A. Evaporation Estimation Using the Penman Equation.

The model is based on the Penman equation [17], an established technique combining energy balance and aerodynamic transfer principles to determine evaporation rates. The model is developed based on different assumptions that match the real scenario. It is assumed that the water reservoir has a uniform surface temperature, and the presence of FPV module is considered to reduce both the net solar radiation reaching the water surface and the wind speed at the surface. The model uses average meteorological data, including solar irradiance, air temperature, humidity, and wind speed. Furthermore, the area covered by the FPV module is treated as a representative portion of the total surface, enabling comprehensive estimates of its impact on evaporation reduction. The general Penman equation can be written as,

$$E(t) = \frac{\Delta}{\Delta+\gamma}.\frac{R_n}{\lambda} + \frac{\gamma}{\Delta+\gamma} f(u)(e_s - e_a), \tag{1}$$

where, E represents the evaporation rate (mm/day), R_n denotes the net radiation at the water surface (MJ/m²/day), λ is the latent heat of vaporization (2.45 MJ/kg), Δ refers to the slope of the saturation vapor pressure curve (kPa/°C), γ is the psychrometric constant (0.066 kPa/°C), f(u) depicts the wind function (mm/day per kPa), e_s represents the saturation vapor pressure (kPa), and e_a indicates the actual vapor pressure,

$$R_n = (1-\alpha)\cdot I\cdot(3.6). \tag{2}$$

R_n represents the solar energy available at the water surface after the portion of incoming solar radiation that is reflected. It is calculated by multiplying the incoming solar irradiance by the absorbed solar radiation (1-α), where α is the surface albedo and represents the solar energy absorbed by the surface, which is available for the evaporation process,

$$\Delta = \frac{4098\cdot e_s}{(T+237.3)^2}, \tag{3}$$

$$f(u) = 0.26[1 + 0.54u(t)]. \tag{4}$$

Due to FPV installation, the wind speed is reduced by a factor β. For Karli Lake, β was set at 0.7 to show that reduced wind reduces evaporation. This value of β represents a scenario in which the FPV system reduces the near-surface wind speed by approximately 70% through its shielding effect. This value is in line with the known ranges for medium- to small-sized reservoirs.

$$f(u_{reduced}) = 0.26 \cdot (1 + 0.54 \cdot (1 - \beta) \cdot u), \quad (5)$$

$$e_s = 0.6108 \cdot \exp\left(\frac{17.27T}{T + 237.3}\right), \quad (6)$$

$$e_a = \frac{RH}{100} e_s. \quad (7)$$

By substituting parameters into the Penman equation, two different equations are obtained based on two scenarios that include E_{np} evaporation from a natural open water reservoir with no PV panel installed and E_{wp} evaporation from the water surface covered by FPVs. Hence, the evaporation loss is determined by multiplying the daily evaporation rate by the number of days in the respective month in both scenarios.

$$E(t)_{np} = \frac{\Delta}{\Delta + \gamma} \cdot \frac{(1 - \alpha_{water}) \cdot I \cdot (3.6)}{\lambda} + \\ + \frac{\gamma}{\Delta + \gamma} .0.26(1 + 0.54u) \cdot (e_s - e_a), \quad (8)$$

$$E(t)_{wp} = \frac{\Delta}{\Delta + \gamma} \cdot \frac{(1 - \alpha_{panels}) \cdot I \cdot (3.6)}{\lambda} + \\ + \frac{\gamma}{\Delta + \gamma} . 0.26(1 + 0.54 \cdot (1 - \beta) \cdot u) \cdot (e_s - e_a). \quad (9)$$

B. *Evaporation Expression for Estimation with Partial PV Panel Coverage.*

The model incorporates a combined evaporation equation to represent a realistic scenario where only a portion of the lake surface is covered with FPVs. This equation accounts for the exposed and PV-panel-covered lake surface areas. Let f be the fraction of the lake area covered by floating panels. The total evaporation from the lake surface is calculated as equation (10), a weighted average of the evaporation from open water and evaporation from the panel-covered area.

$$E_{\text{combined}} = (1 - f)E_{\text{np}} + fE_{\text{wp}} . \quad (10)$$

C. *ODE Expression for Water Volume Dynamics*

An expression for the volume-loss model is developed using a first-order ordinary differential equation (ODE) to evaluate the long-term impact of evaporation on the water reservoir. The expression integrates the Penman equation, using the evaporation rate *E(t)* as a time-dependent variable representing the continuous reduction in water volume over time. Let *V(t)* represent the volume of water in the water reservoir at time t (months), and A be the surface area of the lake (m²). The time-dependent rate of volume change due to evaporation is given by the following ODE with the initial condition $V(0) = V_0$,

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -A \cdot E(t). \quad (11)$$

Applying the initial condition $V(0) = V_0$,

$$V(t) = V_0 - A \int_0^t E(t)\mathrm{d}t . \quad (12)$$

The expression in eq. (12) shows that the cumulative water volume loss equals the integral of the evaporation depth over time, scaled by the reservoir surface area. In this case, only a portion of the reservoir can be covered by FPVs, as shown in equation (10). Substituting this into the volume loss equation, the ODE becomes,

$$V(t) = V_0 - A \int_0^t \left[(1 - f)E_{\text{np}} + f . E_{\text{wp}}\right] \mathrm{d}t. \quad (13)$$

This expression shows the remaining volume of the lake at time t, from the initial volume V_0 , minus the cumulative water loss due to evaporation in both covered and non-covered conditions. This ensures that the model realistically accounts for the impact of partial FPV coverage on reducing overall evaporation. The major contribution of this study is to adopt the classical Penman equation to evaluate evaporation from FPV-based reservoirs. The proposed model incorporates the effects of FPV installations to assess changes in surface albedo and near-surface wind speed, thereby enabling estimation of evaporation under both natural and FPV-covered conditions.

2.2. EXPERIMENTAL SETUP

The experimental chamber is designed to assess the impact of water evaporation from the reservoir by installing a floating panel power system. The experimental chamber is designed to mimic a water reservoir setup. The chamber is designed with a polymethyl methacrylate sheet with a 2 x 1 x 2 ft³ dimension. The experimental chamber is equipped with data acquisition sensors that are utilized to gather the real-time parameters. The data acquisition devices include temperature (DS18b20), humidity (BH 1750), evaporation (P 45), lux (GY 2561), Anemometer (SN-3000), and voltage (HW-525). All the data acquisition sensors are managed by the control units that log all the data acquired from the sensors. Figure 2 demonstrates the experimental setup design and chamber used for experimental validation.

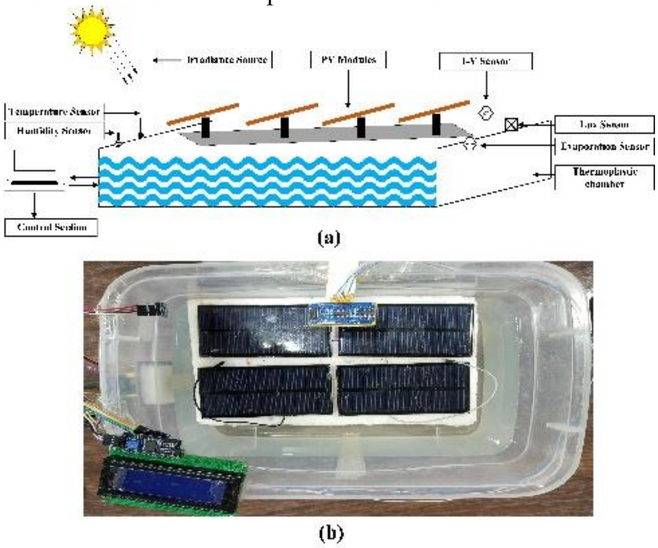

Fig. 2 – (a) Design of experimental setup (b) Experimental chamber.

The chamber is filled with 114 liters of fresh water collected from Karli Lake, Sindh, Pakistan, with a TDS of 353 mg/L and a pH of 7.7, which is moderately alkaline. The experimental chamber was installed in a nearby lake area for 12 days, and four polycrystalline PV modules were connected in series and installed on it. The data were collected at half-hour intervals and automatically logged into the controller unit. Table I depicts the design specifications for the PV modules used in the experimental chamber.

Table 1

Design specification of one PV module.

S.no	Parameters	Specifications
1	Maximum Power	3 Watts
2	Cell Type	Polycrystalline
3	Open Circuit Voltage	6.0
4	Maximum Power Voltage	6.0 V
5	Maximum Power Current	0.5 A
6	Short Circuit Current	0.55 A

2.3. APPLICATION OF THE MATHEMATICAL MODEL ON KARLI LAKE

Karli Lake, situated in the Thatta District of Sindh, Pakistan (24.7°N, 68.3°E), is a freshwater reservoir covering 133 km² with a gross water storage capacity of 0.515 million acre-feet. The lake is approximately 16.5 meters above sea level in the Indus basin and features gently undulating terrain. It is vital in regional hydrology as one of the principal drinking water sources for Karachi and neighboring metropolitan areas. The freshwater has a TDS greater than that of pure water, which is assumed in the Penman model equation and may slightly alter evaporation properties. However, the effect is minimal at this salinity and thus not explicitly addressed in this model. Karli Lake has strong potential for installing floating solar power plants.

3. **RESULTS AND DISCUSSION**

A mathematical model has been developed to gauge the impact of FPV on water evaporation from the lake. Based on the principles of heat and mass transfer governing air-water interactions, evaporation is described using the energy balance approach by [17]. The surface temperature is also influenced through the Clausius relation that links it with solar irradiance, air temperature, and the dynamics of water vapor [18]. The model has been validated using an experimental approach, in which different physical quantities have been measured. Although the experimental chamber cannot fully replicate the wind, hydrodynamic, and climate effects of a lake with a large area, it provides an effective first-order platform to isolate principal mechanisms and generate baseline data important for scaling and mathematical model validation. In this section, the data evaluated using a mathematical model and an experiment chamber have been compared.

3.1. COMPARISON OF MATHEMATICAL MODEL WITH EXPERIMENTAL OUTPUTS

The model used twelve days for the physical quantities. Table II presents the evaluated water evaporation values obtained using the mathematical model, and Table 3 presents the measured values obtained during the experimental procedure. Figure 3 compares the experimental and mathematical results and shows the discrepancy between the two configurations.

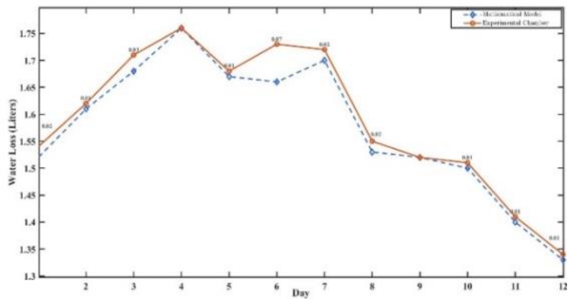

Fig. 3 – Comparison between mathematical and experimental water loss.

Table 2

Evaluation of water evaporation adopting a mathematical model.

Day	Temp (°C)	RH (%)	Wind Speed (m/s)	Irradiance (kWh/m²/day)	Evaporation (mm/day)	Cumulative evaporation (mm)	Water Loss (Ltr)	Cumulative Water Loss (Ltr)
1	38	45	3.5	6.8	8.19	8.19	1.52	1.52
2	39	42	4.2	7.1	8.68	16.87	1.61	3.13
3	40	40	5.0	7.3	9.06	25.93	1.68	4.82
4	41	38	6.1	7.5	9.48	35.41	1.76	6.58
5	42	35	3.8	7.2	9.00	44.41	1.67	8.25
6	43	32	4.5	7.0	8.92	53.33	1.66	9.91
7	44	30	7.0	6.9	9.15	62.48	1.70	11.61
8	41	36	2.5	6.7	8.23	70.71	1.53	13.14
9	40	39	5.5	6.5	8.19	78.90	1.52	14.66
10	39	43	6.8	6.4	8.08	86.98	1.50	16.16
11	38	46	4.0	6.2	7.53	94.51	1.40	17.56
12	37	48	3.2	6.0	7.17	101.68	1.33	18.90

Table 3

Evaluation of water evaporation adopting an experimental setup.

Day	Temp (°C)	RH (%)	Wind Speed (m/s)	Irradiance (kWh/m²/day)	Evaporation (mm/day)	Cumulative evaporation (mm)	Water Loss (Ltr)	Cumulative Water Loss (Ltr)
1	39	47	3.4	6.9	8.31	8.31	1.54	1.54
2	39	40	4.1	7.2	8.72	17.03	1.62	3.16
3	41	42	5.0	7.1	9.23	26.26	1.71	4.87
4	40	40	6.1	7.2	9.51	35.77	1.76	6.63
5	41	33	3.7	7.1	9.09	44.86	1.68	8.31
6	44	35	4.4	6.9	9.34	54.20	1.73	10.04
7	43	29	7.0	6.8	9.26	63.46	1.72	11.76
8	40	36	2.4	6.6	8.35	71.81	1.55	13.31
9	41	40	5.6	6.6	8.23	80.04	1.52	14.83
10	40	41	6.9	6.5	8.13	88.17	1.51	16.34
11	38	47	4.0	6.1	7.61	95.78	1.41	17.75
12	36	46	3.3	5.9	7.21	102.99	1.34	19.09

3.2. MATHEMATICAL MODEL APPLICATION ON KARLI LAKE

To assess the water-conservation potential of FPV-scribing water reservoirs, the mathematical model described in the methodology section was applied to Karli Lake to evaluate the potential to minimize water loss. An average of 12 months of environmental data from Karli Lake was collected to evaluate water evaporation in two scenarios: non-panel and panel coverage on the water's surface. Table 4 shows the average water evaporation in Karli Lake.

Table 4

Evaluation of water evaporation adopting an experimental setup.

Month	Avg Temp (°C) (±0.5)	Avg RH (%) (±2)	Avg Wind (m/s) (±0.1)	Avg irradiance (kWh/m²/day)	Avg evaporation (mm)	Avg Water Loss (m^3)
Jan	17.4	36.0	3.2	3.80	114.01	15,359,247
Feb	20.2	36.2	3.5	4.48	131.27	17,690,169
Mar	25.2	37.4	4.0	5.29	177.82	23,936,754
Apr	29.3	39.7	4.9	6.31	215.11	28,960,317
May	31.9	46.3	6.4	6.68	242.57	32,683,479
Jun	32.6	53.2	6.9	6.69	235.40	31,672,380
Jul	31.4	60.5	6.8	5.77	206.78	27,858,966
Aug	30.1	63.2	6.0	5.43	190.60	25,672,020
Sep	29.6	56.7	5.0	5.29	179.27	24,140,469
Oct	28.2	40.5	3.3	4.72	164.20	22,110,540
Nov	23.8	33.5	2.9	3.93	126.78	17,077,566
Dec	19.0	32.6	3.1	3.58	111.64	15,024,141
Cumulative					2095.4	282,186,048

The cumulative water evaporated and water loss per month over one year, based on environmental data when no FPV is installed, were analyzed using the mathematical model depicted in Fig. 4.

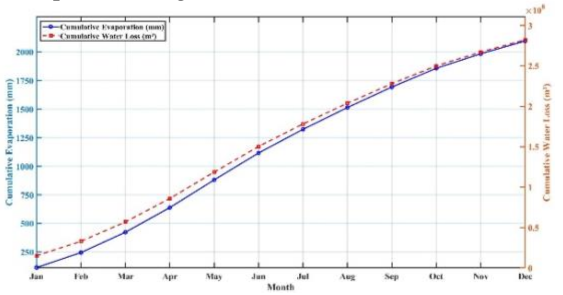

Fig. 4 – Cumulative water loss due to evaporation for twelve months.

In the second scenario, different coverage areas have been allocated based on the area specified on Karli Lake. In this case, FPV assigned 10%,30%,50%, 70%, and 100% coverage areas. However, the 100% coverage scenario is theoretical, as practical deployment is constrained by, operational, environmental, and ecological factors. Based on the simulated results, water evaporation and water loss were analyzed over a 12-month period.

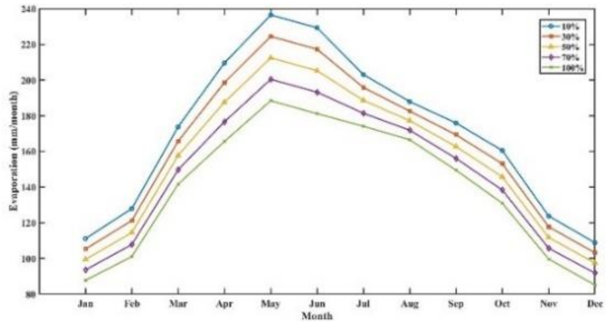

Fig. 5 – Evaporation estimates for twelve months in Karli Lake due to FPV coverage (10-100)%.

Table 5 depicts the water evaporated and water loss over the 12-month period. Under different FPV coverage levels, the relative line graphs of monthly evaporation and related water loss show a steady decrease in both as coverage increases. With 10% coverage, the evaporation rate (mm/month) is the highest, as depicted in Fig. 5.

Table 5

Water evaporation estimates due to FPV coverage (10%, 30%, 50%, 70%, 100%).

Month	Evaporation with different FPV coverages (mm/month)					Water loss with different FPV coverages (million m3/month)				
	10%	30%	50%	70%	100%	10%	30%	50%	70%	100%
January	111.09	105.24	99.40	93.55	87.70	14.89	14.10	13.31	12.53	11.74
February	127.91	121.18	114.46	107.73	101.00	17.58	16.64	15.70	14.76	13.82
March	173.80	165.75	157.71	149.67	141.62	23.29	22.20	21.12	20.03	18.95
April	209.61	198.60	187.60	176.60	165.59	28.09	26.61	25.14	23.66	22.19
May	236.55	224.52	212.50	200.47	188.45	31.69	30.09	28.49	26.89	25.29
June	229.38	217.33	205.28	193.23	181.18	30.73	29.12	27.51	25.90	24.29
July	203.15	195.90	188.64	181.39	174.13	27.22	26.23	25.24	24.25	23.26
August	187.93	182.59	177.25	171.90	166.56	25.18	24.47	23.76	23.05	22.34
September	175.96	169.34	162.73	156.11	149.49	23.56	22.68	21.79	20.91	20.02
October	160.50	153.11	145.72	138.33	130.95	21.49	20.50	19.52	18.53	17.55
November	123.77	117.74	111.72	105.70	99.67	16.79	15.98	15.16	14.35	13.53
December	108.80	103.13	97.45	91.78	85.10	14.58	13.82	13.05	12.29	11.53

Figure 6 shows that water loss (million m/month) follows a similar downward trend. The summer months (April to June) show the highest peak evaporation and water loss, highlighting a crucial time for potential water savings. These findings confirm the efficiency of FPV systems in reducing water loss from surface evaporation, particularly during high temperatures and hot, dry months, with the greatest conservation achieved at full PV panel coverage. Under several FPV coverage levels, Fig. 7 surface graphic shows Karli Lake's monthly water volume change.

Surface evaporation and FPV coverage show a clear negative relationship; the lake retains more water over time as the percentage of coverage rises. The lake volume steadily drops from January to December across all coverage levels, mostly from accumulated evaporation losses. As FPV coverage increases from 70% to 100%, this drop is much smaller, indicating a reduction in water loss. The present study extends previous site-specific research [19] by developing a general analytical model to predict FPV evaporation. Particularly in the summer months, the slope of lake volume across the coverage axis further emphasizes the efficiency of FPV systems in conserving water resources.

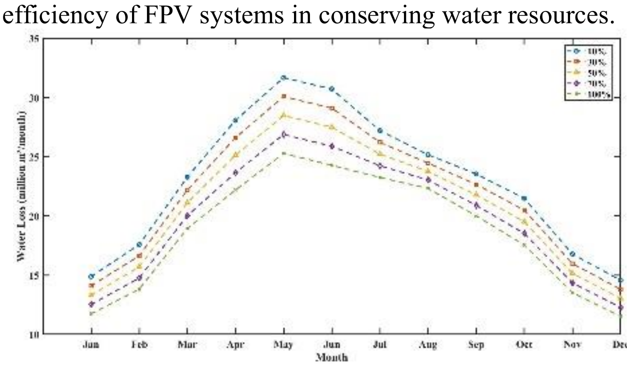

Fig. 6 – Water loss estimates for twelve months in Karli Lake due to FPV coverage (10, 30, 50, 70, 100) %.

Figure 7 highlights the important role that FPV installations may play in maintaining water storage levels in reservoirs like Karli Lake in arid and semi-arid conditions, which can be further used for agriculture.

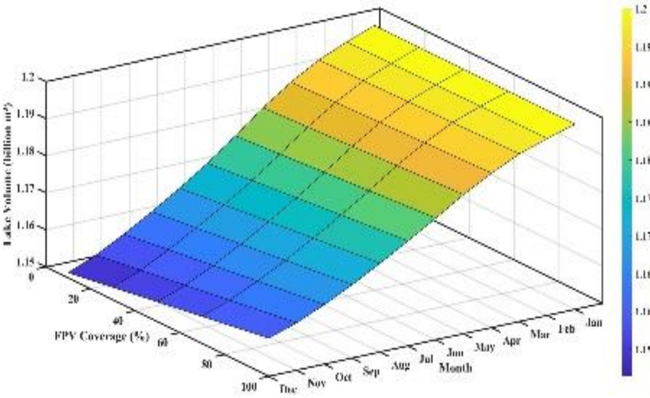

Fig. 7 – Reduction in lake water volume due to FPV coverage (10, 30, 50, 70, 100) %.

4. **CONCLUSIONS**

The paper presents an analytical model with experimental chamber data, offering both theoretical and empirical proof that FPV deployment can significantly reduce lake evaporation. The proposed model had an error of 1.09% and a standard deviation of 0.20%. The mean error fell within a 95% confidence interval of up to 1.22% between experimental and mathematical water loss. This study theoretically advances evaporation modeling by integrating hydrological processes with renewable energy. The mathematical model estimated that Karli Lake loses 2095.47 mm of water each year, amounting to 282 million liters of freshwater due to evaporation. The model estimates that FPV deployment from 10% to 100% preserves up to 424 mm of water annually, with an optimal coverage of 70% resulting in about 300 million liters of savings. The results emphasize the advantages of FPVs in improving food production through water recovery for irrigation in communities. The experimental validation was limited to a 12-day laboratory-scale study due to practical constraints, and reservoir-scale validation is planned for future work. In addition, FPV's continuing ecological effects on aquatic life and water quality were not addressed. From these findings, future research should include multi-lake evaluations and grid-based renewable energy planning.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

BASIT ALI: Conceptualization, modeling
SARWAT ISHAQUE: Writing, methodology
KANIZ FATIMA: Mathematical formulation, references
ASIF SUMEER: Literature review, software, validation
QAISER HAFEEZ: Analytical model, experimental setup

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