Iranian (Iranica) Journal of Energy & Environment
Journal Homepage: www.ijee.net
IJEE an official peer review journal of Babol Noshirvani University of Technology, ISSN:2079-2115

Floating Solar Power Plants: A Way to Improve Environmental and Operational Flexibility

M. Esmaeili Shayan[1]*, J. Hojati[2]

[1] *Department of Biosystems Engineering, Tarbiat Modares University (TMU), Tehran, Iran*
[2] *Deputy of Design and Operation, Iran Water & Power Resources Development (IWPCO), Tehran, Iran*

P A P E R I N F O

Paper history:
Received 30 September 2021
Accepted in revised form 22 November 2021

Keywords:
Clean energy
Electricity demand
Floating photovoltaic systems
Solar power
Water evaporation

A B S T R A C T

The Photovoltaic modules installed on the surface of the water are naturally cooled, reducing the loss of thermal power generation. Floating photovoltaic systems (FPVS) combine existing photovoltaic systems with a floating structure to generate clean energy. To meet the growing electricity demand, FPV systems will be integrated alongside existing dams to enhance existing power sources. The results indicate that the investment toward installing FPV systems over the dams' reservoirs leads to a significant improvement in the overall system reliability minimizes load curtailment, and could potentially add more flexibility to the operator to dispatch power generated by hydropower plants during peak demands. The execution of the Karun-4 FPV power plant with an annual production of 16758969 kWh of energy has reduced the water evaporation of the dam's reservoir water and after eight years and four months, the investment cost was returned and its nominal performance is 81.7 percent. Adding a floating solar power plant with 10% of the lake reservoir cover of six dams saves 70.7 million cubic meters of water per year. This amount of fresh water is enough to meet the annual needs of one million people.

***doi**: 10.5829/ijee.2021.12.04.07*

INTRODUCTION

Renewable energy research almost came to a halt in the 1980s and 1990s due to the abundance and low cost of oil and gas at the time. However, due to high oil and gas prices, as well as the new risk of global warming caused by the emissions of greenhouse gases from fossil fuels, renewable technologies, including solar energy, has re-emerged as a focus of attention. According to the Ministry of Energy's 2019 report, Most power plants use fossil fuels [1]. Almost all renewable electricity is generated by major hydropower facilities, with wind energy, solar energy, small hydropower, etc. playing a minor role. As a result, only 200 megawatts of electricity generated in Iran is produced from renewable sources – other than large hydropower, but fossil fuels are finite resources, so researchers are looking for alternative sources of energy supply when planning the country's energy portfolio [2–4]. Solar irradiation conditions revealed that the majority of Iran's geographical area is in hot and dry regions having a strong potential for photovoltaic and solar heating system operation [5]. At the same time, it promotes stationary water evaporation [6]. The worldwide average annual evaporation potential is 700 mm, whereas Iran has three times the global average yearly evaporation [7]. High-potential photovoltaic technology has the potential to contribute to 5% of Europe's power needs by 2030 and 11% by 2050 [8]. However, just 1% of total electrical power required by humans, or 18,400 terawatts, is supplied by various solar-to-electricity conversion systems [9].

In addition to the benefits listed above, floating solar power plants have a strategic advantage in terms of Iran's location. Karun 4 Dam is the largest arch dam in the country and the world's fifth-largest dam and hydropower plant [10]. With its prior features and the utilization of new resources, this dam can be a pioneer in establishing the balance of energy management and a viable model for

*Corresponding Author Email: *Mostafa.esmaeili@modares.ac.ir* (M. Esmaeili Shayan)

Please cite this article as: M. Esmaeili Shayan, J. Hojati, 2021. Floating Solar Power Plants: A Way to Improve Environmental and Operational Flexibility, Iranian (Iranica) Journal of Energy and Environment, 12(4), pp. 337-348. Doi: 10.5829/ijee.2021.12.04.07

transitioning to renewable energy in the economic and executive management systems, as well as in energy policy [11]. An overview of studies shows that the use of a floating solar power plant can have many benefits. The cooling impact of water minimizes temperature-associated losses, lowering evaporation charge of water bodies, and decreasing protection costs [6]. Research about Karun-4 Floating PV Solar Power Plants: A Techno-Economic Assessment needs to be carried out because this solar power plant can hybridize the hydroelectric power plant and increase its performance while reducing water evaporation at the source behind the dam.

LITERATURE REVIEW

Long-term initiatives for sustainable development are required to solve the environmental problems we are now dealing with. One of the most efficient and successful options in this regard appears to be the use of renewable energy sources. Because of this, renewable energy and sustainable development are inextricably linked [12]. The world's energy consumption is outpacing the world's installed generation capacity. Energy demand should be met and developed in a safe, efficient manner to meet future energy needs [13]. Energy-related CO_2 emissions account for two-thirds of total greenhouse gas emissions (GHG). Innovative technologies, particularly in solar energy, will facilitate this energy revolution [14].

Japan presently produces more than half of the world's solar energy [15], followed by Europe (25%) and the United States (19%). Although crystal silicon solar cells are very poor absorbers and require a considerable thickness of a few microns for appropriate performance, they have been absorbed in most systems from the past to the present. They are employed in sunlight and are widely used in microelectronics technology, with 11 to 24% efficiency [16].

While solar energy has a tiny role in Iran's electricity production, it has a global share of over 30% [17]. Although the slightest change in this technology can have a positive effect on system performance [18]. Rural electricity supply began in 2006 in Qazvin, then Gilan, Zanjan, Bushehr, Yazd, and Kurdistan. In 2008, a project to offer power to 634 rural families was defined, with a capacity of over 386 kW [19]. In terms of solar energy consumption, Morocco now leads the Middle East and North Africa [20]. Around the world, large-scale photovoltaic power facilities (solar farms) have been designed and simulated. Canada created a 5 kW floating PV plant [21]. In 2017, Zhong et al. [22] examined the issue of small consumers using solar electricity. Recently, the parametric design of solar farms and small-scale power plants to address urban electricity needs was investigated [23, 24]. To count for the shadow effect in surface-based solar power plant design, Jin et al. [25] proposed a model to estimate Sun orientation by a single image using Laser Technology. In 2018, Pratumnopharat et al. [26] used MATLAB to simulate the best solar power plant. Esmaeili Shayan et al. [27] on a floating surface, the ideal angle of solar panels may be calculated. Khatib et al. [28] identified key variables in PV plant design. International Energy Agency (IEA) in Denmark simulates, designs, and deploys a 14.5 kW floating photovoltaic project [29]. The use of solar power tracking by genetic algorithm method was an innovation that has increased the efficiency of photovoltaic solar systems [30]. Switzerland uses climatic data management software to develop and build. Also, two 226/52kW power plants were calculated on a pond to prevent surface evaporation [31]. Parallel to solar-powered gas-fired power plants, South Korea studies low-energy companies. Also, COMFAR software was utilized in an economic analysis of a floating photovoltaic system [32]. The small floating photovoltaic power plant reduces greenhouse gases while meeting peak consumption needs [33]. A study looked at the performance and cost of energy distribution in traditional power plants. The results demonstrated that by lowering the cost of solar systems, they can soon compete with fossil power plants. This study and others [7, 34] found that floating photovoltaic power plants can generate yearly returns of 15 to 40%. A 20-year scenario was used to evaluate the technical-economic feasibility of a grid-connected photovoltaic system for developing areas and countries. The results demonstrated that using floating PV systems in reservoirs reduces surface evaporation as well as heat loss [35]. On the surface of the dam, two Swiss projects of 26 and 52 kW were simulated, planned, and built. Software text was exceptional for simulation, weather computations, and shading. In a few months (January and November), the simulated data differed from the actual data, but the annual production capacity was appropriately projected [36]. A power station atop a reservoir was designed and simulated in South Korea to examine floating solar systems. This power plant's features include heat capacity, heat dissipation, intelligent control in various climates, and 30 kW photovoltaic power output. The plant had a nominal capacity of 28.1 kW and an annual production capacity of 24.85 MW. This power station employed 580 Samsung SM-50 50 watt panels. An inverter matching section reported substantial power loss due to the shading effect of panels in some months [37]. 20-year research evaluated off-grid floating solar systems for developing countries and areas. The expense of grid-independent solar systems is the biggest impediment to employing them in these locations [38]. In 2007, Japan created the world's first floating solar PV plant. Some other countries have since attempted small-scale solar floating photovoltaic power plants for scientific purposes. First commercial installation of a 175 kW floating photovoltaic power plant in a food processing factory [39]. Immediately, South Korea and the USA built 80 and

12 MW floating solar power plants [6]. now, 20 countries have developed 40 megawatts of floating solar power [40]. In June 2017, Huainan launched a 40-megawatt floating solar power facility. On an abandoned coal mine [38], this floating solar power station can give electricity to a small town and around 15,000 people.

In 2019, a floating solar power plant was installed in one of London's most important water reservoirs. 23000 solar panels formed a 6MW power plant. Temperatures, especially in the summer, lower the effectiveness of all floating solar power plants, but water and its cooling action prevent such action [41]. China will connect the world's largest 50 MW floating solar power facility to the grid in 2020. The first phase of this 150 MW project has entered the network. Price: $ 151 million [42]. By 2019, around 300 floating PV solar power plants will be operating globally. The Mackenzie Institute expects a 22% annual rise in demand for floating solar power facilities from 2019 to 2024 [7]. According to a recent report, the market for floating solar power plants will rise by over 31% annually from 2018 to 2022. The Americas will have a 52% rise in capacity, while the global capacity will expand by 1.5 GW annually [36]. We are currently in the early stages of developing grid-connected hybrid systems that mix energy and floating solar PV. There are more than 400,000 square kilometers of extant reservoirs, man-made ponds worldwide. The effect of water cooling on enhancing the efficiency of floating solar power plants by about 20% has been documented in Iran [34]. Floating photovoltaic power plants have positive benefits on lowering pollution, encouraging the community to embrace renewable sources, and reducing CO_2.

This research presents a projected meteorological model with GIS and a roadmap to construct combined floating hydropower and solar power facilities. This study designed and analyzed the Karun 4 mega solar power project. The floating solar power plant was designed using real-time weather data from 2000 to 2020 and a forecasting model from 2020 to 1425. In this study, a floating solar power plant on a dam reservoir is investigated for technical, economic, and environmental sustainability. This study looked at 5 main Iranian dams. The amount of evaporation was calculated using algorithms based on satellite pictures. The solar energy production model is designed for a one square kilometer area of the Karun 4 dam reservoir, and the technical, environmental, and economic impacts were studied.

MATERIALS AND METHODS

The Armand, Sarkhoon, and Bazaft rivers are tributaries of the Karun River, 670 kilometers from the Persian Gulf. The base is 230 meters high, the canopy is 440 meters long and 8 meters wide, and the overflows are 8600 cubic meters per second. The dam's reservoir volume is 2279 million cubic meters (MCM) and the lake is 41 kilometers long. This dam is Iran's largest double-arch dam. Figure 1 shows that the Karun 4 Dam site is 185 kilometers from Shahrekord and 35 km from Lordegan, in the Chaharmahal, Bakhtiari, and Khuzestan provinces (west-southwest of Lordegan).

The research uses real and virtual data from meteorological stations at Karun 4 dam for two 20-year periods from 2000 to 2020 and 2020 to 2040. PVsyst and AutoCAD were used to speed up design. The floating solar power plant's economic performance was based on engineering economics. In this economic plan, evaluation, investment, and decision to reject or accept the project have been evaluated using mathematical techniques and quantitative criteria. Economists' criteria the design and economic performance tests were done with COMFAR 3. Minitab has also been used to analyze data. Temperature and precipitation are important variables in hydrology. A floating photovoltaic power plant could be affected by these variables and shading.

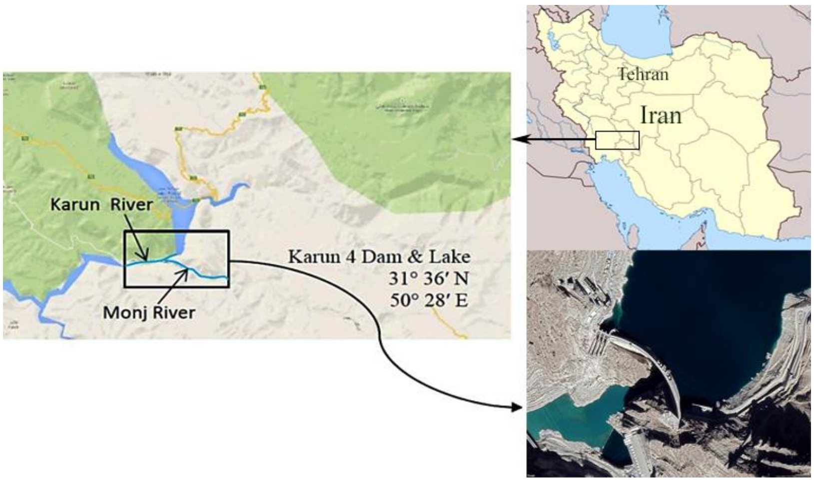


Figure 1. Location of Karun 4 Dam in the geography of Iran [10]

In this study, the output of six atmospheric circulation models was subscale with LARS-WG statistical model to investigate and analyze the effect of climate change on temperature and precipitation in the Karun 4 dam. The best model and scenario for the production of temperature and precipitation data for the period 2020 to 2040 were selected. As a result, the A1B scenario uses the HADCM3 model for precipitation and the A2 scenario uses the MPEH5 model for temperature. This project is the first to provide an integrated model for the use of hydropower and solar energy in Iran. Table 1 shows Karun 4 power plant's technical data. The Karun 4 hydropower power plant can generate 2107 GWh of energy per year using 4 units of 250 MW turbines.

The lack of land space and the utilization of the water cooling effect, which can improve the performance of the solar panel by 5 to 10%, are significant advantages of floating solar power plants on dams and lakes. Other potential advantages include less shading, fewer building activities, less water evaporation, better water quality, and fewer algae growth. A schematic of the major components of a large-scale floating solar power plant is depicted in Figure 2. The Net Present Value (NPV), Internal Rate of Return (IRR), and Return on Capital are some of the economic indicators of a floating solar power plant (PP).

Table 1. Technical information of Karun 4 hydroelectric power plant [10]

Property	Unit	Specifications
Average annual energy	GWh	2107
Power plant capacity	MW	1000
Number of units	MW	4 per 250
The total volume of the tank	M^3	2190
Tank area	Km^2	29
Height from the base	m	230
Turbine rotation speed	rpm	187.5
Normal operation head	m	191
Nominal voltage of generator	kV	75.15
Rated output power	MVA	263
Maximum output power	MVA	300
Number of transformers	-	13
Nominal power of transformer	MVA	100
Secondary nominal voltage of transformer	kV	(410/√3)±5%
Production capacity in normal head	MW	255
Flow design per unit (cubic meters per second)	M^3/sec	171

Evaporation from lakes behind dams and freshwater lakes is one of the causes of water waste. In general, the evaporation of water from the surface of the water, such as an open tank, swimming pool, or reservoir behind a dam, is affected by the water temperature, air temperature, humidity, and air velocity above the water surface. Equation (1) is used to compute the amount of water evaporated [6].

$$g_h = \theta A(X_s - x) \quad (1)$$

where g_h is equal to the amount of water evaporated per hour in kilograms per hour, θ is equal to the evaporation rate in kilograms per square meter (also similar with Equation (2)), and A is equal to the water level per square meter. X_s and x are the maximum ratios of saturated air humidity at the same temperature as the water level and the ratio of air humidity in kilograms per kilogram or kg H_2O per kilogram of dry air, respectively. Since this equation is experimental and laboratory, the dimensions of the variable θ do not match. In relation (2) V is the velocity of the air above the water surface in meters per second [7].

$$\theta = (25 + 19\,V) \quad (2)$$

The heat required for water to reach the evaporation phase is taken from the water itself and the energy of the solar irradiation, which can be calculated by Equation (3) [43].

$$q = h_{we} g_s \quad (32)$$

where q is the heat supplied in units (kW) and h_{we} is the heat of evaporation of water in units (kJ/kg). The Molar diagram and the law of ideal gases are used to calculate the air humidity and the humidity ratio of the partial pressure of the vapor, respectively. It is clear the unit conversion for 1 kW = 3412 Btu / h.

Net present value

Net present value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time Net cash flow (NCF) is a metric that tells you whether or not greater cash got

Figure 2. A floating solar power plant's components [9]

here in or went out of a commercial enterprise inside a selected duration of time [44]. This balance is compared to interest rates as a predetermined criterion for project management. This interest is called the "minimum absorbed interest" or "cost of capital". Equation (4) calculates the net present value of the cash flows:

$$NPV = \mathrm{NCF}_0 + \frac{NCF_1}{(1+i)} + \frac{NCF_2}{(1+i)^2} + \frac{NCF_t}{(1+i)^t} \quad (4)$$

In the above relation, i is equal to the discount rate and t is equal to the financial period. The NPV may be a negative number (no project selection) or a positive number (project selection). If the net present value equals zero, then the designer will be indifferent in choosing or not choosing to carry out the project.

Internal rate of return

Internal rate of return (IRR) is a well-known criterion in the economic evaluation of projects. This criterion considers that the condition for accepting the project is that the IRR is greater than the cost of capital. IRR is the discount rate at which the net present value of the project (NPV) is zero. If the NPV of a project is positive, the IRR of that project is higher than the rate of return used for the investment. In calculating the NPV, it is assumed that the discount rate is known and the project NPV is determined.

Return on investment

Using the criterion of the period of return on investment, the period in which the total annual income with the investment cost is equal to (overhead) is determined. PP is an approximate and simple way to deal with risk and is beneficial to projects that earn more in the early years. The product of the Karun 4 Dam floating photovoltaic power plant is electricity and reduction of surface evaporation loss, which the solar system generates electricity at nominal capacity. The service life or useful life of the systems is equal to 25 years. The inflation rate based on the average inflation rate in the last five years between 2015 to 2020 related to the category of water, electricity and fuel goods is considered an average of 10 percent. The deposit interest rate in Iran has freshly reduced to 15%, but in the last 10 years, it has equated to 16.7%, which is regarded as the benchmark discount rate [45]. According to the Iranian parliament's legislation, each kilowatt of renewable electricity is purchased from the consumer at ~0.05 $/kWh, which this price is supposed to be 20 years of the solar system's useful lifetime [46]. Dehghan et al [47] have considered the different Feed-In Tariff (FiT) rate to be 0.05 $/kWh.

The project's NPV is set to zero and the discount rate, which is the same as the project's IRR, is determined. The calculation of the IRR is based on the NPV which can be expressed as a function of the IRR. The IRR is the compounded discount rate for a given series of cash flows that leads to an NPV of 0. IRR calculates by COMFAR through trial and error because you are trying to arrive at whatever rate makes the NPV equal to zero. The price increase rate of energy carriers is equal to 10% per annum. To calculate the discount, the rate of return of securities in the Tehran Stock Exchange market is considered as the rate of return in the market, which according to the statistics of the last 5 years was equal to 24%. Iran's discount rate is 16%. To get the discount rate in dollar calculations, plus 24% after deducting domestic inflation (according to the Central Bank, the average inflation rate in Iran over the past 5 years has been 20%) and add the US inflation rate (to 2% in 5 years past) is reduced from 8% risk-free interest rate [48].

RESULTS AND DISCUSSION

The Karun 4 Dam was built to regulate the discharge of the Karun River, build a linked network with the Karun 3, Karun 1, Masjed Soleiman, and Gotvand dams, and control the disastrous floods. This dam will also add 1 GW per year to Iran's hydroelectric network. The water level in the dam reservoir is measured daily and is an independent variable that can affect the hydropower plant's efficiency. Figure 3 illustrates the time record of the reservoir water level from March 2010 to March 2017.

Figure 4 demonstrations a comparison between the implementation of a model for predicting the future operation of a solar floating photovoltaic power plant and actual meteorological data. B_n is the average of direct irradiation on a surface with zero slopes and T_a is the mean of ambient temperature and FF is the mean of wind speed for a period of 20 years from 2020 to 2040. Dashed lines are real data for a period of 20 years, from 2000 to 2020.

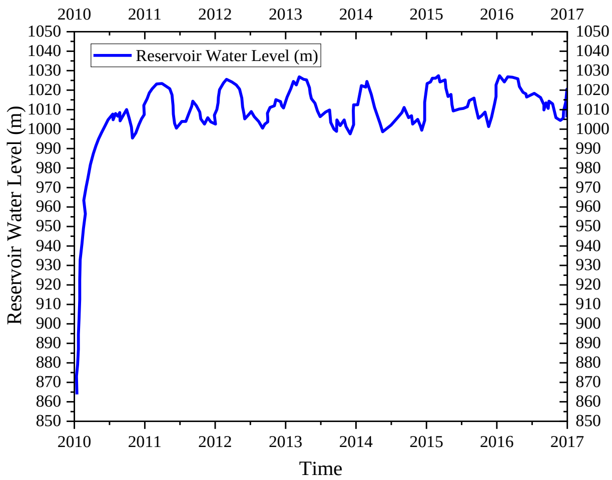


Figure 3. Reservoir water level [10]

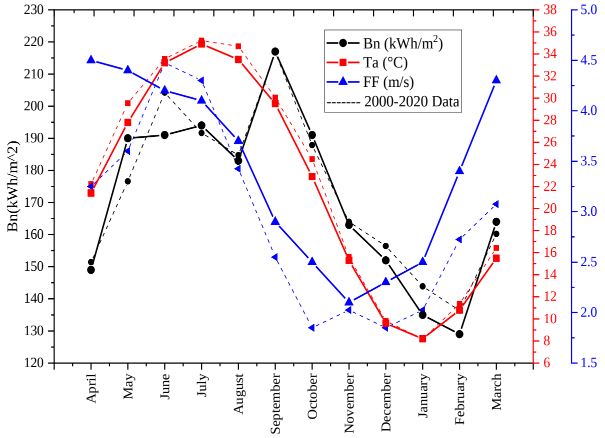


Figure 4. Real and predicted data from 2000 to 2040

The majority of the irradiation is attributed to the months of May to October. The intensity of radiant irradiation reaches more than 200 kWh per square meter in August and September. Since April, the temperature has been increasing, reaching more than 34 degrees Celsius in July. Temperatures will continue to fall from September to January, then rise again after February. The intensity of solar irradiation has a direct relationship with the surface evaporation of dam reservoir water. From April until mid-August, the average wind speed will be 3 meters per second or higher. From September through January, wind speeds were at their lowest. Wind energy can evolve the combined energy source from mid-January through March. Figure 5 displays a comparison of rainfall levels and rainy days from 2000 to 2020, as well as the predicted scenario up to 2040.

The volume of rainfall is hard to estimate based on statistics from 2000 to 2020. If the amount of rainfall from October to April exceeds that from July to October. The rainiest days fall between November and February,

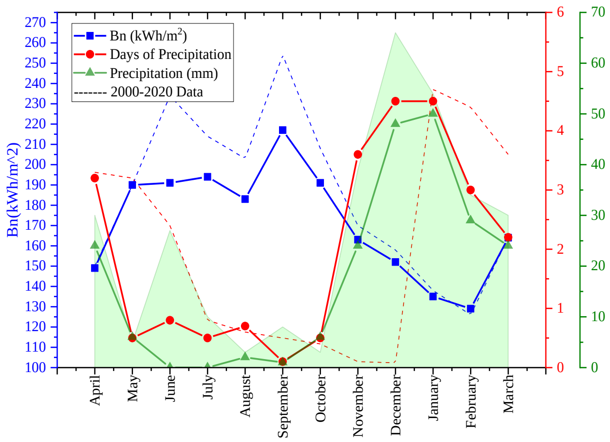
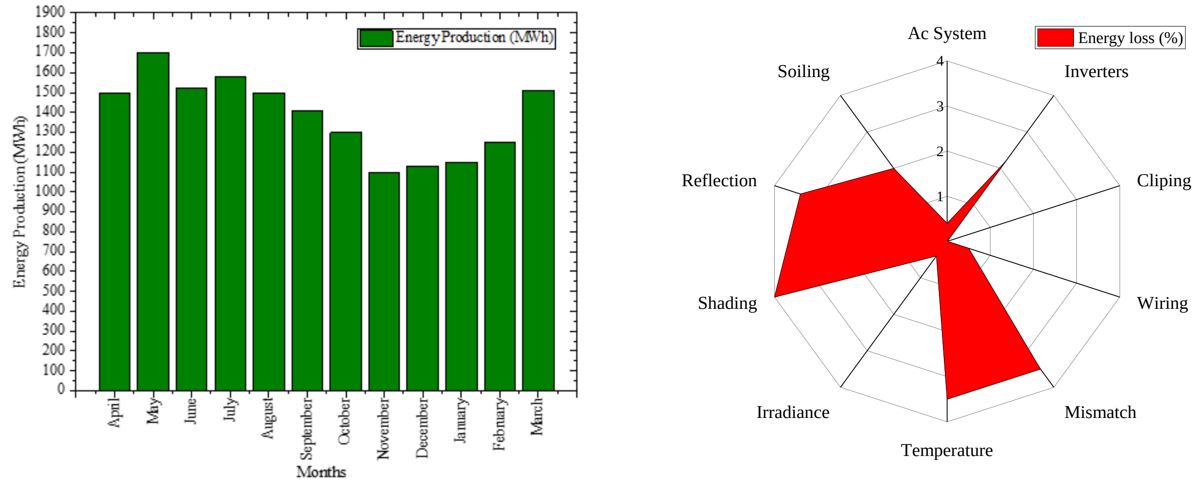


Figure 5. Real data and prediction of rain and solar energy from 2000 to 2040

whereas the brightest days fall between May and October. If throughout the 20-year prediction scenario until 2040, the intensity of solar irradiation energy has fallen somewhat compared to 2000-2020, the radiant energy will be more than 150 kWh per square meter from April to November. The results of water evaporation from 2000 to 2020 show that the reservoir of Karun 4 dam with a reservoir area of 29 square kilometers and a maximum ratio of saturated air humidity at the same temperature as the water level in winter with an average temperature of 10 degrees Celsius equal to 0.0076 kg/kg in summer with an average temperature of 30 degrees Celsius equal to 0.0271 kg/kg and a maximum ratio of saturated air humidity at the same temperature as the water level In winter, with an average wind speed of 2.5 m/s, it is equal to 37845 kg/h (10.5 kg/s and input heat of 25767 kW) and in summer, with an average wind speed of 4 meters per second, it is equal to 248965 kg/h (69.2 kg/s and the input heat is 169817 kW). Winter evaporation is 557 percent more than summer evaporation in an hour. Calculations of evaporation from 2020 to 2040 reveal that the highest ratio of saturated air humidity in summer with an average temperature of 32 degrees Celsius is 0.0311 kg/kg, while the ratio of humidity in winter is 0.0076 kg/kg. Kg and in summer is equivalent to 0.0325 kg/kg and in winter is equal to 2454 kJ/kg with an average wind speed of 1.5 m/s equal to 27927 kg/h (7.76 kg/s and input heat of 19043 kW). In the summer, with an average wind speed of 3 meters per second, it is 3341090 kg/h (928 kg/s, and the input heat is 2277312 kW). In one hour, the difference in water evaporation between winter and summer will be more than 11863 percent. This will suggest a shift in the climate toward warmer summers. Summer evaporation capacity is 1241 percent higher than winter evaporation capacity. The Karun 4 floating solar power plant is designed to be 200 meters by 500 meters, or 100,000 square meters. This power plant is a single frame in the south direction, a 20-degree slope, and a 70 cm row spacing and uses Yingli 365-watt solar panel YL365D-36b. The solar power station has 30203 panels with a capacity of 11 MW. This facility also utilized 177 STP 50-40 inverters from SMA with a capacity of 8.85 MW, 1657262578 meters of copper wire, and 177136298 meters of aluminum wire. Using real data from 2000 to 2020 and model data from 2020 to 2040. In the first scenario, the 11 MW power plant with a load factor of 1.25 will produce 8.85 MW. This power plant's annual production capacity is 16760 MWh and its nominal performance is 81.7 percent. In the second scenario, the yearly production capacity of the power plant is 18880 MWh, and the nominal performance is 81.2 percent. This power plant's hourly production capacity is 1712.2 kWh/kWp.

Figure 6 indicates the output capacity of the Karun 4 Dam floating solar power plant and energy loss in substantial segments of the operation per month. The total



Monthly production   Energy loss

Figure 6. Monthly production capacity and energy loss in the power plant

percentage of losses is 19.9% and the highest is related to the shading effect. As is usually the case in solar power plants, the loss is due to the effect of temperature, but here the effect of temperature has reduced the performance by 3.5%.

The months of April through August have the largest production capacity, whereas November, December, and January have the lowest production capacity. The average monthly radiation was 1387.5 MWh and the lower 95% CI of Mean was 1262 MWh and the upper 95% CI of Mean was 1512 MWh. The lowest power generation month was recorded with the amount of 1100 MWh for November and the highest in May with the amount of 1700 MWh. Cable losses of 3.4 percent, soil and air pollution losses of 2%, irradiation losses of 0.4 percent, negative effect of temperature on the performance of solar panels, followed by temperature deviation from the standard (25 degrees Celsius) losses of 5.3 percent, shading losses of 4%, subsystem level losses of 3.5 percent, and total transmission wire losses of 3.5 percent. Figure 7 depicts the floating solar power plant of Karun 4 Dam, as well as the geometric dimensions, and potential shading challenges.

The dimensions of Karun-4 dam's floating solar power plant are 200 meters by 500 meters, with a total area of 100,000 square meters. This power plant has a single frame with a slope angle of 20 degrees and a row spacing of 70 cm. Figure 7 depicts guidance for connecting solar panels to the AC fuse, system maintenance panel, power meter monitoring, and mains circuit. The shading study findings reveal that solar irradiation on the surface is 97.5 %, and by adjusting the angle structure, the inclination angle is suitable to reduce the shading effect and achieve the best nominal performance, 27.1 degrees in 175 degrees will be azimuth. The average amount of irradiation in this situation is found to be 2138.2 kWh per square meter.

Table 2 presents the capacity, technical production, and environmental calculations of the Karun 4 Dam floating solar power plant based on the first scenario. The total emission of greenhouse gases equivalent to the energy produced by the floating solar power plant, which is equivalent to carbon dioxide, was calculated to be 13349 metric tons.

Economic results show that investment costs for energy production return in 8.25 years. Floating solar power plant in the operation phase of 01/2020 to 01/2045 for 25 years and figures with a unit of one USD is assumed. The total cost of fixed investment before production is US$ 3,345,392. The net present value of total capital at 16.7% equal to US$ 2,685,633.66 and the Internal rate of return on investment (IRR) is equal to 26.96%. The period of return on movable capital at a discount rate of 16.7% is 8.25 with a 0.8 NPV Ratio. The net present value of the capital of the Karun 4 floating

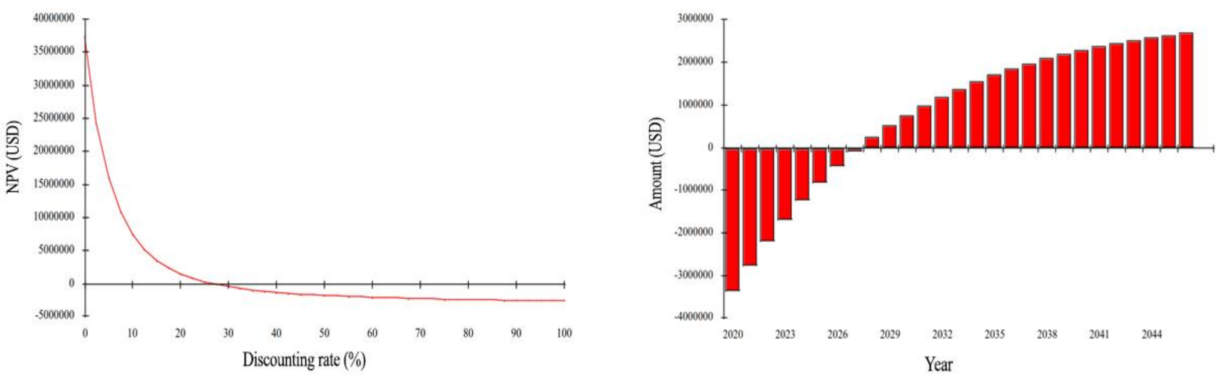
Figure 7. Karun-4 Dam's floating solar power plant

solar power plant at different discount rates and the net cumulative cash flows are shown in Figure 8. At zero discount rate, the net present value is equal to US$ 37,483,490.90 and at 10% is equal to US$ 7,454,148.63. At a discount rate of 30% net, the value of the negative capital is calculated -408,120.93. In this case, the NPV will be negative and the project will not be economical. The value of a scrap of site number one of the floating solar power plant of Karun 4 dam in 2045 (end of operation period) will be equal to US$ 2,685,633.66. In this study, the benefit cost ratio was calculated to 1.61.

Expansion of analyses shows that if a floating solar power plant covers 10% of the lake reservoir of 5 dams with the requirements of Table 3, a total of 70.7 MCM will be saved each year. In terms of residential usage, this amount of water is enough to cover the annual demands of a city of one million people.

Table 2. Floating solar power plant technical production and greenhouse gas emissions

Characteristic	Description	Production (units)	Percentage error
Irradiation energy (kWh.m^2)	Irradiation on a horizontal surface	1726.3	-
	Shadow irradiation	1786.9	-4
	Irradiation after contamination/dust	1682	-2
	Total	1691.9	0
Energy (kWh)	Nominal capacity (installed)	18654230.8	-
	Performance at standard temperature	17936195.3	-3.5
	DC function	17206950.7	-0.5
	Inverter performance	16827839	-2.2
	Total energy to the grid	16758969	-0.4
Temperature	Average operating temperature of the power plant (degrees Celsius)	18.9	
	Average solar cell temperature (degrees Celsius)	29.7	
Time	Power plant operation time (hours)	4297	
Prevents the release of carbon dioxide (gallons of gasoline)		1502072	
Energy equivalent to oil barrels (annual)		30906	
Equivalent to home electricity consumption (annual)		2260	



NPV of Total Equity Capital Invested (US$)

Cumulative NPV - Dynamic Payback (US$)

Figure 8. Net present value of floating solar power plant and net cumulative cash flows

Table 3. Expansion of design results of Karun 4 dam floating solar power plant in Iran dams

Characteristic	Unit	Dosti	Aras	Karkheh	Doroodzan	Kazemi
Coordinates	Degree	35°56′55″N 61° 09′48″E	39°05′28″N 45° 24′08″E	32°29′21″N 48° 07′36″E	30°12′29″N 52° 25′02″E	36°18′31.2″N 4 6°30′16.03″E
Height	m	78	40	127	60	50
Dam tank volume (NWL)	ha	4932	15200	2100	5500	4150
NWL save the entire tank	MCM	1250	1254	5600	960	650
Annual production energy	GW/h	-	86	394	45.5	-
Farm cover area	ha	32442	69152	344615	102000	66165
Cover energy 2% of the dam reservoir surface	10^6 kWh	235.71	1178.53	2357.06	589.64	942.24
Cover energy 10% of the dam reservoir surface	10^6 kWh	591.47	2959.29	5918.43	147.10	236.74
Reduction of evaporation by covering 2% of the dam reservoir surface	MCM	524.1	1.469	6.911	3.076	1.161
Reduction of evaporation by covering 10% of the dam reservoir surface	MCM	7.620	7.345	34.554	15.378	5.804

CONCLUSIONS

This article described the 11 MWp FSPV design in Iran. The results obtained are an FSPV design with the potential of the Karun-4 dam in Iran, which can deliver more than 11 MWp of energy production. The amount of evaporation varies across the 29 square kilometers of the reservoir of the Karun 4 dam, with evaporation increasing from shallow to deeper locations. This demonstrates the inefficiencies of extending point measurements to the entire surface of the dam reservoir. This is one of the advantages of the algorithms used by satellite images. The surface evaporation of the water tank is high, demonstrating the importance of considering strategies to avoid water loss in this approach. This conclusion should be utilized in complete water resource management planning studies to provide a more accurate measure of water loss by evaporation at the surface of freshwater dam reservoirs. According to the current study, installing a floating solar power plant at a level more than one square kilometer above the dam reservoir's surface provides 194 to 257 GWh of electricity per year. If the average yearly per capita power consumption in Iran is 2727 kWh, the development and covering of one square kilometer of floating solar systems will provide the electricity required by 8400 people while also benefiting the environment and reducing water evaporation.

The research of climatic and meteorological circumstances revealed that the next period's precipitation will drop by 9 mm, with the minimum temperature reaching 8 °C and the maximum temperature reaching 32.4 °C. In addition, the uncertainty at the minimum temperature will be 1.05 °C, while the uncertainty at the maximum temperature will be 0.87 °C. The disturbance of the temporal distribution of precipitation, as well as the fall in temperature and increase in wind speed, is significant, and will most likely have a detrimental impact on the hydropower power plant and storage tank. In future plants, the design and optimization of the FSPV components can be investigated in the form of a float to support FSPV operations and the viability of FSPV can invest economically and invest. Following the sustainable development model, combining surface-floating photovoltaic power plants with conventional hydropower grid networks will minimize energy cost management and consumption in the following patterns:

- Power plant energy and water consumption management should be modified in compliance with standard models.
- The overall weight of the distribution network's input load will be proportionate to the network's balance or imbalance.
- Solar power plants boost the capacity to use local renewable energy, hence reducing environmental damage.

Floating solar power plants have a strategic advantage for Iran's geography, in addition to all of the benefits listed above. If China and the United Kingdom have resorted to employing floating solar power plants to produce clean energy due to lack of land, such power plants are a beneficial solution to some of our country's water crisis difficulties. Solar-powered power plants on a local scale in Japan and industrial-scale solar power plants in the United Kingdom and China minimize evaporation from surfaces covered by float-builders and solar panels by roughly 80%. Estimates on useable water reservoir levels are based on global irradiation statistics. In the future, solar technology will be cheaper and the use of floating solar power plants for power supply and hybridization will increase. The execution of the Karun-4 FPV power plant with an annual production of 16758969 kWh of electricity has decreased the evaporation of the dam's reservoir water and after 8 years and 4 months, the investment cost was returned. This power plant could supply the required electricity to 2260 houses and prevent the emission of carbon dioxide in the amount of 1502072 tons.

REFERENCES

1. Ameri, M., Farzan, H., and Nobari, M. 2021. "Evaluation of Different Glazing Materials, Strategies, and Configurations in Flat Plate Collectors Using Glass and Acrylic Covers: An Experimental Assessment." *Iranian Journal of Energy and Environment*, 12(4), pp.297–306. https://doi.org/10.5829/IJEE.2021.12.04.03
2. Vaziri Rad, M. A., Toopshekan, A., Rahdan, P., Kasaeian, A., and Mahian, O. 2020. "A comprehensive study of techno-economic and environmental features of different solar tracking systems for residential photovoltaic installations." *Renewable and Sustainable Energy Reviews*, 129, pp.109923. https://doi.org/10.1016/j.rser.2020.109923
3. Khojasteh, D., Khojasteh, D., Kamali, R., Beyene, A., and Iglesias, G. 2018. "Assessment of renewable energy resources in Iran; with a focus on wave and tidal energy." *Renewable and Sustainable Energy Reviews*, 81, pp.2992–3005. https://doi.org/10.1016/j.rser.2017.06.110
4. Ifaei, P., Farid, A., and Yoo, C. 2018. "An optimal renewable energy management strategy with and without hydropower using a factor weighted multi-criteria decision making analysis and nation-wide big data - Case study in Iran." *Energy*, 158, pp.357–372. https://doi.org/10.1016/j.energy.2018.06.043
5. Esmaeili Shayan, M., Esmaeili Shayan, S., and Nazari, A. 2021. "Possibility of supplying energy to border villages by solar energy sources." *Energy Equipment and Systems*, 9(3), pp.279–289. https://doi.org/10.22059/EES.2021.246079
6. Gonzalez Sanchez, R., Kougias, I., Moner-Girona, M., Fahl, F., and Jäger-Waldau, A. 2021. "Assessment of floating solar photovoltaics potential in existing hydropower reservoirs in Africa." *Renewable Energy*, 169, pp.687–699. https://doi.org/10.1016/j.renene.2021.01.041
7. Ranjbaran, P., Yousefi, H., Gharehpetian, G. B., and Astaraei, F. R. 2019. "A review on floating photovoltaic (FPV) power generation units." *Renewable and Sustainable Energy Reviews*, 110, pp.332–347. https://doi.org/10.1016/j.rser.2019.05.015
8. IEA. "Global Energy Review 2021 – Analysis - IEA."
9. Esmaeili Shayan, M. 2020. "Solar Energy and Its Purpose in Net-Zero Energy Building." In A. Pérez-Fargallo & I. Oropeza-Perez (Eds.), Zero-Energy Buildings - New Approaches and Technologies. IntechOpen. https://doi.org/10.5772/intechopen.93500
10. Akbarifard, S., Sharifi, M. R., and Qaderi, K. 2020. "Data on optimization of the Karun-4 hydropower reservoir operation using evolutionary algorithms." *Data in Brief*, 29, pp.105048. https://doi.org/10.1016/j.dib.2019.105048
11. Esameili Shayan, M., Najafi, G., and Esameili shayan, S. 2021. "Design of an Integrated Photovoltaic Site: Case of Isfahan's Jarghouyeh photovoltaic plant." *Journal of Energy Planning And Policy Research*, 6(4), pp.229–250. Retrieved from http://epprjournal.ir/article-1-858-en.html (In Persian)
12. Alijani, Z., Hosseinali, F., and Biswas, A. 2020. "Spatio-temporal evolution of agricultural land use change drivers: A case study from Chalous region, Iran." *Journal of Environmental Management*, 262, pp.110326. https://doi.org/10.1016/j.jenvman.2020.110326
13. Gandjalikhan Nassab, S. A., and Moein Addini, M. 2021. "Performance Augmentation of Solar Air Heater for Space Heating Using a Flexible Flapping Guide Winglet." *Iranian Journal of Energy and Environment*, 12(2), pp.161–172. https://doi.org/10.5829/IJEE.2021.12.02.09
14. Elliot, T., Almenar, J. B., and Rugani, B. 2020. "Impacts of policy on urban energy metabolism at tackling climate change: The case of Lisbon." *Journal of Cleaner Production*, 276, pp.123510. https://doi.org/10.1016/j.jclepro.2020.123510
15. Sadorsky, P. 2021. "Wind energy for sustainable development: Driving factors and future outlook." *Journal of Cleaner Production*, 289, pp.125779. https://doi.org/10.1016/j.jclepro.2020.125779
16. Sarbu, I., and Sebarchievici, C. 2017. "Solar Collectors." In Solar Heating and Cooling Systems (pp. 29–97). Elsevier. https://doi.org/10.1016/B978-0-12-811662-3.00003-7
17. Noorollahi, Y., Janalizadeh, H., Yousefi, H., and Jahangir, M. H. 2021. "Biofuel for energy self-sufficiency in agricultural sector of Iran." *Sustainable Energy Technologies and Assessments*, 44, pp.101069. https://doi.org/10.1016/j.seta.2021.101069
18. Gandjalikhan Nassab, S. A., and Moein Addini, M. 2021. "Effect of Radiative Filling Gas in Compound Parabolic Solar Energy Collectors." *Iranian Journal of Energy and Environment*, 12(3), pp.181–191. https://doi.org/10.5829/IJEE.2021.12.03.01
19. Esmaeili shayan, M., Najafi, G., and Gorjian, S. 2020. Design Principles and Applications of Solar Power Systems (First Edit.). Tehran: ACECR Publication- Amirkabir University of Technology Branch. (In Persian)
20. Gourdo, L., Fatnassi, H., Tiskatine, R., Wifaya, A., Demrati, H., Aharoune, A., and Bouirden, L. 2019. "Solar energy storing rock-bed to heat an agricultural greenhouse." *Energy*, 169, pp.206–212. https://doi.org/10.1016/j.energy.2018.12.036
21. Abdi, A., and Taghipour, S. 2018. "An optimization model for fleet management with economic and environmental considerations, under a cap-and-trade market." *Journal of Cleaner Production*, 204, pp.130–143. https://doi.org/10.1016/j.jclepro.2018.08.345
22. Zhong, R. Z., Cheng, L., Wang, Y. Q., Sun, X. Z., Luo, D. W., Fang, Y., Bush, R. D., and Zhou, D. W. 2017. Effects of anthelmintic treatment on ewe feed intake, digestion, milk production and lamb growth. *Journal of Agricultural Science* (Vol. 155). SPRINGER Verlag, SINGAPOR.
23. Sinha, S., and Chandel, S. S. 2014. "Review of software tools for hybrid renewable energy systems." *Renewable and Sustainable Energy Reviews*, 32, pp.192–205. https://doi.org/10.1016/j.rser.2014.01.035
24. Doggart, N., Ruhinduka, R., Meshack, C. K., Ishengoma, R. C., Morgan-Brown, T., Abdallah, J. M., Spracklen, D. V., and Sallu, S. M. 2020. "The influence of energy policy on charcoal consumption in urban households in Tanzania." *Energy for Sustainable Development*, 57, pp.200–213. https://doi.org/10.1016/j.esd.2020.06.002
25. Jin, X., Sun, X., Zhang, X., Sun, H., Xu, R., Zhou, X., Li, X., and Liu, R. 2019. "Sun orientation estimation from a single image using short-cuts in DCNN." *Optics & Laser Technology*, 110, pp.191–195. https://doi.org/10.1016/j.optlastec.2018.08.009
26. Pratumnopharat, P., and Leung, P. S. 2011. "Validation of various

windmill brake state models used by blade element momentum calculation." *Renewable Energy*, 36(11), pp.3222–3227. https://doi.org/10.1016/j.renene.2011.03.027

27. Esmaeili, M. S., and Najafi, G. 2019. "Energy-Economic Optimization of Thin Layer Photovoltaic on Domes and Cylindrical Towers." *International Journal of Smart Grid - ijSmartGrid*, 3(2), pp.84–91. Retrieved from https://www.ijsmartgrid.ijrer.org/index.php/ijsmartgridnew/article/view/61
28. Khatib, T., Mohamed, A., and Sopian, K. 2013. "A review of photovoltaic systems size optimization techniques." *Renewable and Sustainable Energy Reviews*, 22, pp.454–465. https://doi.org/10.1016/j.rser.2013.02.023
29. IEA. 2017. "Sustainable Technology at the Brundtland Centre Denmark." International Energy Agency, 9.
30. Jamiati, M. 2021. "Modeling of Maximum Solar Power Tracking by Genetic Algorithm Method." *Iranian Journal of Energy and Environment*, 12(2), pp.118–124. https://doi.org/10.5829/IJEE.2021.12.02.03
31. Reuter, M., Narula, K., Patel, M. K., and Eichhammer, W. 2021. "Linking energy efficiency indicators with policy evaluation – A combined top-down and bottom-up analysis of space heating consumption in residential buildings." *Energy and Buildings*, 244, pp.110987. https://doi.org/10.1016/j.enbuild.2021.110987
32. Ghasemzadeh, F., Esmaeilzadeh, M., and Esmaeili shayan, M. 2020. "Photovoltaic Temperature Challenges and Bismuthene Monolayer Properties." *International Journal of Smart Grid*, 4(4), pp.190–195. Retrieved from https://www.ijsmartgrid-org.ijrer.org/index.php/ijsmartgridnew/article/view/131
33. Rauf, H., Gull, M. S., and Arshad, N. 2020. "Complementing hydroelectric power with floating solar PV for daytime peak electricity demand." *Renewable Energy*, 162, pp.1227–1242. https://doi.org/10.1016/j.renene.2020.08.017
34. Sulaeman, S., Brown, E., Quispe-Abad, R., and Müller, N. 2021. "Floating PV system as an alternative pathway to the amazon dam underproduction." *Renewable and Sustainable Energy Reviews*, 135, pp.110082. https://doi.org/10.1016/j.rser.2020.110082
35. Haas, J., Khalighi, J., de la Fuente, A., Gerbersdorf, S. U., Nowak, W., and Chen, P.-J. 2020. "Floating photovoltaic plants: Ecological impacts versus hydropower operation flexibility." *Energy Conversion and Management*, 206, pp.112414. https://doi.org/10.1016/j.enconman.2019.112414
36. Lee, N., Grunwald, U., Rosenlieb, E., Mirletz, H., Aznar, A., Spencer, R., and Cox, S. 2020. "Hybrid floating solar photovoltaics-hydropower systems: Benefits and global assessment of technical potential." *Renewable Energy*, 162, pp.1415–1427. https://doi.org/10.1016/j.renene.2020.08.080
37. Zhang, N., Jiang, T., Guo, C., Qiao, L., Ji, Q., Yin, L., Yu, L., Murto, P., and Xu, X. 2020. "High-performance semitransparent polymer solar cells floating on water: Rational analysis of power generation, water evaporation and algal growth." *Nano Energy*, 77, pp.105111. https://doi.org/10.1016/j.nanoen.2020.105111
38. Pouran, H. M. 2018. "From collapsed coal mines to floating solar farms, why China's new power stations matter." *Energy Policy*, 123, pp.414–420. https://doi.org/10.1016/j.enpol.2018.09.010
39. Li, Y., Gao, W., and Ruan, Y. 2018. "Performance investigation of grid-connected residential PV-battery system focusing on enhancing self-consumption and peak shaving in Kyushu, Japan." *Renewable Energy*, 127, pp.514–523. https://doi.org/10.1016/j.renene.2018.04.074
40. Rauf, H., Gull, M. S., and Arshad, N. 2019. "Integrating Floating Solar PV with Hydroelectric Power Plant: Analysis of Ghazi Barotha Reservoir in Pakistan." *Energy Procedia*, 158, pp.816–821. https://doi.org/10.1016/j.egypro.2019.01.214
41. Ghasemzadeh, F., and Esmaeili Shayan, M. 2020. "Nanotechnology in the Service of Solar Energy Systems." In Nanotechnology and the Environment. London: IntechOpen. https://doi.org/10.5772/intechopen.93014
42. Fereshtehpour, M., Javidi Sabbaghian, R., Farrokhi, A., Jovein, E. B., and Ebrahimi Sarindizaj, E. 2021. "Evaluation of factors governing the use of floating solar system: A study on Iran's important water infrastructures." *Renewable Energy*, 171, pp.1171–1187. https://doi.org/10.1016/j.renene.2020.12.005
43. Kalogirou, S. 1997. "Survey of solar desalination systems and system selection." *Energy*, 22(1), pp.69–81. https://doi.org/10.1016/S0360-5442(96)00100-4
44. Lopez, A., Mai, T., Lantz, E., Harrison-Atlas, D., Williams, T., and Maclaurin, G. 2021. "Land use and turbine technology influences on wind potential in the United States." *Energy*, 223, pp.120044. https://doi.org/10.1016/j.energy.2021.120044
45. Adesanya, A. A., and Pearce, J. M. 2019. "Economic viability of captive off-grid solar photovoltaic and diesel hybrid energy systems for the Nigerian private sector." *Renewable and Sustainable Energy Reviews*, 114, pp.109348. https://doi.org/10.1016/j.rser.2019.109348
46. Zakeri, B., Cross, S., Dodds, P. E., and Gissey, G. C. 2021. "Policy options for enhancing economic profitability of residential solar photovoltaic with battery energy storage." *Applied Energy*, 290, pp.116697. https://doi.org/10.1016/j.apenergy.2021.116697
47. Dehghan, M., Rahgozar, S., Pourrajabian, A., Aminy, M., and Halek, F.-S. 2021. "Techno-economic perspectives of the temperature management of photovoltaic (PV) power plants: A case-study in Iran." *Sustainable Energy Technologies and Assessments*, 45, pp.101133. https://doi.org/10.1016/j.seta.2021.101133
48. Esmaeili shayan, M., Najafi, G., and Banakar, A. 2019. "Design Green Branches of Iran's Banks with Renewable Power Plant." *Human & Environment*, 19(1), pp.145–159.

Persian Abstract

چکیده

نیروگاه خورشیدی شناور بر روی سطح آب نصب می‌شود و به طور طبیعی فرایند خنک‌کاری و کاهش تلفات دمایی هنگام تولید برق تجدیدپذیر رخ می‌دهد. ترکیب کردن نیروگاه‌های فتوولتاییک شناور با نیروگاه¬های برق آبی از یک سو موجب ارتقاء نفوذ انرژی تجدیدپذیر، و از سوی دیگر کاهش تبخیر سطحی آب شیرین در مخازن سدها را رقم می‌زند. برای بررسی این هدف، نیروگاه خورشیدی شناور سد کارون ۴ با ظرفیت ۱۱ مگاوات طراحی و مدلسازی شده است. نتایج نشان می‌دهد نصب نیروگاه خورشیدی شناور موجب بهبود قابلیت اطمینان شبکه ترکیبی برق تجدیدپذیر شده و به طور بالقوه انعطاف‌پذیری نیروگاه‌های برق آبی در زمان اوج تقاضا را مدیریت انرژی می‌کند. اجرای نیروگاه خورشیدی شناور کارون ۴ با تولید سالانه ۱۶۷۵۸۹۶۹ کیلووات ساعت باعث کاهش تبخیر آب مخزن سد شده و پس از هشت سال و چهار ماه هزینه سرمایه‌گذاری برگشت داده شده و عملکرد اسمی آن ۸۱/۷ درصد محاسبه شده است. از بعد سیاست گذاری، چنانچه نیروگاه خورشیدی شناور با ۱۰ درصد پوشش مخزن دریاچه ۶ سد بزرگ ایران احداث گردد، آنگاه معادل ۷۰/۷ میلیون متر مکعب آب شیرین در سال صرفه‌جویی خواهد شد. این مقدار آب شیرین نیاز سالانه یک میلیون نفر را برای تامین می‌کند.