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Foam-Based Floatovoltaics: A Potential Solution To Disappearing Terminal Natural Lakes

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Foam-Based Floatovoltaics: A Potential Solution to Disappearing Terminal Natural Lakes

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Abstract

Terminal lakes are disappearing worldwide because of direct and indirect human activities. Floating photovoltaics (FPV) are a synergistic system with increased energy output because of water cooling, while the FPV reduces water evaporation. This study explores how low-cost foam-based floatovoltaic systems can mitigate the disappearance of natural lakes. A case study is performed on 10%-50% FPV coverage of terminal and disappearing Walker Lake. Water conservation is investigated with a modified Penman-Monteith evapotranspiration method and energy generation is calculated with an operating temperature model experimentally determined from foam-based FPV. Results show FPV saves 52,000,000 m^3/year of water and US$6,000,000 at 50% FPV coverage. The FPV generates 20 TWh/year of renewable energy, which is enough to offset all coal-fired power plants in Nevada thus reducing carbon-emission based climate forcing partially responsible for a greater rate of disappearance of the lake. The results of this study, which is the first of its kind, indicate foam-based FPV has potential to play a crucial role in mitigation efforts to prevent the disappearing of natural lakes worldwide.

Keywords: floatovoltaic; floating photovoltaic system; photovoltaic; water conservation; solar energy; terminal lakes

Nomenclature

A	Total area of the FPV system (m²)
a	Albedo
E_{day}	Daily evapotranspiration (mm/day)
I_s	Incident solar irradiation (W/m²)
P	Atmospheric pressure (kPa)
P_a	Real vapor pressure of the air (kPa)
P_{out}	Output power of the FPV module (W)
P_w	Average saturation vapor pressure of the air (kPa)
Q	Daily heat storage flux (MJ/m²/day)
r_a	Aerodynamic resistance (s/m)
R_N	Daily net solar irradiation (MJ/m²/day)
R_S	Global horizontal irradiation (W/m²)
Rh	Relative humidity (%)
T_a	Air temperature (°C)
T_{dw}	Dew point temperature (°C)
T_{eo}	Effective operating temperature of the FPV module (°C)
T_{ref}	STC operating temperature of the PV module (°C)
T_w	Water temperature (°C)
w_s	Wind speed (m/s)

β_{ref}	STC temperature coefficient of the PV module (%/°C)
γ	Psychrometric constant (kPa/°C)
Δ	Slope of the saturation vapor pressure curve (kPa/°C)
η_e	Electrical efficiency of the FPV module (%)
η_{ref}	STC efficiency of the PV module (%)
η_s	Overall efficiency of the FPV system (%)
λ	Latent heat of vaporization of water (MJ/kg)

1. Introduction

Solar photovoltaic (PV) systems have long been established as a sustainable means of electricity generation [1]. A relatively new solar floating photovoltaic (FPV) or floatovoltaic technology, which combines traditional solar PV systems with a partially covered surface of a natural or manmade body of water, has the potential to both directly and indirectly further help the environment. Floatovoltaic systems present synergistic advantages both to the PV systems and to the water body. Existing studies have demonstrated that FPV systems have an increased performance because of the cooling effect conferred by the proximity of a water reservoir [2–9]. This increased performance is translated into a low-carbon renewable energy production gain that has been estimated between 1.5 and 22% depending on the water body and FPV racking type [5,10–12]. Increased solar electricity output from FPV indirectly helps the environment by offsetting carbon emissions responsible for global warming previously established for rapid innovation and distribution of PV globally [13–16]. On the other hand, the installation of FPV systems on a water body decreases the evaporation rate thereby directly benefiting the environment through water conservation [4,17,18]. In addition, FPV may have some advantages to aquaculture [19], which has the potential to contribute to sustainable food security globally [20,21]. These aspects put floatovoltaic systems at the forefront of solutions of energy-water-food challenges [22–25].

Fortunately, FPV systems are a rapidly growing renewable energy generation technology [4,8]. The development of FPV technology has been boosted by the land use challenges that land-based PV systems face [26–28]. The first FPV systems started in the early 2000s in Japan and the U.S. [8,28]. Since then, 1.6 GWp of FPV power have been installed worldwide [29], and the growth rate of floating PV is predicted to reach 31% in 2024 [30]. Different racking technologies are used in FPV systems to ensure the floatability of the modules on the water surface: (i) pontoon based tilted system with rigid modules [31–34], (ii) submerged rigid FPV modules [2,5,6,35,36], (iii) microencapsulated phase change material (MEPCM)-based pontoon systems [37,38], (iv) thin film FPV with no pontoon supporting structure [8,36,39], and (v) foam-based FPV systems that that combines polyethylene foam with flexible solar PV (thin film and silicon water PV) in order to decrease the cost of racking for FPV systems [10,39]. Images of both crystal silicon and thin film amorphous silicon foam-based PV as well as details of the commercial foams available can be seen in [10,39]. The foam-based FPV has installation times faster than conventional FPV as the racking is attached to the PV [39]. A recent study by the U.S. National Renewable Energy Laboratory has investigated the potential of PV systems on man-made reservoirs in the U.S. [28], but did not include natural lakes many of which are currently under stress. In addition, there is potential of FPV to partially mitigate climate change impacts on water body temperature and stratification [40].

There is, however, a potential in the combination of FPV systems with water conservation initiatives, especially in arid and semi-arid regions that are faced with water shortages. This is particularly true for terminal lakes worldwide [41]. A terminal lake is a body of water that is located at the end of a river drainage system and that has no other natural outlet other than evaporation [42]. Terminal lakes are disappearing throughout the world due to various reasons [41,43–45]. The diversion of the lake's tributaries for other purposes such as irrigation on farmlands is one of the major causes for terminal lake shrinkage [44,46], but this diversion is not the sole cause of the drop in lake levels. The final state of terminal lakes is affected by both human activities directly and indirectly with climate change [41,45,47,48]. Climate change is causing the rise of global temperature which in turn accelerates the evaporation in lakes [41,49,50]. The shrinkage of terminal lakes is negatively affecting not only the marine life, but also, the nearby human population and the economies tied to lucrative activities around lakes [41,43,51,52]. No studies are available on the potential of FPV to help conserve terminal lakes.

To overcome this knowledge gap, this paper explores how the relatively new low-cost foam-based floatovoltaic systems can be incorporated into the mitigation efforts of disappearing natural lakes. A case study is conducted using weather data obtained on Walker Lake [53]. Walker Lake is a terminal lake located in the state of Nevada in the United States. To understand the interactions that can exist between foam-based FPV and the lake, two factors are investigated, the water conservation potential and the energy production of a foam-based FPV. The water conservation potential is estimated through a modified Penman-Monteith daily evapotranspiration method that has been in use by the Food and Agriculture Organization of the United Nations (FAO) since 1998 [54,55]. The energy generation is calculated by using a cell operating temperature model of foam-based FPV that was developed by Hayibo et al. [10]. A simulation is performed on both the energy production and water saving potential of the foam-based FPV and a sensitivity analysis is run for different coverages of the lake surface ranging from 10 to 50% in 10% increment. The economic value of the energy production is estimated as well as the cost avoided by the water evaporation prevention. The results are discussed in the context of water preservation efforts of the Walker Basin Conservancy [56]. The implications of the results for Walker Lake are then generalized to the role of foam-based FPV in i) water conservation efforts on natural terminal lakes worldwide, ii) mitigation of anthropogenic climate change using PV systems, and iii) in the sustainable energy-water-food nexus.

2. Methods

The energy production and water saving model previously developed [10] is used to investigate the case of Walker Lake [56] in the state of Nevada in the United States (Figure 1).

Figure 1. Satellite image of Walker Lake from Google Earth.

2.1. Data Collection and Cleaning

Weather data is collected for Walker Lake from SOLCAST [57], and water temperature data was obtained from the United States Geological Survey (USGS) [53].

Walker Lake is a natural Lake that was formed since the Pleistocene era. The total surface of the lake is approximately 100 km^2 and the maximum depth of the lake is 28 m as of 2015 [58]. The weather buoy used to collect the water temperature data is installed at a latitude of 38.79 °N and at a longitude of 118.72 °W [59].

The water temperature (T_w) (°C) data has been collected from Walker Lake with a time resolution of one hour and the data from 2017 is used in this study. The data obtained from SOLCAST also in 1-hour increments includes the wind speed (w_s) (m/s), the atmospheric pressure (P) (kPa), the air temperature (T_a), the dew point temperature (T_{dw}) (°C), the relative humidity (Rh) (%), the global horizontal irradiation (R_S) (W/m^2), and the albedo (a).

The raw data obtained from both sources has been matched in a spreadsheet after the temperature data was cleaned by using an open source MATLAB script [60]. The original script is tailored for data sets with hourly missing data. In the water temperature dataset obtained from the USGS, there were three days of data missing. Therefore, some post-processing data cleaning was performed on the result obtained from the script. The three days of missing data are the 183rd, 184th, and 185th days of the year. Along with these three days, there were seven days with one missing data each (27th, 71st, 88th, 170th, 205th, 331st, and 342nd days of the year), one day with four missing data points(191st day of the year), one day with eight missing data points (182nd day of the year), two days with 10 missing data points (199th and 354th days of the year), two days with 12 missing data points (186th and 200th days of the year), and one day with thirteen missing data points (353rd day of the year). In total, 142 hourly data points were missing from the temperature dataset. The missing data points represent 1.62% of the total hourly data and were considered to not have a significant impact on the results since only 6 days have more than 4 missing data points. Figure 2 shows the raw data compared to the cleaned data. The outliers or missing data points are shown separately and were removed in the cleaned data. As displayed, the outliers are well separated and appears to have all been set to the same value in the original data file. This is because the raw data was validated by the USGS before publication [53]. After the hourly data is cleaned, a daily average of each of the parameter was calculated by averaging the hourly data [10,61,62]. The maximum and minimum daily values of the water temperature and relative humidity were also obtained from the hourly dataset.

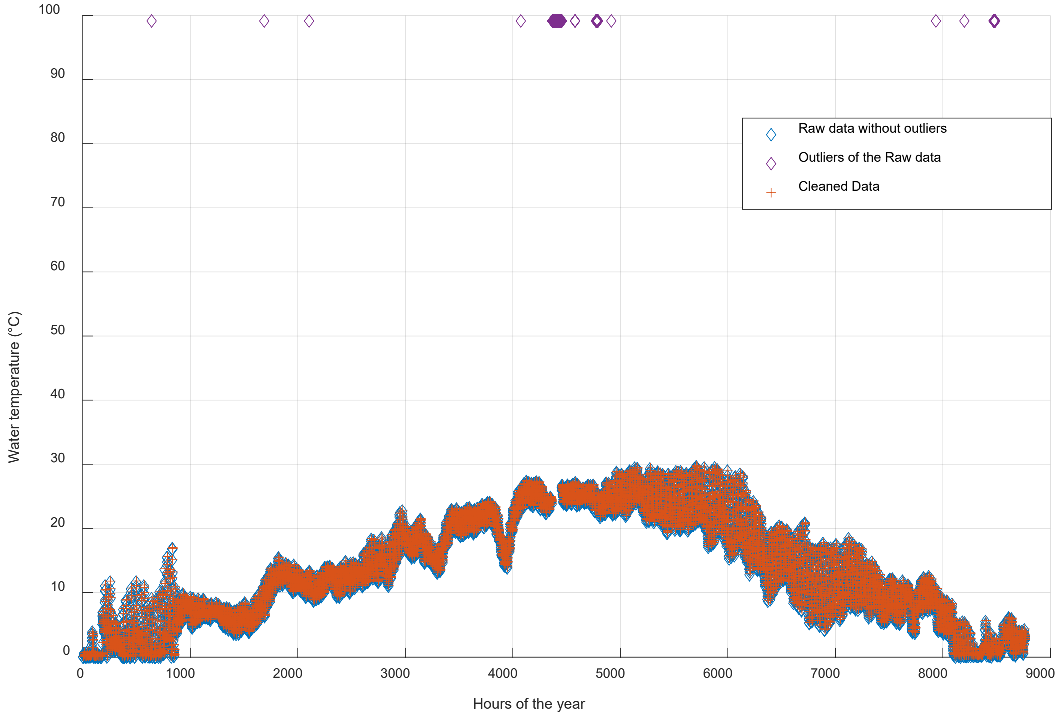

Figure 2. Plot of the raw data compared to the cleaned data.

2.2. Water Evaporation Model

A modified Penman-Monteith water evaporation model is used to appraise the water evaporation in Walker Lake. The original Penman-Monteith evaporation model was developed by Penman [63] and modified by Monteith [64] to assess the evapotranspiration in canopies. The Food and Agriculture Organization of the United Nations (FAO) has developed a detailed calculation procedure of evapotranspiration in crops using the Penman-Monteith model [54]. The Penman-Monteith model have since been adapted in several studies to estimate the evaporation in open water surfaces. This is achieved by using the water temperature instead of the air temperature in the calculation of some of the parameters that are included in the Penman-Monteith model [10,55,65–67]. Equation (1) shows the expression of the daily evapotranspiration (E_{day}) (mm/day) calculation [10,67,68].

$$E_{day} = \frac{1}{\lambda} \times \frac{\left(\Delta \times (R_N - Q) + 86400 \times \rho_a \times Cp_a \times \frac{(P_w - P_a)}{r_a}\right)}{\Delta + \gamma} (mm \cdot day^{-1}) \qquad (1)$$

In Equation (1), (λ) (MJ/kg) is the latent heat of vaporization of water, (Δ) (kPa/°C) is the slope of the saturation vapor pressure curve, (R_N) (MJ/m^2/day) is the daily net solar radiation, (Q) (MJ/m^2/day) is the daily heat storage flux, (P_w) (kPa) and (P_a) (kPa) are respectively the average saturation vapor pressure and the real vapor pressure of the air, (r_a) (s/m) is the aerodynamic resistance, and (γ) (kPa/°C) is the psychrometric constant. The collected weather data on Walker Lake is used for the calculation of each of the components in Equation (1). An open-source spreadsheet is then used to calculate evaporation on a water surface using the Penman-Monteith model [69] by each component for the case study in Walker Lake.

2.3. Energy Production Model

The solar photovoltaic panel considered in this study for the design of the FPV system is a single crystalline solar panel model SPR-E-Flex manufactured by SunPower [70]. In a recent study, an after-market conversion of the flexible panel into an FPV system has been demonstrated using green polyethylene foam as the floating support [39]. A temperature model has been developed [10] for the new foam-based FPV by adapting Kamuyu et al.’s model [71]. The original model proposed by Kamuyu et al. described the operating temperature of a pontoon-based tilted FPV as the linear function of the solar irradiation, the wind speed, the air temperature, and the temperature, while the model used is for foam-based FPV where the impact of wind speed is negligible in the operating temperature of foam-based FPV as it is lying flat on the water surface. The temperature model is shown in Equation (2), is used in this study to evaluate the energy production of an FPV system installed on Walker Lake.

$$T_{eo} = -13.2554 - 0.0875 \times T_w + 1.2645 \times T_a + 0.0128 \times I_S (°C) \qquad (2)$$

where T_{eo} (°C) is the effective operating temperature of the foam-based solar panel, T_w is the water temperature (°C), T_a is the air temperature (°C), and I_S (W/m^2) is the incident solar irradiation.

The operating temperature is then used to calculate the electrical efficiency (η_e) of the solar panel [10,71,72]:

$$\eta_e = \eta_{ref} \times \left[1 - \beta_{ref} \times \left(T_{eo} - T_{ref}\right)\right] (\%) \qquad (3)$$

In Equation (3), η_{ref} (%) is the efficiency of the panel in standard test conditions (STC), β_{ref} (%/°C) is the temperature coefficient of the panel in STC, T_{eo} (°C) is the effective operating temperature calculated using Hayibo and Pearce’s model [10], and T_{ref} is the operating temperature of the panel in STC.

The output power P_{out} (W) of a solar PV system is calculated by equation (4).

$$P_{out} = I_S \times A \times \eta_s (W) \qquad (4)$$

where the incident solar irradiance on the system is I_S (W/m^2), the total area of the system is A (m^2), and the overall efficiency of the system is η_s.

The overall efficiency of a solar system installed on lake surface accounts for the electrical efficiency as well as different losses that impact the operation of the system. Such losses include the shading losses, the soiling and hotspot losses, and the mismatch losses. Walker Lake is located at a high elevation, 1198 m above sea water level, and there are no nearby obstacles and shading from far horizon obstacle is minimal, therefore, the shading losses have been neglected in this study. Also, because the tilt angle of the solar panel is 0° (foam-based FPV panels are flat on the water surface), the global horizontal solar irradiation is used for the calculations. The other losses are the soiling losses, and the mismatch losses can be minimized as described in past studies [10,29,73]. The value used for the different losses is summarized in Table 1

Table 1. Parameters used for the energy production calculation.

Parameters	**Value**	**Source**
STC efficiency of the module	23%	[70]
Module inclination	0°	This study- mounted flat on water surface
Shading losses	0%	This study- no obstructions
Soiling	3%	[10,29]
Mismatch losses	6%	[10,73]
DC cable losses	3%	[10,73]

PV module degradation rate	0.5%/year	[71]

The modelling procedure of the water saving potential, and the energy production is summarized as a flowchart in Figure 3.

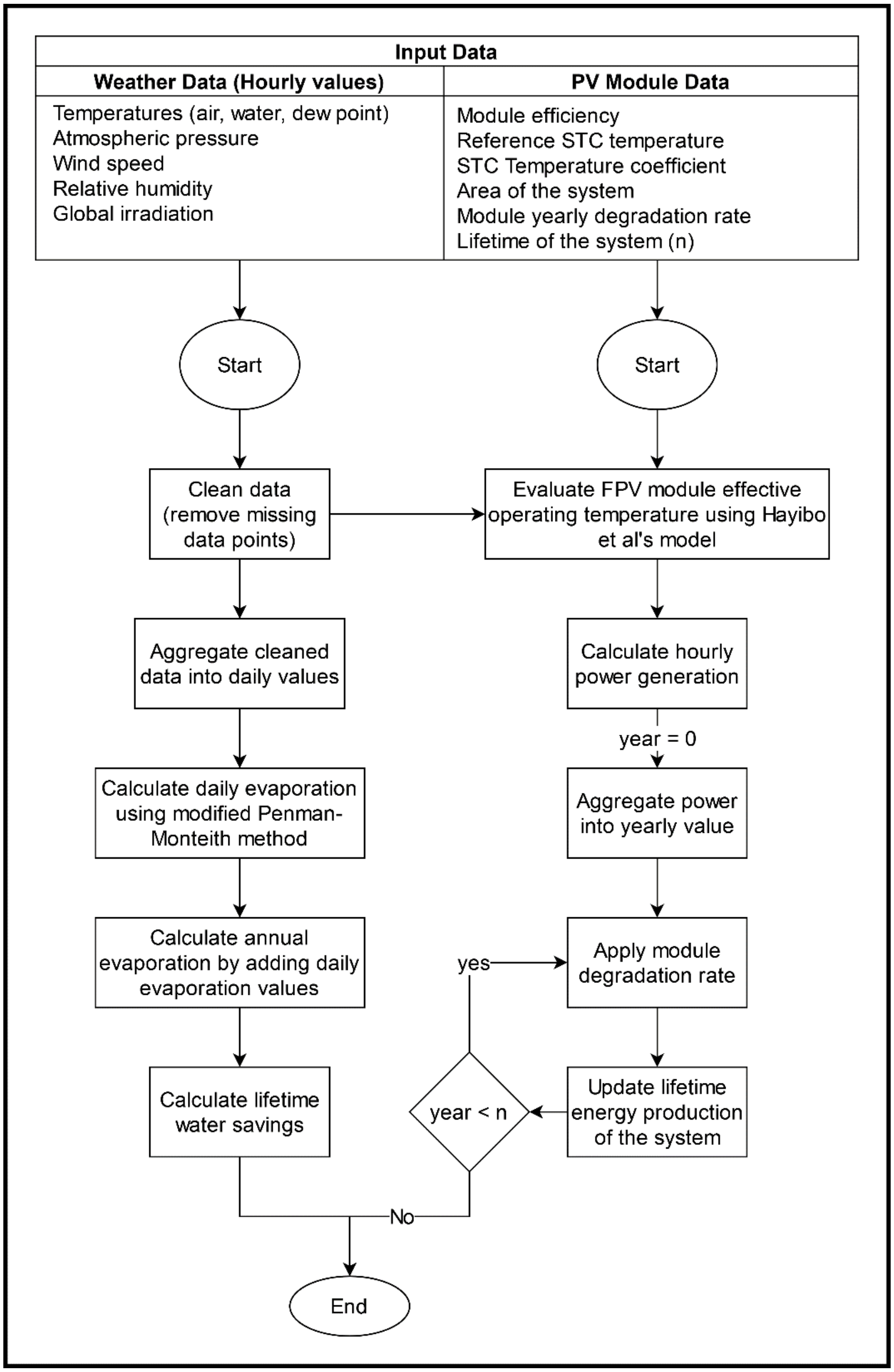

Figure 3. Flowchart of the calculation procedure of the water saving potential, and the energy production of the FPV system.

2.4. Water Saving Potential and Economic Considerations

Recent studies have shown that installing pontoon-based FPV systems on a water surface can help prevent more than 90% of the evaporation in the water body [12,74]. Therefore, the annual water saving potential of the foam-based FPV on Walker Lake has been estimated to 90% of the annual evaporation on the lake. The result obtained using this assumption is conservative because foam-based FPV panels cover the entire surface of the water they float upon. A study by the World Bank Group argues that not more than 50% of a lake surface could be covered by FPV if the lake is used for fishing [29]. As Walker Lake is used for fishing [75], the maximum coverage of the lake by FPV has been set to 50% of its total surface. Figure 4 shows a proposed layout of foam-based FPV covering 10% and 50% of Walker lake. The choice of aligning the FPV closer to the east coast of the lake is motivated by the fact that the major recreation areas are located on the west coast [51]. This design allows the FPV system to produce energy while limiting its impact on the nearby activities. A sensitivity is run on the coverage of the lake from 10% to 50% in increments of 10%. The volume of water saved in each case is calculated by multiplying the annual water evaporation by the corresponding surface of the lake, and the result is corrected by 90%. The economic value of the energy produced, and the water saved by a foam-based FPV system on Walker Lake are estimated by using respectively the cost of electricity purchased from the Hoover Dam in Nevada (USD 0.02/kWh) [76,77], and the cost of water rights acquisition by the Walker Basin Conservancy organization (USD 0.12/m^3) [78].

(a) (b)

Figure 4. Layout of foam-based FPV panels covering Walker Lake. (a) 10% coverage of Walker Lake; (b) 50% coverage of Walker Lake.

3. Results

3.1. Water Evaporation results

According to the modified Penman-Monteith model used for the simulation of the water evaporation on Walker Lake, the annual evaporation rate on the Lake is estimated to 1,156 mm in 2018. Past studies have found similar results. A study performed in in 1995 mentioned an average evaporation rate of 1,249 mm on the lake surface between the years 1939 and 1993 [79]. Another evaporation study performed on the Walker river basin and Walker Lake in 2009 using a water budget methodology has found that annual evaporation between the years 1988 and 1994 was ranged between 1,249 mm and 1,432 mm on Walker Lake [80]. The values found by Lopes and Allander are on the upper limits of the range of values, and this explained by the fact that the riparian evapotranspiration was studied. A riparian evapotranspiration study includes not only the surface of the lake, but also the surrounding wetlands.

On Figure 5 and Figure 6, the daily evaporation results and the monthly evaporation results are respectively displayed for data collected in 2017. Not surprisingly, the evaporation rate peaks during summer months; between June and August; and goes down during the winter, in December and January. The evaporation rate at the peak of the summer (June) is fourteen times greater than the lowest evaporation rate in winter (January). In winter, especially in late November, in December, in January, and in early February, the evaporation is negative as displayed on Figure 5. These negative values are obtained for days where the longwave radiation values are high and the actual vapor pressure is small, inducing condensation of water at the surface of the lake instead of evaporation [54]. Since these values originates from condensation and not from evaporation, they were not included in the monthly calculation of the evaporation. Figure 6 also shows the result for the potential quantity of water that can be saved. The value of the water saving potential is 90% of the water evaporation value. These values are in mm of water for any unit surface area; therefore, it is the saving potential on any portion of the lake. It does not depend on the lake coverage. Instead, it is used to find the total water saving by multiplying these values and the surface area of the portion of the lake that is of interest. For example, if 50% of the lake is covered by FPV, the values are multiplied by 50% of the lake surface to obtain a volume of water saved during the applicable timeframe.

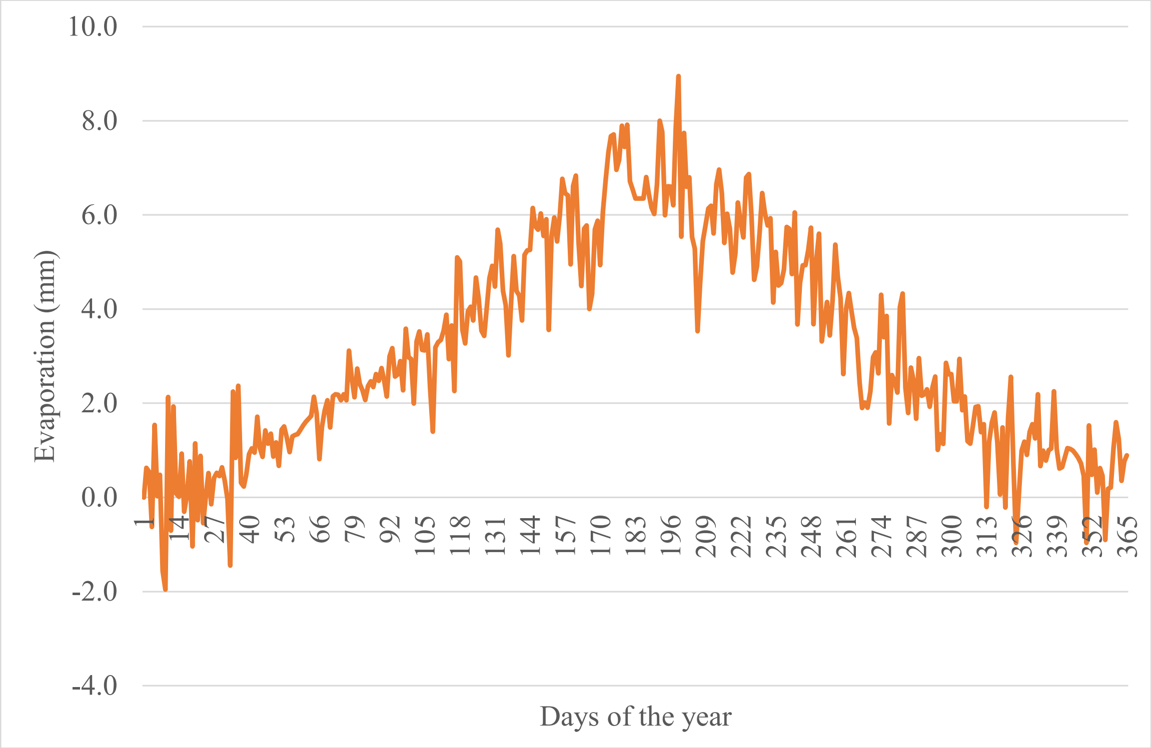

Figure 5. Daily simulated evaporation values (mm) on Walker Lake in 2017.

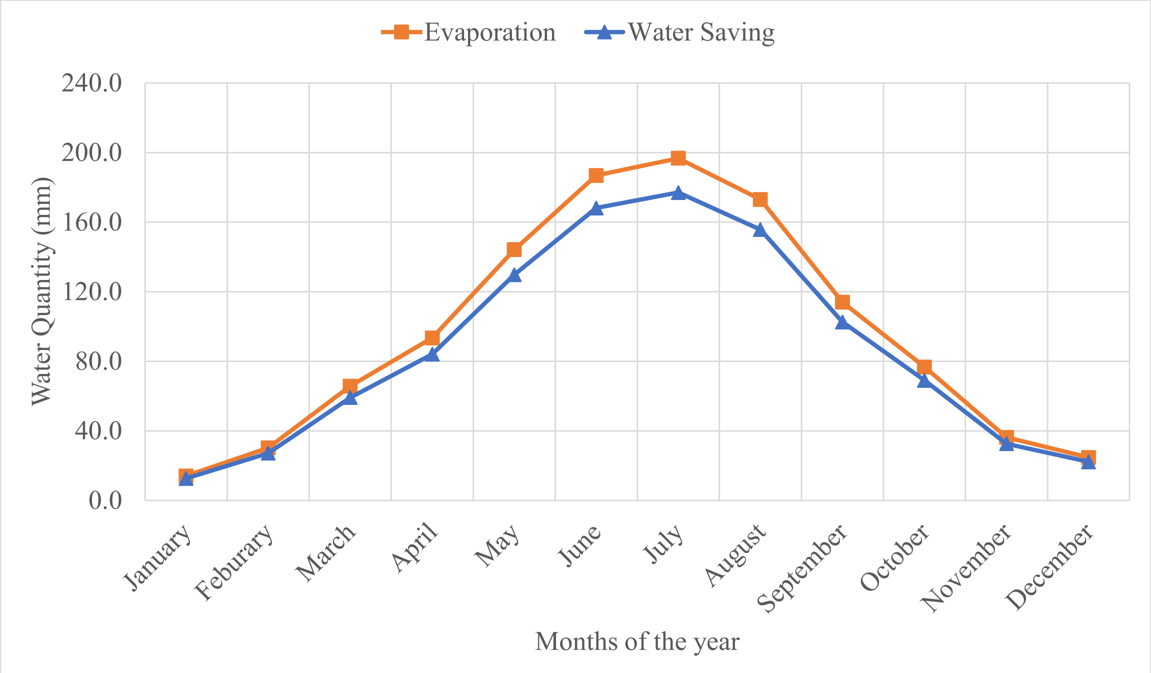

Figure 6. Monthly simulated evaporation values (mm) on walker Lake for data collected in 2017.

3.2. Energy production and water saving potential of foam-based floatovoltaic systems on Walker Lake

The foam-based FPV temperature model [10] is used to run an energy production analysis for 5 different case scenarios where 10 to 50% of the lake surface is covered with foam based FPV panels in an increment of 10%. Figure 7 shows the results for the daily energy production when 10% of the surface of the lake is covered by foam-based FPV. The peak energy production occurs in summer with a value of 19 MWh on 13 May and 18 May, while the lowest production happens during the winter on 22 January with a value of 1.9 MWh.

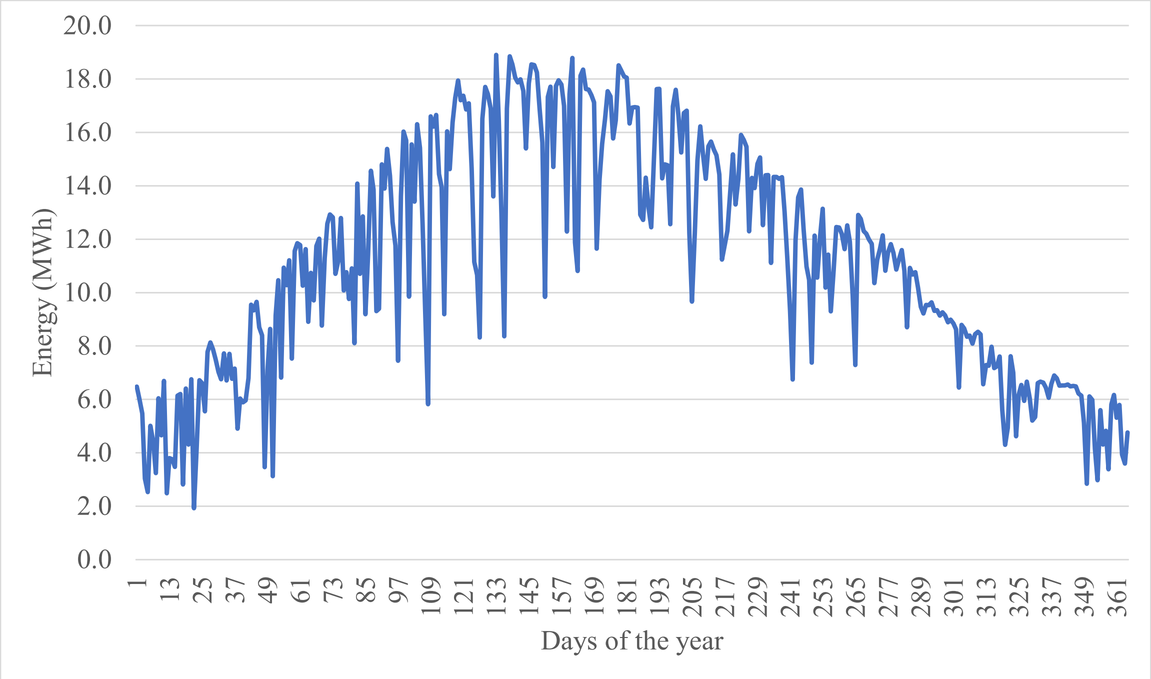

Figure 7. Daily energy production profile (MWh) of foam-based FPV covering 10% of Walker Lake.

The results for the monthly energy production are displayed when 10% to 50% of the lake surface is covered by foam-based FPV panels on Figure 8. The monthly energy production is obtained by summing the daily energy production for each month. The peak production occurs in June and the lowest production happens in January. For example, with 10% coverage of the Lake using the historical data of 2017, the energy production in June is 495 MWh and the energy generation in January is 163 MWh.

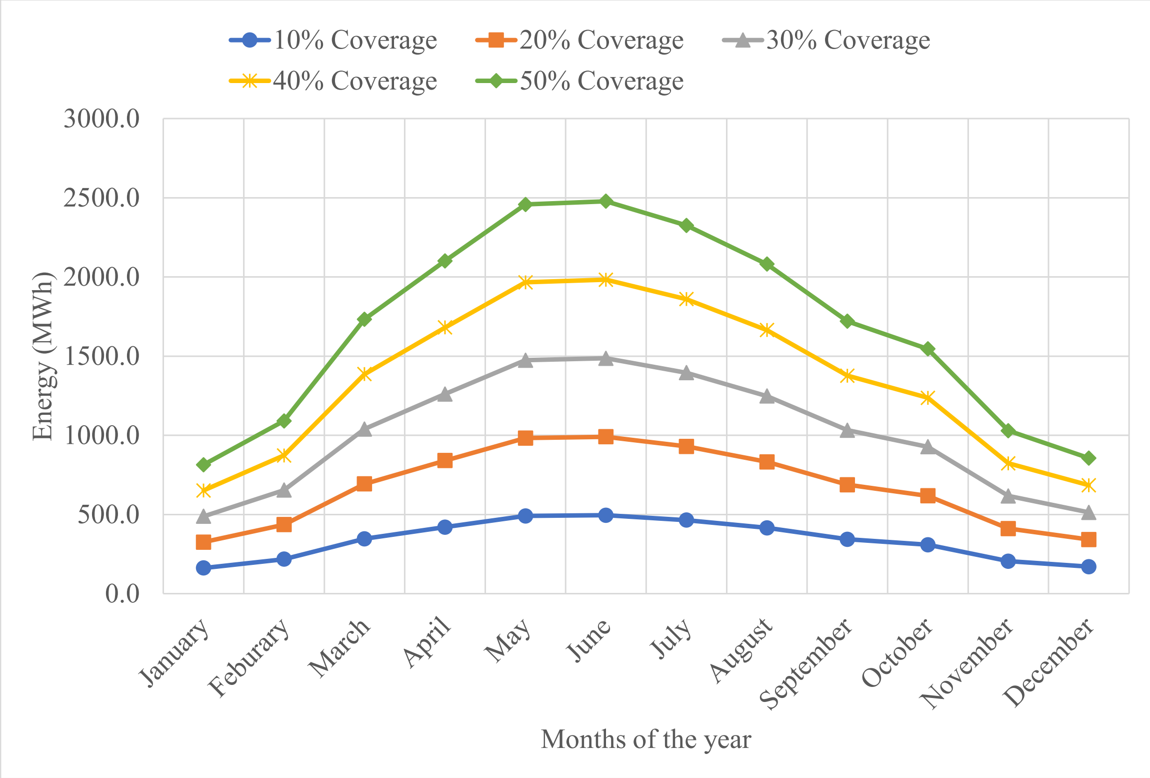

Figure 8. Monthly energy production of foam-based FPV covering 10% of Walker Lake.

The total annual result of the simulation is shown in Figure 9 for the annual energy production and the water savings, for different values of the lake surface coverage by foam-based FPV ranging from 10 to 50%. For example, at a 10% coverage of the surface of Walker Lake, the foam-based FPV panels have an annual energy production of 4 TWh, and the FPV system provide enough cover to save 10 million m^3 of water. For a 50% coverage of the lake surface by foam-based FPV, 20 TWh of energy can be generated and the panels can prevent the evaporation of 52 million m^3 of water.

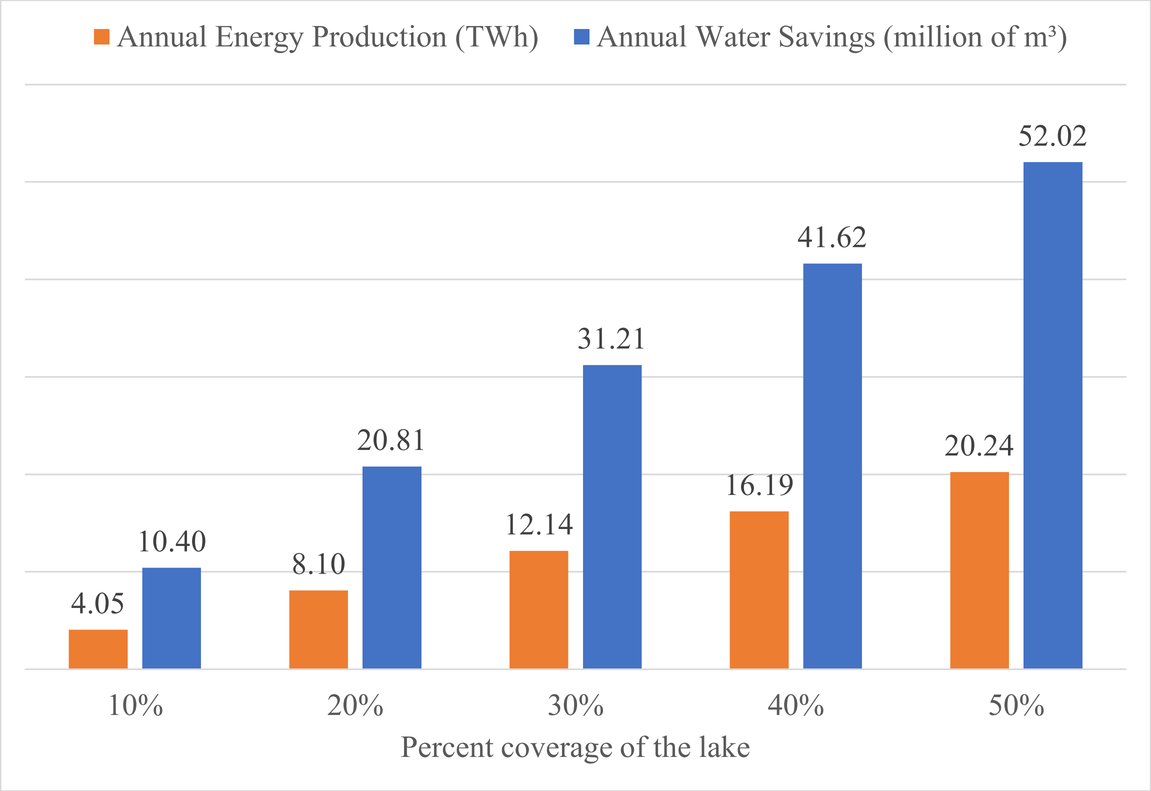

Figure 9. Annual energy production (TWh) and annual water savings (millions of m^3) on Walker Lake using historical weather data, as a function of the percent coverage of the lake's surface.

The results of the cost of the water saved as well as the cost of the energy produced is displayed in Table 2. As can be seen in Table 2, the economic value of the water saved with FPV is roughly 1.6% of the value of the solar electricity. The value of energy generated by a foam-based FPV system installed on Walker Lake is estimated at USD 80 million annually when 10% of the lake surface is covered, and USD 402 million when 50% of the lake surface is covered. On the other hand, when the price at which the Walker Basin Conservancy purchases water rights from farmers is used to estimate the water cost, more than USD 1 million can be saved on water purchases when 10% of the lake surface is covered by foam-based FPV. Additionally, the cost of the water saving when 50% of the surface of Walker Lake is covered is more than USD 6 million.

Table 2. Estimation of the annual cost saved on water purchase and the annual revenues on energy production of a foam-based FPV system installed on Walker Lake for 10 – 50% coverage of the lake surface.

Percent Coverage	**Water Savings/Year at \$0.12/m^3 (millions of \$)**	**Energy Revenues/Year at 2¢/kWh (millions of \$)**
10%	1.25	80.54
20%	2.50	161.09
30%	3.75	241.63
40%	4.99	322.17
50%	6.24	402.72

4. Discussion

Using the modified Penman-Monteith method the resulting water savings potential is estimated at 10 million cubic meters if 10% of the lake surface is covered with FPV. When 50% of the surface of the lake is covered by foam-based FPV, 52 million m^3 of water can be saved. The importance of the quantity of water potentially saved at Walker Lake is emphasized by the fact that Walker Lake is a terminal lake that is drying up. The level of water in Walker Lake has been dropping at an alarming rate [81]. According to the National Aeronautics and Space Administration (NASA), the lake has lost 90% of its volume during the last century [44]. NASA's Landsat satellites has recorded several images that shows the shrinkage of the lake. For example, Figure 10 shows how the lake has shrunk from 1988 to 2017. A GIS surface area analysis performed in Google Earth [82] reveals that the surface of Walker Lake went from approximately 153 km^2 in 1988 to 118 km^2 in 2017, indicating that more than 22% reduction in the surface are of the lake [83]. In 2003, Walker Lake is described as very sick since it has lost 42 m worth of its water in 120 years [52]. The lake level dropped from 69 m in 1882 to 27 m in 2003. The dire situation of Walker Lake affects not only the marine life, but also the ecosystem that depends on the marine life, the local economy, and the native people of the area. In addition, with the loss of water in the lake, the total dissolved solids (TDS) level of the lake has been increasing: the level of TDS in the lake is 22 g/L as of 2019 [56]. At this TDS level, the remaining fish species living in the lake, the Lahontan cutthroat trout is struggling to survive, and the population of fish is kept at an acceptable level only because of stocking [46,52]. As a ripple effect, the population of migratory birds that feeds on the Lahontan cutthroat trout has significantly decreased [41,46,52]. Also, the town of Hawthorne, that thrived economically because of fishing competitions and tourism (bird watchers), has seen its economy gradually impacted by the raise of the TDS level in lake [52,84]. Furthermore, the native Paiute Indian population that lives near the lake are watching a piece of their culture disappear. These negative economic, environmental, and social outcomes are expected due to lake disappearance. Terminal lakes are known to have economic, social, and environmental benefits because they can harness and reprocess nutrients more easily and more effectively than freshwater sources, but these benefits have been found to be difficult to quantify [41].

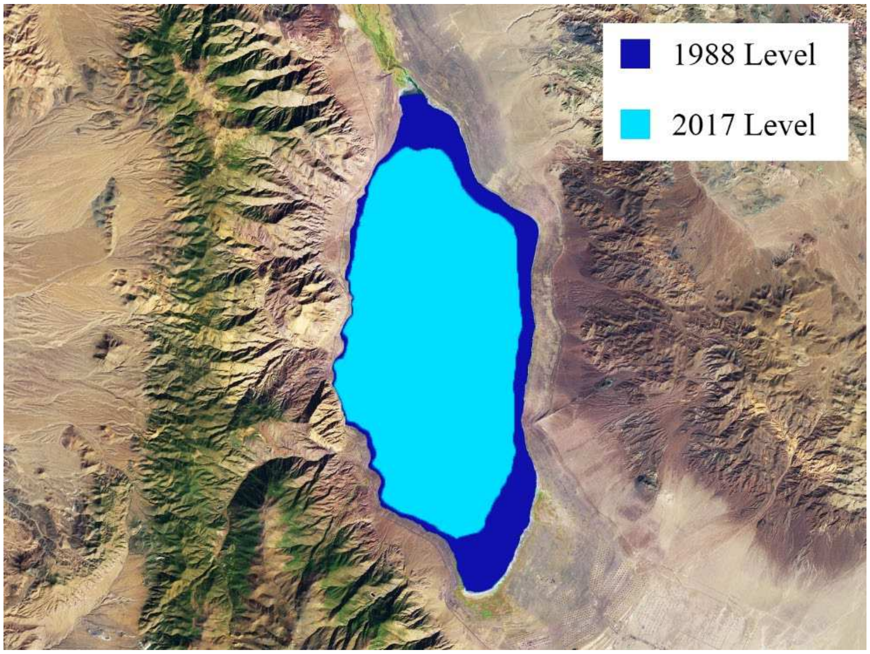

Figure 10. Superimposed view of satellite images of Walker Lake in 1988 and 2017.

The drop in the level of the lake is mainly caused by the diversion of the water from the Walker River. The Walker River water rights have been purchased by farmers who use the water for irrigation, therefore preventing the natural replenishment of the lake [44,52,80]. Another reason that is causing the disappearing of the lake apart from the water diversion for agricultural purposes is the natural evaporation of the remaining water of the lake. This evaporation is worsened by the raise in global temperatures due to climate change [41,44,45,47,48]. As a result, if nothing is done Walker Lake is at risk of completely drying up. Several solutions have been suggested to prevent the lake going completely dry. One significant action is the passing of the Desert Terminal Lake Act [85] bill in 2002 that has been amended in 2009 [85]. The Desert Terminal Lake Act led to the creation of the Walker Basin Restoration Program [86] that is administered by the National Fish and wildlife Foundation (NFWF). The NFWF has been working to re-acquire water rights to allow natural flow of fresh water to the lake [80,87]. This initiative is administered by the Walker Basin Conservancy program that is a non-profit initiative that aims at raising funds to prevent Walker Lake from disappearing and to protect the endangered ecosystems. Nevertheless, the water acquisition process is slow, and in the meantime, Walker Lake is continuing to disappear. Since the start of the program, only 47.5% of the amount of water needed to lower the TDS to an acceptable level (12 g/L) in order to restore the fish population of the lake has been acquired [88].

Interestingly, there has been no attempt to save water in Walker Lake by preventing evaporation. The result in this study shows that if foam-based FPV panels are installed on 50% of the surface of the lake, the evaporation of 10 million of m^3 will be prevented each year. This can cut down the amount of water needed to reach the TDS level required for a safe proliferation of marine life in the lake. The TDS goal set by the Walker Basin Conservancy [89] is to decrease the total dissolved solids level from 22 g/L to 12 g/L in a first restoration stage, then, proceed to acquire more water rights to lower the TDS to 10 g/L. A TDS of 10 g/L represents the level at which the fish species native to Walker Lake will thrive again, this level of TDS has not been reached since 2001 [56]. According to the United States Geological Survey (USGS), the average annual water outflow in Walker Lake between 1971 and 2000 was estimated at 200 million m^3, 194 million m^3 of which was lost due to evaporation on the lake surface, and the remaining water was either lost to evapotranspiration, runoff diversion, or water pumping [80]. If 50% the lake surface was covered by foam-based FPV during the period 1971 to 2000, 25% (50 million m^3) of the water lost could have been conserved.

On the other hand, by using the average American household annual electricity consumption (10,649 kWh) given by the United States Energy Information Administration [90], the foam-based FPV will be producing enough energy to power close to 2 million American homes, if it covers 50% of the lake surface. This means that not only will a foam-based FPV on Walker Lake contributes to its water preservation program, but also the FPV system will produce more than enough clean and renewable energy to power the cities of Hawthorne, Carson, Reno, Las Vegas, and Henderson combined. Furthermore, the energy production of a foam-based FPV system on 10% of Walker Lake in its current state is enough to replace almost 40% of the coal-fired plants across the state of Nevada, and the energy produced by covering 50% of the lake surface by foam-based FPV is the double of what is required to completely shut down all coal-fired plants in the state (10.25 TWh/year) [91]. Therefore, contributing to a reduction in the global emissions of the state of Nevada and having a long-term positive impact on the environment by helping reduce climate change and improving the health of the lake.

5. Future Work

There are ample opportunities to build on this study for future work. The case of Walker Lake is not isolated. There are several natural terminal lakes throughout the world that are facing the same fate [41,44]. In Iran Lake Urmia has lost 90% of its water between 2000 and 2017 while the Aral Sea in Kazakhstan has seen the same amount of its surface water disappear between 1960 and 2017 [44]. The Aral Sea has shrunk to the point where it currently turned into four different basins [43]. Other shrinking lakes mentioned by Gross are the Dead Sea spanning Israel and Jordan and the Great Salt Lake in Utah [43]. On the Mongolian plateau, which is home to several lakes, the number of lakes that have a surface area greater than $1km^2$ went from 785 to 577 in 30 years [92]. Similar observations have been made on the other side of the Mongolian border, in the Gobi Desert in China where 50% of the lakes went completely dry by the year 2000 [93]. This phenomenon can also be seen in Africa by the example of

Lake Chad that has seen its surface reduced by 90% since 1960, causing major impacts on the daily life of the population living in the Lake Basin [94]. In the worst cases, when nothing is done, the lake can completely disappear. This is the case of Owens Lake in California where the lake completely vanished in the 1940s [41] despite the colossal amount of money (USD 2 billion) that were invested by the state for the Lake's restoration. The cause of the endangerment of these lakes is similar to that of Walker Lake. Usually, there is a conflict between the conservation of the lake and the use of the lake tributaries for irrigation and agricultural purposes [41,44,46,48,95].

If foam-based FPV can be part of the solution at Walker Lake as shown in this study, it can be assumed that the use of foam-based FPV on similar lakes will be similarly beneficial to the short-term conservation effort that are happening on these lakes. Furthermore, installing FPV on such lakes will contribute to the percentage of the mix of solar PV energy in the world electricity production, therefore lowering carbon emissions and reducing the thermal stress from global warming that is directly causing some of the water losses. Additionally, preventing the water in natural lakes from evaporating will become even more crucial in the future because wells that contributes 40% of irrigation water throughout the world are also at risk of going dry if groundwater level decreases by only a few meters [96]. In addition, according to a recent study, at the current pace of groundwater pumping, the level could drop in the coming years [96]. One solution proposed is to halt the overuse of groundwater is to turn to natural lake and river waters [96,97]. This would put additional lakes at risk for termination. Instead, the strategic installation of foam-based FPV on lakes worldwide has the potential to contribute to the reduction of the stress on groundwater by mitigating evaporation and the potential disappearance of natural lakes.

An interesting concept that can be introduced by the installation of foam-based FPV on the surface of Walker Lake is the combination of floatovoltaics with aquaculture or aquavoltaics. Aquavoltaic is a subject at the forefront of the energy-water-food nexus research that explores the synergies between sustainable energy generation, food production, and water conservation [19]. There are immense potential benefits in coupling foam-based FPV with aquaculture on Walker Lake. The foam-based FPV system contributes to the preservation of the natural habitat of the fish in the lake by mitigating water evaporation and algae bloom [27]. Simultaneously, the FPV panels benefit from a cooling effect from the lake, as past studies have shown that the energy production of FPV systems is boosted due to the proximity of a water body [4,18,33,98]. This cooling effect has been found to be even greater in foam-based FPV system through the direct contact of the panel with the water surface [10]. Another benefit the water confer on the floatovoltaic system is a potential increase of its operational lifetime by decreasing the degradation rate of the panels below 0.5% [71]. Concurrently, the FPV system has the potential to sustain the fishery by providing the energy necessary to run oxygenation pumps that control the level of oxygen in the lake. Controlling the oxygen level in the lake is crucial to maximizing the production of biomass that serve as natural feed to the Lahontan cutthroat trout [18,19]. The Lahontan cutthroat that is the staple fish of Walker Lake, however, needs light to thrive. As the foam-based FPV covers the surface of the lake, one can argue that it would be detrimental to the cutthroat trout. This is mitigated with two methods. First, by ensuring only a fraction of the lake is covered can provide the fish with ample access to light. Second, this challenge can also be mitigated providing an optimal amount of light for fish growth with the installation of light emitting diodes (LEDs) under the surface of the water shaded by the panels to control the light cycle of the fish [19]. Further research is needed in this area to optimize the energy-water-food nexus.

The results in this study demonstrate the potential of foam-based FPV to mitigate the disappearance of Walker Lake by preventing evaporation. These results also indicate that FPV could be a potential solution to water loss from other terminal natural lakes. There are several areas of future work. First, because the potential solar energy coming from a substantial percentage of Walker Lake coverage is so great more detailed modeling of the energy performance of the system when it is grid-tied over its lifetime is needed. Also, an integrated energy production, water conservation, and more granular economic cost value study will be necessary to determine how the foam-based floatovoltaic system would factor into the conservation efforts initiated by the Walker Basin Restoration Program. Past work on the capital costs of foam-based FPV [39] indicate it is less expensive than conventional FPV or ground mounted systems and after the FPV is fabricated the deployment time is less. A complete economic analysis including labor costs is beyond the scope of this study but can be targeted for future work. The model used here for evaporation can also be compared to other evaporation rate models [99]. Reasonably, the most pressing factor to investigate in future work would be the effect of Walker Lake total dissolved solids (TDS) levels on the materials making up the solar modules as well as on the foam-based racking. This is crucial because the foam-based racking for FPV is a newly proposed technology and there is currently not enough knowledge regarding the effect of water with high TDS levels on the structural stability of foam and on the modules. This could be accomplished with accelerated corrosion studies. Also, future works is needed to investigate the durability of the foam as well as its effect on marine life. Specifically, the behavior of the Lahontan cutthroat trout as well as the behavior of fish species that will be introduced in the lake in the future can be investigated under the conditions of both partially shaded water as well as that which is shaded but also illuminated by LEDs. Because foam-based FPV has the capacity to substitute coal-operated energy plants, it would be interesting to analyze the policies that need to be enforced to replace environment-damaging energy production plants by foam-based FPV plants. Another topic to explore in the future is the CO_2 emissions averted by generating clean electricity on Walker Lake using foam-based FPV systems by performing a full environmental life cycle analysis on the system and comparing it to more conventional PV systems. This would be an interesting subject to analyze because of the synergies between the floatovoltaic system, the water body, and the fishery. The changes in the lake surface albedo [100] caused by the FPV are also an area of future work as it could impact the temperature of the lake. These impacts of the thermal effects of FPV and the impact of temperature of the lake [101] need to be investigated as all of the energy absorbed by the PV that is not converted to electricity is converted to heat and the operating temperature of the FPV is a critical variable in performance [102]. This heat would be expected to be more concentrated at the surface of the lake in an FPV system as compared to the same solar energy being absorbed naturally by the water body. This is because light actually penetrates relatively deeply in many bodies of water (in some cases it has been proposed to run under water FPV [103–108]. In addition, there are opportunities in these FPV systems to consider heat capture as well and innovations in thermal-PV hybrid systems [109] could be investigated to improve synergies. Lastly and perhaps most importantly experimental testing of the concept over a large surface area of the Lake is necessary. More generally, the concept of this study can be extended to other existing natural terminal lakes that are facing the same fate as Walker Lake.

The results of this study indicate a considerable potential for applying this concept to other lakes worldwide. Determining the impact that covering disappearing terminal lakes worldwide that receive a suitable level of solar energy irradiation would have on the mitigation of groundwater depletion, and CO_2 emissions is also a considerable area for future studies. A life cycle analysis study has shown 30-year lifetime foam-based FPV systems have some of the lowest energy payback times (1.3 years), the lowest GHG emissions to energy ratio (11 kg CO^2 eq/MWh) in c-Si solar PV technologies in the literature, 5 times less water footprint (21.5 m^3/MWh) as compared to a conventional pontoon-based FPV (110 m^3/MWh) [110]. As the effect of coal-based energy production plants is worsening climate change effects, solar photovoltaic technologies are known to mitigate CO_2 emissions [111,112]. Therefore, it is crucial to know how foam-based floatovoltaic system would factor in the global effort to keep the temperature rise due to greenhouse gases effect below 2°C [113]. Additionally, the methodology used in this study can be extended to smaller flowing water bodies such as rivers. For example, future work can focus on the interaction of foam-based FPV with rivers by investigating the effect of the turbulences in a river on foam-based FPV modules. The disappearing of lakes is known to put the lives of the nearby populations at-risk [43]. As a result, future studies need to also focus on the exploration of the social, economic, and cultural impacts on human populations near lakes of using foam-based FPV systems as part of water conservation efforts.

6. Conclusions

This was the first study investigating the potential of FPV to help conserve water in disappearing terminal natural lakes. The water saving potential of recently developed foam-based floatovoltaic technology was investigated in this study by performing a water saving analysis and an energy production simulation for the case of Walker Lake. The water saving analysis and energy production simulation are implemented through a modified Penman-Monteith evaporation calculation, and a foam-based FPV module operation temperature model, respectively. The results found that the FPV system will save 52 million cubic meters of water from evaporating each year when half of the lake surface is covered by FPV, which represents 25% of annual water losses between 1971 and 2000. 50% coverage of the Walker Lake also represent USD 6 million savings for the Walker Basin Conservancy. The quantity of clean energy produced by this FPV system on 50% of the lake is 20 TWh per year. This is more than the energy required to provide electricity to the three most populated cities of the state of Nevada: Las Vegas, Henderson, and Reno. Finally, 20 TWh is also enough solar-generated electricity to offset all the coal-fired power plants in the state of Nevada and lead the state towards a cleaner energy future. Overall, the results of this study indicate that foam-based FPV has the potential to play a crucial role in the mitigation efforts to prevent the disappearing of Walker Lake while also reducing climate forcing from greenhouse gas emissions, and more generally disappearing natural terminal lakes worldwide.

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