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Evaluation of Factors Governing the Use of Floating Solar System: A Study on Iran's Important Water Infrastructures

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ABSTRACT

The issue of water and energy crisis have been turned into global matters which need to be tackled jointly. Accordingly, floating solar power plants, in which photovoltaic modules are used on the surface of water infrastructures, has recently been attracting much interest. This system provides some additional advantages over the ground-based system such as conserving the land and the water and increasing the efficiency of the module. This study first reviews the relevant literature comprehensively and then evaluates the potential of using floating solar photovoltaic (FSPV) on some of Iran's water infrastructures which have experienced a large amount of evaporation every year due to high solar radiation. To this end, the five important dam reservoirs are selected as the representatives of the five important watersheds in Iran, and the advantages of the FSPV plant is analyzed in terms of energy generation, evaporation reduction, economic and environmental aspects considering different coverage percentages of reservoir's surfaces. Considering Iran's vast potential for solar radiation, and, on the other hand, huge energy demand and critical water situation, results indicated that Iran can effectively harness solar energy through FSPV systems which help conserve the water in addition to support sustainable energy production.

Keywords: Floating PV system, Sustainable Energy Production, Solar Power Plant, Water Infrastructures, Evaporation, Water Conservation.

1. INTRODUCTION

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In recent years, water and energy resources have been tightly linked together. Water resources are utilized in the procedure of electrical energy generation. On the other hand, energy resources are utilized for water supply, transfer, distribution, and also for treating wastewater (Bauer, 2014). This interdependency between water and energy is the so-called water-energy nexus. In the national and international scales, several water and energy systems have been developed, managed, and regulated to efficiently resolve the water-energy nexus (Reinhard et al., 2017).

Water resources systems are used to supply several demands including potable, agricultural, industrial, and environmental requirements, and satisfy the sustainable development goals. Reservoir dams in many regions of the world have a significant role in supplying water and generating energy (Javidi Sabbaghian et al., 2016). In Iran, Over the last four decades, the capacity of the constructed dams has been increased into more than 50 billion cubic meters (BCM), which is almost 42 percent of the freshwater resources of the country (Mesgaran and Azadi, 2018). Moreover, many hydroelectric power plants have been established inside the country with an annual generation capacity of 53000 Gigawatt hours (GWh), which is about one-fifth of the electrical energy generation of the country (IWRMC, 2019). Accordingly, the reservoir dams can effectively control and manage the water deficit crisis across the country and are necessary for generating electricity as well (Fereshtehpour, 2016).

However, there are challenges related to the reservoir dams especially in the arid or semi-arid regions of the world. In Iran, the most important challenges are the low mean annual precipitation (almost 250 mm/year), climate change, and the long-term increase of the air temperature (about 1.5 degrees of centigrade), which cause a huge amount of evaporation (about 3 BCM/year) (IWRMC, 2019). The air temperature, heat flux, mass transfer in the water surface, and wind speed are the most influential factors on the water surface evaporation from reservoir dams. Several techniques have been introduced for reducing the evaporative losses from reservoir dams (Craig, 2005). Although these methods are effective to reduce the evaporation from the reservoir dams, there are still some limitations such as high operation and maintenance costs, undesirable environmental impacts, and especially loss of solar energy received by the water body for energy generation.

Solar energy is of great importance in the water-energy nexus and is one of the most abundant, clean, affordable, and sustainable energy resources in the world, especially in arid or semi-arid regions. This energy is generated by the global solar radiation on the earth's surface including the continents and the water surfaces. The global solar radiation is defined by the global horizontal irradiance (GHI) and the diffuse horizontal irradiance (DHI) (Gamarra and Ronk, 2019). The global solar radiation would be 1800 times the global primary energy consumption, whereas hydropower plants would supply the global primary consumption for just one year. Therefore, it can be used potentially as a reliable and comprehensive resource for energy generation in the near future (Dizier, 2018).

The potential of receiving solar radiation on the earth's surface depends on the type of surface cover and the climatic conditions. Iran has a desirable potential for utilizing the solar energy generated by solar radiation. The country has a mean annual 300 sunny days (almost 2800 sunny hours per year) in the two-thirds of its area and the solar radiation average is about 4.5–5.5 kWh per square meter per day (Daneshyar, 1978; Fadai, 2007).

Over recent years, one of the most noticeable strategies for decreasing the undesirable impacts of evaporation from the water surface of the reservoir dams and generating sustainable

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energy is utilizing photovoltaic panels mounted on a floating platform for natural or artificial surface water resources. These systems are creating new opportunities to get the most out of solar energy, particularly in regions that have a high potential of harnessing solar radiation. The installation of PV panels on surface water resources in the world has grown considerably, from an installed capacity of 10 megawatts (MW) at the end of 2014 to 1.1 gigawatts (GW) by September 2018 (Abid et al., 2019). Taking into account the success of utilizing floating PV panels in the South Asian region, Abid et al. (2019) suggested that other Central Asian countries such as Pakistan, Afghanistan, and Iran, where a large number of water bodies are available, can effectively utilize these systems. Many researchers have shown the advantages and disadvantages of floating solar systems in comparison with the land-based ones (Table 1).

Despite the benefits of the FSPV, there is an important concern about the installation cost of these systems. However, there is evidence that in the next ten years, the global average installation cost of the utility-scale solar photovoltaics (PV) could fall by around 60% (Barbuscia, 2018). In general, total system costs for utility-scale PV systems are expected to decrease from around 1.8 USD/W in 2015 to 0.8 USD/W in 2025, a reduction of 57% in 10 years. The majority of the decrease in the costs is expected to come from a lower balance of system (BoS) costs.

Table 1
Advantages and disadvantages of Floating Solar PV (FSPV) plant.

Advantages	***Disadvantage***
✓ Preserving land resources (Liu et al., 2017) ✓ Higher efficiency (Liu et al., 2017) ✓ Not time-consuming installation, easy to arrange, roll up and transport the modules (Abid et al., 2019) ✓ Easy cleaning and dust removal from the panel (Majid et al., 2014) ✓ Conserving water due to reducing evaporation (Sharma et al., 2015) ✓ Decreasing algae formation due to less sunlight entering the water body (Abid et al., 2019 & Liu et al., 2017) ✓ Mitigating environmental problems such as destruction of ecosystems (Lee et al., 2014) ✓ Synergy with existing electrical infrastructure (Liu et al., 2017) ✓ Potential incorporation of FSPV system into aquaculture and fish farming (Liu et al., 2017) ✓ Huge potential for energy production on more than 400,000 km^2 of man-made reservoirs throughout the world (Liu et al., 2017)	× High initial installation, structure and maintenance costs in comparison with terrestrial (Durkovic´ and Đurišic´, 2017) × Challenges of designing the stable floating PV panels resisting the natural disasters (Ferrer-Gisbert et al., 2013; Sahu et al., 2016) × Adverse effects on panels due to the high humidity (Kumar et al., 2015) × Difficult installation on the sea due to the constant change in the position of the solar panels (Tsoutsos et al., 2005) × Water quality degradation when using silicone modules and high-density polyethylene (HDPE) thermoplastic floats (Düzenli et al., 2018) × Electrical accidents and undesirable effects on the existing ecosystem because of the underwater cables (Düzenli et al., 2018) × Undesirable impacts on tourism, fishing, and navigation. × Stress and vibration problems due to the wind, waves, and other external forces, leading to micro-crack formation between modules and thus reduction in electricity production and durability (Düzenli et al., 2018).

In recent years, several studies have been conducted to investigate multiple aspects of the FSPV systems including their total costs, environmental impacts, energy generation, and efficiency generally in terms of the potential assessment of floating solar power plants. Choia et al. (2013) evaluated the energy generation efficiency of FSPV plant in comparison with the ground-mounted systems and showed that FSPV system has a higher generation efficiency of more than 10%. Santafé et al. (2014) investigated a floating photovoltaic cover for water irrigation reservoirs based on experimental and theoretical assessment using a prototype of 20 kWh. The

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case study was the zones near to the Spanish eastern Mediterranean coastline. They concluded that FSPV system can improve the water and energy balances in areas having limited water resources especially in arid and semi-arid zones. Teixeira et al. (2015) studied the feasibility of a floating PV system operating at a hydropower station for water supply in southern Brazil. Their study demonstrated that there is an initial cost of USD 1715.83/kW and energy cost of USD 0.059/kWh. Hartzell (2016) evaluated FSPV potential on water management infrastructure. They modeled a small pilot installation on Lake Pleasant Reservoir, Arizona. The results showed that hydropower reservoirs could be ideal locations for floating photovoltaic installations within a sustainable development paradigm.

Song and Choi (2016) analyzed the potential for FSPV system use on Mine Pit Lakes in Korea in terms of solar site assessment, design of a photovoltaic system, and simulation of PV system based on economic and GHG emission criteria. Liu et al. (2017) examined the power generation efficiency of FSPV plant in terms of the variations in temperature and cooling effects using a finite element model. The results demonstrated that there is a potential of 160 GW, utilizing floating PV systems covering 2500 km^2 water surface in China. This results in 2×10^{27} m^3/year water saving from evaporation and 1.25×10^{12} m^3/year indirect water-saving if water saved from evaporation is being used by hydropower plant.

Durkovic´ and Đurišic´ (2017) conducted studies on a large Floating Photovoltaic Power Plant (FPPP) with an innovative azimuth angle control method in Montenegro. Proper economic savings and a significant reduction in CO_2 emissions at this recommended power plant were the results of this study. Kim et al. (2019) investigated the potential of FSPV use on 3401 reservoirs in Korea. The results of this study showed an annual power production of 2932 GWh. Besides, the annual reduction in greenhouse gas (GHG) was estimated at about 1294450 tons.

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A comprehensive review of the literature was conducted to derive important aspects of the floating solar PV (FSPV) projects implemented since 2013. The type of the FSPV system, coverage area percentage, their benefits, and costs are summarized in Table 2.

Previous studies have shown that floating solar PV (FSPV) plants should be considered as a promising alternative for energy production and to prevent surface evaporation in water bodies due to their significant benefits. To date, there is not a scientific paper focusing on the potential assessment of FSPV application in Iran and thus this study can pave the way for future studies.

The present study proposes a practical framework to evaluate the multiple aspects of using FSPV systems based on their specific characteristics. The methodology is applied to Iran's water infrastructures. Five important reservoirs are selected as the representatives of the water infrastructures within the five main basins of Iran and the potential for installing FSPV plant with different coverage scenarios are investigated in terms of power that could be generated, amount of water that can be saved from evaporation and the reduction in CO_2 emissions. Moreover, an economic analysis is carried out to estimate the total investment, the operation and maintenance (O&M), and the energy production costs for each FSPV coverage scenario of the case studies. This analysis is based on the variation of the economic parameters including the interest rate, the availability factor for FSPV system, and the exploitation period of the system. Furthermore, the expected years for returning the investment costs are estimated for each scenario of the case studies.

The paper has been organized as follows: Section 2 introduces the selected study areas for the implementation of floating solar PV in Iran, proposes the process of the model and illustrates the methodology for evaluating the governing factors such as water-saving, energy generation, economic benefits and environmental advantages. In section 3, the proposed approach is applied

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to the study areas and the results are presented and discussed. Finally, in section 4 the conclusions and recommendations for future practical applications are presented.

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Table 2
Summary of studies on Floating Solar PV (FSPV) system

Location	*FSPV system*	*Lake area: Coverage area (% of the lake)*	*Cost*	*Benefits*	*Authors*
USA (Silver Lake)	PWR[1]: 305 Wp	0.4047 km²: 0.4047 km² (100%)	Value of water saving per year: $208,000	EG[4]: 53 GWh/year WS[5]: 0.32 MCM/year	McKay (2013)
Spain (irrigation water reservoir)	PVT[2]: 10° (Fixed) PVA[3]: 0° (Fixed) PWR: 240Wp	0.00449 km²: 0.00449 km² (100%)	Installation cost: $2.37/Wp $242.1/m²	EG: 0.425 GWh/year WS: 0.005 MCM/year GRGH[6]: 72.71 ton/year	Santafé et al. (2014)
Brazil (three reservoirs – Castanhão, Orós and Banabuiú)	---	Castanhão 40 km²: 2 km² (5%) Orós 30.6 km²: 1.53 km² (5%) Banabuiú 17 km²: 0.85 km² (5%)	---	EG: 699.351 GWh/year	Sacramento et al. (2015)
Canada (McFaulds Lake)	Thin film FSPV	9.5 km²: 0.6857 km² (7.2%)	Installation cost: $6.62 Million Operation cost: $40,000/year	EG: 20.22 GWh/year GHGR: 12048.9 ton/year	Trapani and Millar (2016)
Arizona state (Lake Pleasant Reservoir)	PVT: 12° (Fixed) PVA: Sun tracking PWR: either 43,637 modules with power 275Wp or 48,000 with 250Wp	17.118 km²: 0.12 km² (0.7%)	Installation cost: $33.6 Million	EG: 27.65 GWh/year WS: 0.247222 MCM/year	Hartzell (2016)

[1]The maximum electric power (PWR)
[2]Photovoltaic tilt angle (PVT)
[3]Photovoltaic Azimuth angle (PVA),
[4]Energy Generation (EG);
[5]Water Saving (WS)
[6]Greenhouse Gas Reduction (GHGR)

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Table 2
Summary of studies on Floating Solar PV (FSPV) (continued)

Location	*FPV system*	*Lake area: Coverage area (% of the lake)*	*Cost*	*Benefits*	*Authors*
India (large reservoirs)	---	12812.2 km^2: 2562.44 km^2 (20%)	---	EG: 909.05 GWh/year WS:16233 MCM/year	Sharma and Kothari (2016)
Korea (Ssangyong Open-Pit Limestone Mine pit lake)	PVT: 40° (Fixed) PWR: 215.25 Wp	0.2254 km^2: 0.0876 km^2 (38.9%)	Installation cost: $2.73 Million Operation cost: $19,040/year	EG: 0.9716 GWh/year GHGR: 471.21 ton/year	Song and Choi (2016)
India (Karasur village's lake)	PVT: 12° PWR: 300Wp	0.0374 km^2: 0.0125 km^2 (33.3%)	Installation cost: $1.6 Million	EG: 2.658 GWh/year GHGR: 240 ton/year	Singh et al. (2017)
India (lake in Kota)	---	0.7198 km^2: 0.1439 km^2 (20%)	---	EG: 25.74 GWh/year WS: 0.545 MCM/year GHGR: 23990 ton/year	Mittal et al. (2017)
Australia (Bolivar basin)	PVT: 25°(Fixed) PVA: Sun tracking PWR: 320Wp	3 km^2: 0.42 km^2 (14%)	---	EG: 103.032 GWh/year WS: 0.672 MCM/year	Rosa-Clot et al. (2017)
Albania–Montenegro border (Skadar Lake)	PVT: 44°(Fixed) PVA: Sun Tracking PWR: 300Wp	475 km^2: 5.23 km^2 (1.1%)	Installation cost: $127.8 Million Operation cost: $2,120,970/year	EG: 186.05 GWh/year WS: 5.41 MCM/year GHGR: 83420 ton/year	Durkovic´ and Đurišic´ (2017)

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Table 2
Summary of studies on Floating Solar PV (FSPV) (continued)

Location	*FPV system*	*Lake area: Coverage area (% of the lake)*	*Cost*	*Benefits*	*Authors*
China (water surface in the eastern regions)	---	124700 km^2: 2500 km^2 (2%)	---	EG: 160 GW/year WS: 2×10^{21} MCM/year	Liu et al. (2017)
Brazil (São Francisco River basin)	PVT: 3° (Fixed) PWR: 250 Wp	6369.71 km^2: 101.86 km^2 (1.6%)	Installation cost: (tilt angle = 0°) $5726.81 Million (tilt angle = 5°) $6547.38 Million	EG: 10.5536 GWh/year	Silvério et al. (2018)
Portugal (Alqueva dam)	PVT: 20° (Fixed) PVA: 0° (Fixed) PWR: 260 Wp	92200 km^2: 0.00335 km^2	Installation cost: $3.51 Million Operation cost: $19,412.82/year	EG: 0.4557 GWh/year	Barbuscia (2018)
Taiwan (site of Sugu, south of Taiwan)	PVT: 12° (Fixed) PVA: 82&-98° (two fixed angle) PWR: 295 Wp	0.03235 km^2: 0.0091 km^2 (28.27%)	Installation cost: $1.6267 Million Operation cost $28,320/year	EG: 1.5433 GWh/year	Dizier (2018)
Bosnia and Herzegovina (Jablanica Lake)	PVT: 35° (Fixed) PWR: 210 Wp	13 km^2: 0.38025 km^2 (less than 3%)	Installation cost: $68.37 Million Operation cost: $4.39 Million/year	EG: 36.55 GWh/year	Pašalić et al. (2018)
USA (man-made waterbodies in the contiguous United States)	PVT: 11° (Fixed)	21410 km^2: 5780.7 km^2 (27%)	---	EG: 786000 GWh/year WS: 36403 MCM/year	Spencer et al. (2018)

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Table 2
Summary of studies on Floating Solar PV (FSPV) (continued)

Location	***FPV system***	***Lake area: Coverage area (% of the lake)***	***Cost***	***Benefits***	***Authors***
Korea (1134 reservoirs which satisfy the condition of FPP in Korea)	PV: 20° (Fixed) PVA: South-facing slope (Fixed) PWR: 210Wp	430.6 km^2: 43.06 km^2 (10%)	Installation cost: $3,007.29 Million Operation cost: $21.83 Million/year	EG: 2931.94 GWh/year GHGR: 1294450 ton/year	Kim et al. (2019)
Vietnam (three reservoirs – Hoa Binh, Tri An and Dau Tieng)	PVT: 11° (Fixed) PVA: 0° (Fixed)	603.5 km^2: 91.28 km^2 (15%)	Installation cost: $10300 Million Operation cost: $240 Million/year	EG: 13700 GWh/year WS: 136 MCM/year GHGR: 11000000 ton/year	Bui (2019)
India (Neel-Nirjan Dam located in Bakreswar)	PWR: 320Wp	---: 0.12 km^2	Installation cost: $9.365 Million Operation cost: $221,075.4/year	EG: 14.97 GWh/year WS: 0.21 MCM/year GHGR: 13632.06 ton/year	Goswami et al. (2019)
Brazil (Gavião reservoir, located in the Northeast of Brazil)	PVT: 10° (Fixed) PWR: 245Wp	6.17 km^2: 5 km^2 (81%)	Installation cost: $755 Million Operation cost: $4.674 Million/year	EG: 835.82 GWh/year WS: 2.595 MCM/year	Rodrigues et al. (2020)
Turkey (Mumcular Dam located in Aegean Region of Turkey)	PVT: 33° (Fixed) PVA: 0° (Fixed) PWR: 350Wp	0.00301 km^2	Installation cost: $0.295 Million Operation cost: $18,203/year	EG: 0.182 GWh/year	Temiz and Javani (2020)

2. Materials and Methods

To accomplish the objectives of this study, first, the selected case studies are introduced and then the different aspects of FSPV such as (i) energy generation; (ii) evaporation reduction; (iii) environmental issues, and (iv) economic analysis are investigated. Fig. 1 shows the schematic of the workflow for the present study.

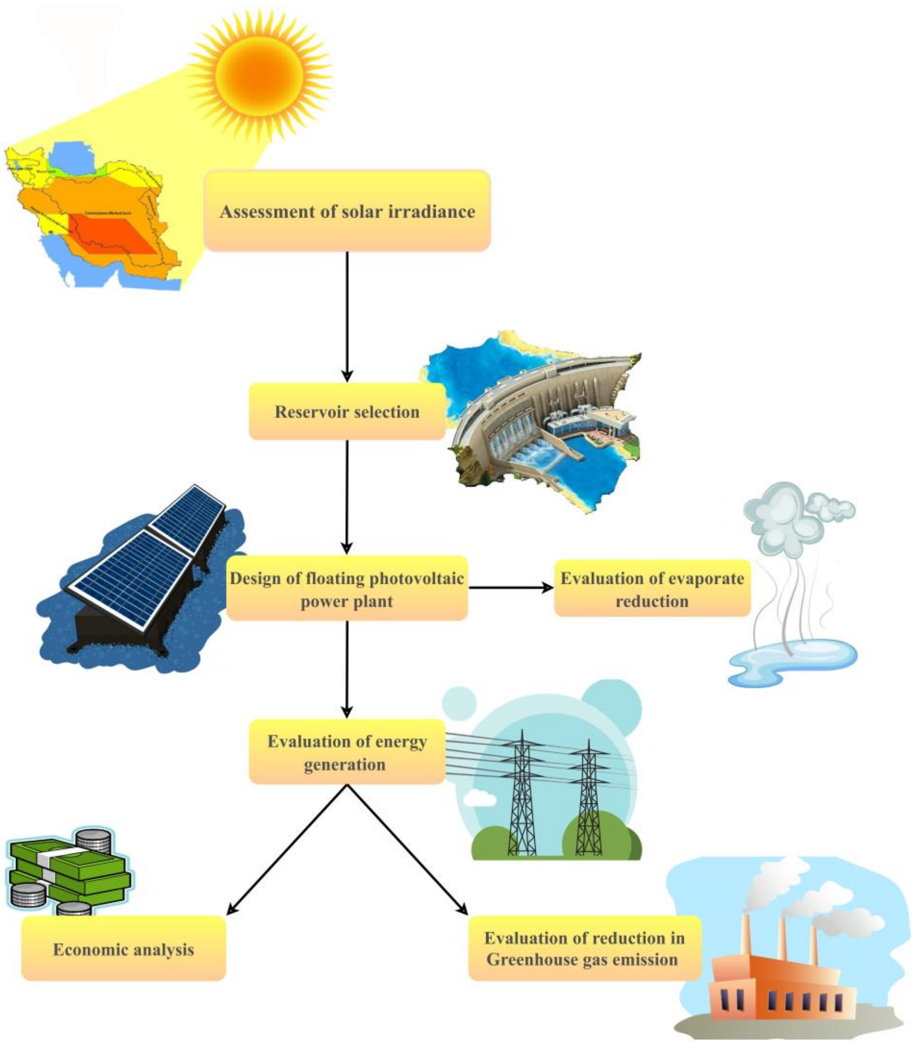

Fig. 1. Schematic explaining the workflow of the present study.

2.1 Study Area

Based on the divisions made by the Ministry of Energy in Iran, the catchment area of the country includes six main basins equal to the total area of the country, each of which is itself divided into small basins. These six main basins are: 1- Khazar basin, 2- Persian Gulf and Oman Sea basin, 3- Urmia Lake basin, 4- Central plateau (Markazi) basin, 5- Hamoon basin, 6- Sarakhs basin.

Currently, there are 383, 365, 104, 314, 71 and 40 dams in the Khazar, Persian Gulf, Urmia, Markazi, Hamoon and Sarakhs basins, respectively, under operation, implementation and study. A total of 647 reservoirs having a volume of more than 48 BCM are in operation, with the Persian Gulf catchment area accounting for the largest share in the reservoir volume. In addition, 683 dams are in two stages of implementation or study. If they reach the stage of operation, 75 BCM will be added to the current capacity. These capacities indicate the high potential for developing FSPV systems in Iran. In this study, to evaluate a portion of this capacity, the five important dams in five main basins with the largest area of the reservoir are selected, namely Aras, Karkheh, Shahid Kazemi, Doroudzan, Doosti dams (Fig. 2). It should be noted that while the annual evaporation volume in Hamoon basin is significant, no dam has been selected from this basin since there is not enough data for conducting the research. However, the results of this study could effectively pave the way for the application of FSPV in Hamoon basin in future.

To have better insights into the application of the FSPV power plant, several scenarios of the coverage percentage of dam’s lake such as 2, 10, 20, 50 and 80% are adopted. Although, the implementation of the scenarios 50% and 80% is economically and administratively unjustifiable, these scenarios can better highlight the theoretical potential for harvesting the solar energy from the surface of water bodies.

Fig. 2 represents the location of the selected dams within the six solar radiation zones, which has been specified by Iran's Renewable Energy Organization (http://www.satba.gov.ir/). The amount of solar radiation varies in different parts of the world and has the highest amount in the solar belt of the earth. Iran is also located in areas with high radiation and studies show that the use of solar equipment in Iran is appropriate and can provide part of the country's energy needs. Having 300 sunny days in more than two-thirds of the country and average radiation of 4.5~5.5 kWh/m^{2}day, Iran has been introduced as one of the countries with high potential in the field of solar energy. As can be seen in Fig. 2, Iran has been divided into six areas based on the potential of solar radiation. The central and southern regions of the country receive a higher amount of solar radiation, whereas the cities in the northern part near the Caspian Sea absorb the lowest amount of radiation. Three of the selected dams namely Aras, Doosti, and Shahid Kazami are located at regions with minimum solar irradiation of 3.8 kWh/m^{2}day. Karkheh and Doroudzan dams receive solar radiation at a higher intensity of at least 4.5 and 5.2 kWh/m^{2}day, respectively. The specific characteristics of the selected dams are briefly explained as follows.

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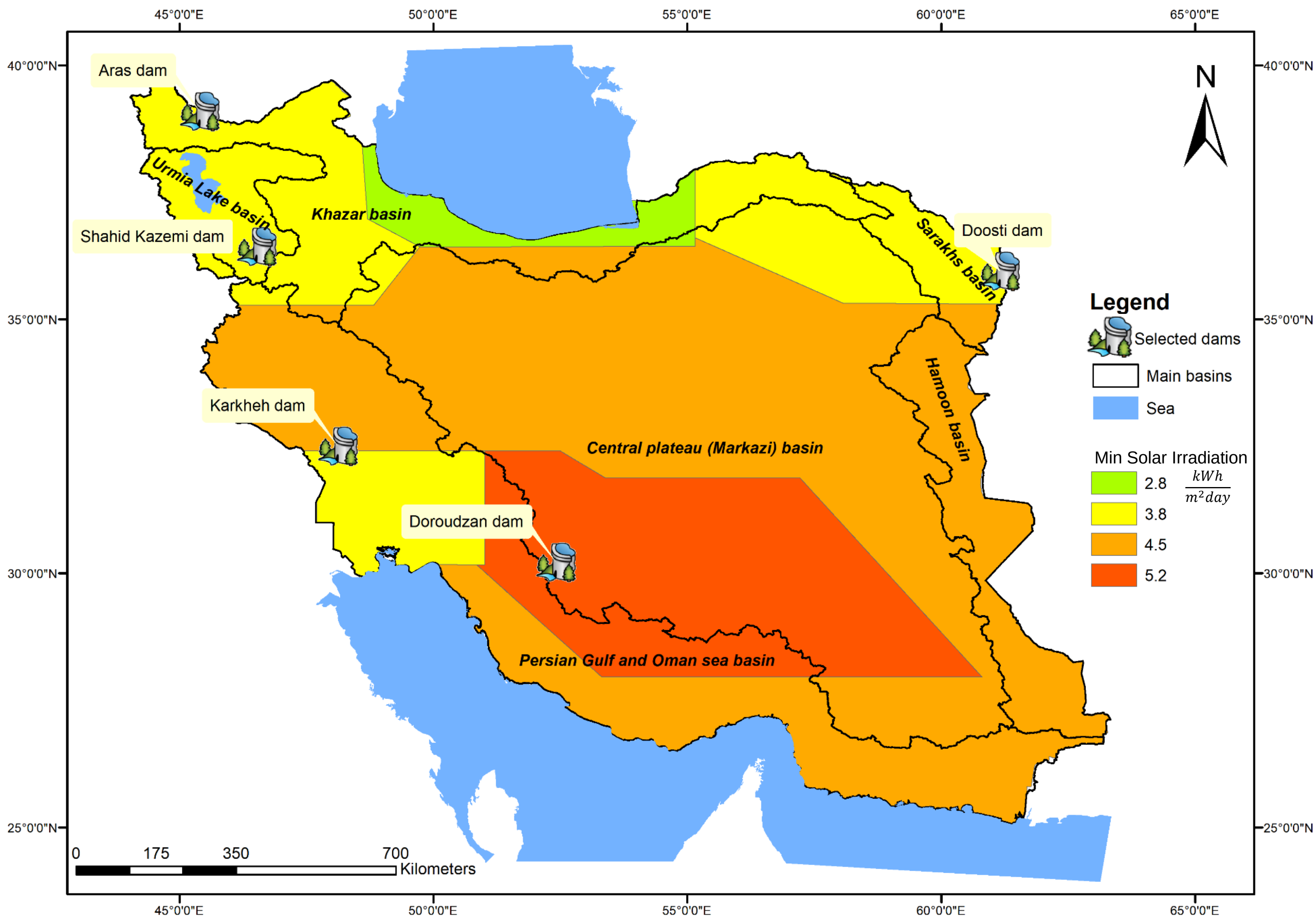

Fig. 2. Map of potential solar radiation in main basins of Iran and the location of the selected dams.

Aras Dam (Khazar Basin). Aras Dam is an embankment dam located 40 kilometers from the town of Jolfa on the Aras River on the border of Iran and Azerbaijan. Construction and operation of this dam have been done jointly by Iran and the Republic of Azerbaijan (http://www.azarwater.ir/). The purpose of this reservoir dam is to supply agricultural water and generate electricity. The total volume and area of the reservoir are 1254 MCM and 15200 ha in normal water elevation (NWL), respectively. It generates about 172000 GWh of electricity per year (86000 GWh per share). The dam consists of four turbines (two in each side) with a total power of 44 MW (11 MW each). Aras Dam Lake has a great variety of freshwater fish and is a good tourist and fishing destination. About 167 MCM of water is evaporated annually which is the highest amount of evaporation in the Khazar Basin (http://daminfo.wmr.ir).

Karkheh Dam (Persian Gulf and Oman sea Basin). Karkheh Dam is located 21 km north-west of the city of Andimeshk. The objectives of the dam are (1) storage and management of irrigation water of 320,000 hectares of land in the downstream plains located in the northwest and west of the province of Khuzestan, (2) generation of hydroelectric power of 934 GWh per year, and (3) prevention of devastating flooding (Haghiabi et al., 2009). The maximum area and volume of the lake in NWL are 16600 ha and 5600 MCM, respectively. In this dam, 334.14 MCM of water is evaporated annually.

Shahid Kazemi Dam (Urmia Lake Basin). Shahid Kazemi (hereinafter referred to as Kazemi) dam located in Boukan city of west Azarbaijan province was built on Zarrineh River (Emami et al. 2019). The purposes of the construction of Shahid Kazemi dam were to irrigate 85000 ha of Miandoab plain lands, control of destructive floods, adjust the water level of the Zarrineh River, supply the drinking water of upstream and downstream cities and protect aquatic ecosystems. The maximum area and volume of the lake in NWL are 4150 ha and 808 MCM, respectively. In this dam, 41.1 MCM of water is evaporated annually.

Doroudzan Dam (Markazi Basin). Doroudzan Dam is one of the largest dams in southern Iran. The reservoir of this multipurpose earth-fill dam is located near the northwest of Shiraz on the Kor River and in the Bakhtegan Lake catchment area. The total storage capacity of the reservoir is 993 MCM. This reservoir is the main source of water supply for 112,000 hectares of agricultural land, domestic-industrial needs, and power plant of Shiraz, the capital of the province of Fars (Goodarzi et al., 2014). The maximum area of the lake in NWL is 5500 ha. The annual evaporation volume is 94.38 MCM.

Doosti Dam (Sarakhs Basin). Doosti Dam was jointly built by Turkmenistan and Iran on the Harirood River at the boundary of both countries, 180 km north-east of the city of Mashhad. It is a rockfill dam having a storage capacity of 1,250 MCM (Mozafari et al., 2012). This dam provides irrigation and municipal water to both Iran and Turkmenistan. (Majidi et al.,2015; Ghandehari et al., 2020). The maximum area of the lake in NWL is 4932 ha. Since this dam is situated in a semi-arid region of Iran, water evaporation is of great importance. About 83 MCM of water is evaporated annually which is the highest amount of evaporation in the Sarakhs basin.

2-2 Energy Generation

Hourly energy generation (W) by the FSPV can be estimated as follows (Durkovic and Đurišic´, 2017):

$$W = I \times A \times \eta \tag{1}$$

where I is mean hourly insolation and A is the covered area by the floating panels of efficiency η, which is determined as

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$$\eta = \eta_{module} \times \eta_{temp} \times \eta_{invertor} \quad (2)$$

where η_{module} is the degree of efficiency of a module, η_{temp} is the PV conversion efficiency, and $\eta_{invertor}$ is the efficiency of the invertor. In this paper based on the selected PV panel[1] (polycrystalline 157×157 mm cell with peak power watts of 260 Wp and module dimensions of 1640×992×35 mm), η_{module} and $\eta_{invertor}$ were adopted as 0.1601 and 0.96, respectively. η_{temp} is calculated by Eq. (3).

$$\eta_{temp} = \eta_{stc}[1 - 0.0047 \times (T_{panel} - 25^{\circ})] \quad (3)$$

where η_{stc} is an efficiency defined for a panel when utilizing it in a standard condition (*stc*), 0.0047 is the temperature coefficient of power of PV panel (-0.47 %/°C) and T_{panel} is the temperature of a PV panel that is estimated according to the following formula:

$$T_{panel} = T_{amb} + (\frac{NOCT - 20}{0.8}) \times I \quad (4)$$

where $NOCT$ is the operation cell temperature that is 44° based on selected PV panel in this study and T_{amb} is the ambient air temperature that was assumed equal to the temperature of dam's lake area.

2-3 Evaporation estimation

Preventing evaporation by the PV plant is not only for the area covered by them but also for the entire lake's surface. The reduction of water evaporation occurs due to the two main reasons. The first reason is the reduction in water and air interaction from the covered area which directly affects the evaporation reduction. The second reason is the change in the heat balance of the lake

[1] The trade name of the module is SSF-P60 produced by Solar Sanat Firouzeh Co. (www.ssf-solar.com)

after the power plant being built which causes the lake to be colder and thus reduces the total evaporation throughout the entire lake's surface (Durkovic´ and Đurišic´, 2017).

Estimating evaporation appropriately is essential. However, a large number of parameters influence the process for estimating water evaporation such as air saturation deficit above the surface, wind speed, the amount of solar radiation reaching the water surface, air pressure, and the chemical characteristics of water. The evaporation rate in water surfaces has been studied in the literature utilizing different models. Generally, water budget, mass transfer, pan evaporation, Penman-Monteith model, and energy balance method are used to measure evaporation. Furthermore, many empirical relations and equations have been developed incorporating temperature, solar day hours, and solar radiation.

Penman's method is one of the most frequently used methods among many mathematical methods that has been modified in different ways (Penman, 1948; Jensen, 2010). Valiantzas (2006) defined this equation in a simplified way using routine weather data as follows:

$$E_0 \approx 0.051(1-\alpha) \times R_S \times \sqrt{T+9.5} - 2.4\left(\frac{R_S}{R_A}\right)^2 + 0.052 \times (T+20)(1 - \frac{RH}{100}) \times (a_u - 0.38 + 0.54u) \quad (5)$$

where E_0 is the average daily water surface evaporation (mm/day) at the sea level ($z = 0$), and R_s is the average sunny hours per day, calculated as follows:

$$R_S = R_A \times (0.5 + 0.25\frac{n}{N}) \quad (6)$$

where n and N are the observed average number of sunny days and the maximum possible number of sunny days for the selected month, respectively. Having geographic width φ, for a selected month (i), N can be calculated as follows:

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$$N \approx 4 \times \phi \times sin(0.53i - 1.65) + 12 \quad (7)$$

The solar irradiance on the surface of the atmosphere (R_A) is approximated as follows:

$$\begin{aligned} R_A &= 3N sin(0.131N - 0.95\phi) & |\phi| > \frac{23.5\pi}{180} \\ R_A &= 118N^{0.2} sin(0.131N - 0.2\phi) & |\phi| < \frac{23.5\pi}{180} \end{aligned} \quad (8)$$

where α denotes the reflection coefficient called albedo. It is related to the water surface that ranges from 0 to 1 and supposed to be 0.08 in this study. T is the average of extreme temperatures (T_{min}, T_{max}) for the analyzed month ($^{\circ}C$):

$$T = \frac{T_{max} + T_{min}}{2} \quad (9)$$

Daily mean percentage of relative air humidity is represented by R_H and u is the average value of wind speed (m/s) at an altitude of 2 m above the water surface.

Equation (6) is adjusted empirically for higher altitudes z (m) (Valiantzas, 2006):

$$E = E_0 + 0.00012 \times z \quad (10)$$

The daily volume of water evaporated can be determined by multiplying the amount of evaporation (E) by area of the lake (A):

$$V(m^3/day) = E(m/day) \times A_{Lake}(m^2) \quad (11)$$

To find out how much water can be saved by implementing FSPV system, the amount of evaporation (E) is multiplied by the FSPV coverage area A_{CA} as follows:

$$\Delta V(m^3/day) = k \times E(m/day) \times A_{CA}(m^2) \quad (12)$$

where k is a reduction factor determined by the type and platform's reflective functionality, its coverage level with panels, and the panel's performance. This coefficient decreases the evaporation volume due to the fact that a portion of solar irradiance passes through panels and reaches the water surface.

2.4 Economic analysis

One of the most important issues that should be considered to evaluate the implementation of FSPV for water infrastructures is the economic analysis (Zhou et al., 2009). In this paper, the overall cost for producing 1 MWh electrical energy is considered as the economic criterion. Accordingly, the most important factors and the related parameters that affect the overall energy production cost are determined. Then, the components of economic costs such as the interest rate, the exploitation period considering for the FSP system, the availability factor of the system, the initial costs (the total investment costs), and the running costs (O&M costs) are determined to calculate the overall energy production cost for each scenario over the selected case studies (Ali, 2017; Durkovic and Durisic, 2017). Moreover, the sensitivity of the results of the economic criterion for the several scenarios to the variations of the economic factors is analyzed. The proposed process of economic analysis is presented in Fig. 3.

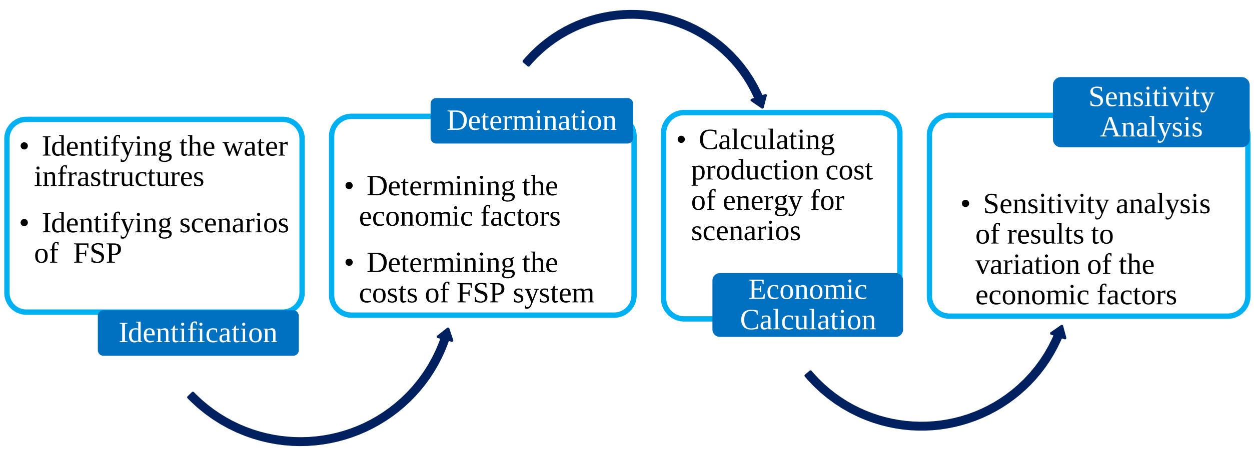

Fig. 3. The proposed workflow for economic analysis process of FSPV plant.

The overall energy production cost (EPC) for FSPV is calculated as follows (Masters, 2004; Durkovic and Durisic, 2017)

$$EPC\left(\frac{USD}{MWh}\right) = \frac{\left(\frac{IR \times (1+IR)^t}{(1+IR)^t - 1}\right) \times IC_{tot}(USD)}{AF \times E_{tot}(MWh)} + OMC\left(\frac{USD}{MWh}\right) \tag{13}$$

where EPC is the total price for producing 1 MWh electrical energy, which is called the overall energy production cost (USD/MWh). In Eq. (13), IR is the interest rate that is considered as an internal rate of return (IRR), t is the exploitation period of the FSPV plant that is named also the amortization period ($year$), and AF is the availability factor that is related to the availability of grid during the exploitation period. IC_{tot} and OMC denote the total investment costs as the total initial costs (USD) and the O&M costs as the running costs during the operation period (USD/MWh), respectively. E_{tot} is the annual production of electrical energy from the FSPV plant (MWh).

To calculate the overall energy production cost for each scenario based on Eq. (13), first, the effective economic factors in this equation should be determined. The interest rate, which refers to the internal rate of return (IRR) (Desideri and Asdrubali, 2019), is considered as an integer number in the interval of [0,24] in term of percentage. The sensitivity analysis is accomplished over the entire range of interest rate percentage (Durkovic and Durisic, 2017). The exploitation period of the FSPV system, which is started from the end of the construction phase and terminated at the end of the operation phase, is considered between 20-25 years (Sahel Ettehad Co., 2020; Durkovic and Durisic, 2017). Accordingly, the sensitivity analysis is carried out for the six cases of exploitation period including 20, 21, 22, 23, 24, and 25 years. Moreover, the availability factor of the FSPV system, which is related to the availability of the grid and maintaining the existing desirable conditions of efficiency of the FSP panel during the exploitation period, is analyzed with the six values including 0.70, 0.75, 0.80, 0.85, 0.90 and 0.95 (Masters, 2004; Durkovic and Durisic, 2017).

The total investment costs (IC_{tot}) is calculated as follows:

$$IC_{tot}(USD) = C_{invertor} + C_{panel} + C_{structure} + C_{installation} \quad (14)$$

where $C_{invertor}$ is the invertor cost (USD), C_{panel} is the panel cost (USD), $C_{structure}$ is the floating structure cost (USD) and $C_{installation}$ is the installation cost (USD). Each of these costs should be determined for each of the FSPV scenarios. The four items of the total investment costs in Eq. (14) could be estimated according to the economic data obtained from the consultant companies that have knowledge and experience in the design, construction, and exploitation processes of installing FSPV (Sahel Ettehad Co., 2020). It is noteworthy that the scale and type of FSPV plant affect the overall costs (Ferrer-Gisbert et al., 2013). Our investigations revealed that the investment costs in the FSPV systems have been estimated 30% higher than the corresponding costs for PV power plants on the ground.

The following considerations have been taken into account in order to estimate the total investment cost: (1) the information about the utilized cell material (crystalline silicon), module cover (glass), array type (fixed open rack), azimuth (180°) and the optimal tilt (25° for some of case studies and 30° for the others) are determined; (2) the annual produced energy (E_{tot}) is estimated for each coverage percentage scenarios; (3) for each coverage scenario of each case study, the relevant nominal capacity of the FSPV is calculated by dividing E_{tot} by the annual average sunny hours; (4) according to the energy generation results and the economic information, the total investment costs for unit power of FSPV power plant (1 MWp) is estimated 650000 (USD/MWh) (Sahel Ettehad Co., 2020); (5) with respect to the nominal capacity of the FSPV system as well as the overall investment costs for unit power, the total investment costs (IC_{tot}) is calculated.

In order to estimate the O&M costs for the FSPV, recent studies have been considered. The international renewable energy agency (IREA) suggested 6.5 $USD/kWyear$ as the fixed annual O&M costs in evaluating the cost-efficiency for PV systems (IREA, 2012). Hammad et al. (2015) considered 12 $USD/kWp/year$ as the annual O&M costs for a 20 MWp PV power plant. Bolinger and Seel (2015) expressed that the mean O&M costs of the ground PV power plants have been gradually decreased from about 19 USD/MWh in 2011 to about 8 USD/MWh in 2014. In 2016, according to the USA energy information administration, the O&M costs for one-axis solar tracker power plant related to a 20 MWp power are slightly higher compared with the O&M costs of a fixed inclination and azimuth angle with the same power (USA energy information administration, 2016). Whaley (2016) investigated the annual O&M costs of large and small PV power plant systems and recommended 0.5% and 1% of initial costs for the large and small systems, respectively. Durkovic and Durisic (2017) recommended 10 USD/MWh as O&M costs for FSPV systems, which is considerably higher than the O&M costs for large-scaled ground PV power plants. In this paper, regarding the previous studies and the recommendations of the Iranian consultant companies, the O&M cost is estimated at about 5~10 USD/MWh depending on the scale of scenarios. Consequently, the annual benefit and the required years for returning the investment costs could be estimated (Sahel Ettehad Co., 2020). Furthermore, the sensitivity analysis process on the economic results is accomplished based on the variations of the economic factors.

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2.5 Environmental impact analysis

As the operation of the FSPV is associated with some environmental consequences, besides its advantages, mitigating negative effects is one of the governing factors in building procedures (Durkovic and Durišic, 2017). Life cycle assessment (LCA) is a common tool for the evaluation of the human activities' potential outcomes (Hou et al., 2015; Raouz, 2017). Environmental impacts of constructing FSPV include the primary energy return on investment, global warming potential, and eutrophication potential.

The total life cycle energy input of the FSPV station is calculated using Eq. 15 in which *i* i denotes the life cycle stages from manufacturing to dismantling.

$$E_{tot} = \sum_{i=1} E_i\,, \quad i = 1, \ldots, n \tag{15}$$

The energy payback time (EPBT), represents the required time to produce the same amount of energy that was consumed for FSPV construction (Raouz 2017). For the estimation of EPBT, E_{tot} is the total energy input during the construction of the FSPV station and E_{yr} is the annual energy production:

$$EPBT = \frac{E_{tot}}{E_{yr}} \tag{16}$$

Another index for addressing environmental issues in FSPV analysis is the environmental impact indicator. This indicator includes eutrophication potential and global warming potential (GWP) regarding the GHG reduction. A significant advantage of FSPV is related to the algae bloom containment. This problem can be alleviated by covering the basin partially and reducing the light below the surface (Cazzaniga et al., 2018).

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The impact of FSPV system on the reduction of greenhouse gas emissions is estimated using Eq. 17. It is obtained based on the generated greenhouse gases within a fossil-fuel energy system producing the same amount of electricity generation (Durkovic and Durišic, 2017)

$$G_t = E_s \times G \times (1 + \beta) \tag{17}$$

where G_t represents the annual reduction of GHG (tCO_2/year), E_s is annual energy production (MWh/year), G is a standard value of GHG emissions for the country of the study area (tCO_2/MWh), and β is a dimensionless parameter denoting the average loss rate related to the power transmission and distribution systems.

3. Results and Discussion

3.1. Energy Production

3.1.1. Mean hourly insolation (I)

NREL information network and the PVWatts calculator (https://pvwatts.nrel.gov/) were used to calculate the amount of I (kWh/m^2day) for each of the studied dams in a monthly scale. The results can be seen in Fig. 4. For calculating I, the specifications considered in the PVWatts tool were based on the SSF-P60 solar cell provided by Solar Sanat Firouzeh company (http://www.ssf-solar.com/) (See Table 3). It should be noted that the optimal tilt angle for each dam is calculated separately.

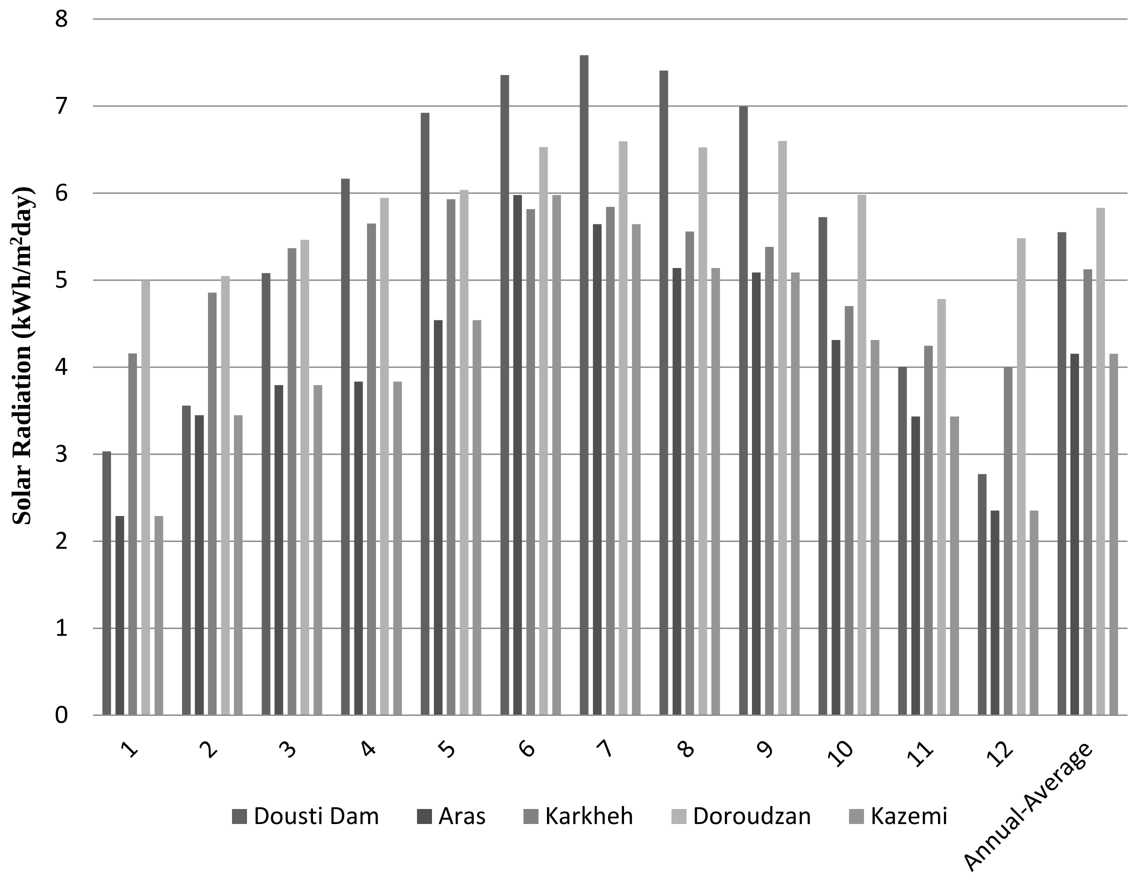

Fig. 4. Solar radiation on selected dams ($\frac{kWh}{m^2 day}$)

Table 3
System information for dams in PVWatts

Dams	Cell Material	Module Cover	Array type	Azimuth(deg)	Tilt (deg)
Doosti	Crystalline Silicon	Glass	Fixed (open rack)	180	30
Aras	Crystalline Silicon	Glass	Fixed (open rack)	180	30
Karkheh	Crystalline Silicon	Glass	Fixed (open rack)	180	25
Doroudzan	Crystalline Silicon	Glass	Fixed (open rack)	180	25
Shahid Kazemi	Crystalline Silicon	Glass	Fixed (open rack)	180	30

As can be seen in Fig. 4, based on the annual average, Doroudzan dam has the highest solar radiation among the other dams, which corresponds to the position of this dam in the radiant region of southern Iran (Fig. 2). Although Doosti dam located northeastern Iran has the most solar radiation among the studied dams in the spring and summer, it is in second place based on the average annual solar radiation. Karkheh dam is in the third place after Doosti Dam with average annual radiation of 5.13 kWh/m^{2}day. Shahid Kazemi and Aras dams, which are located in northwestern parts of Iran, have the lowest amount of solar radiation among the selected dams.

3.1.2. Yearly energy production

As mentioned earlier, the total annual energy production values in the studied dams with different coverage percentages were calculated which can be seen in Fig. 5.

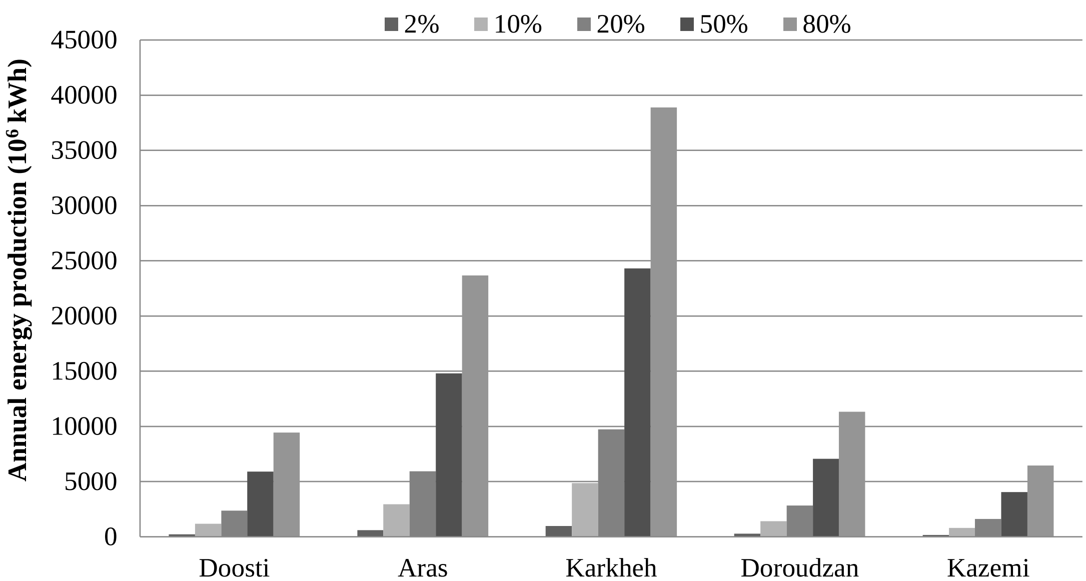

Fig. 5. Annual energy production of PV panels in different dams (10^6 kWh).

Table 4
Comparison of electricity generated by solar panel system compared to conventional fossil fuel methods.

Type of energy	Dam	FSPV coverage percentages				
		2%	10%	20%	50%	80%
Energy generated (10^6 kWh)	Doosti	235.71	591.47	972.41	282.79	161.49
	Aras	1178.53	2959.22	4862.03	1413.94	807.44
	Karkheh	2357.06	5918.43	9724.07	2827.89	1614.88
	Doroudzan	5892.64	14796.08	24310.17	7069.71	4037.20
	Kazemi	9428.23	23673.73	38896.27	11311.54	6459.51
Equivalent thermal value (kCal)	Doosti	5.08E+11	2.54E+12	5.08E+12	1.27E+13	2.03E+13
	Aras	1.28E+12	6.38E+12	1.28E+13	3.19E+13	5.11E+13
	Karkheh	2.10E+12	1.05E+13	2.10E+13	5.24E+13	8.39E+13
	Doroudzan	6.10E+11	3.05E+12	6.10E+12	1.52E+13	2.44E+13
	Kazemi	3.48E+11	1.74E+12	3.48E+12	8.71E+12	1.39E+13
Equivalent fossil fuel (Gas) (MCM)	Doosti	58.93	294.63	589.26	1473.16	2357.06
	Aras	147.87	739.80	1479.61	3699.02	5918.43
	Karkheh	243.10	1215.51	2431.02	6077.54	9724.07
	Doroudzan	70.70	353.49	706.97	1767.43	2827.89
	Kazemi	40.37	201.86	403.72	1009.30	1614.88
Equivalent fossil fuel (Oil) (10^6 No. Barrels)	Doosti	0.35	1.74	3.47	8.69	13.90
	Aras	0.87	4.36	8.73	21.81	34.90
	Karkheh	1.43	7.17	14.34	35.84	57.34
	Doroudzan	0.42	2.08	4.17	10.42	16.68
	Kazemi	0.24	1.19	2.38	5.95	9.52

As can be seen in Fig. 5, the electricity generated by the selected dams is in line with the lake area behind the dams. Accordingly, Karkheh dam has the highest amount of electricity with an annual production of 972.4 GWh and 38900 GWh for 2% and 80% coverages, respectively. It is noteworthy that the generated electricity resulted from 2% coverage is approximately similar to the energy that is currently generated by the hydropower plant at Karkheh dam. Shahid Kazemi dam has the lowest amount among the selected dams which is 161.5 GWh and 6500 GWh for 2 and 80% coverage, respectively. In order to evaluate the electricity generated by the FSPV in comparison with the common ways of energy generations, the equivalent fuels required to generate that amount of energy has been calculated. To generate every kWh of electricity in Iran, 2157 kcal

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of energy is burned. Accordingly, burning every cubic meter of gas in Iran's thermal power plants produces 4 kWh and each barrel of crude oil produces about 680 kWh of electricity. As can be seen in Table 4, in Karkheh and Shahid Kazemi dams, which have the highest and lowest electricity generation, only 2% coverage of the lake's surface can generate power equivalent to burning 243 and 40 MCM Gas and 1,400,000 and 238,000 barrels of crude oil in Iran's thermal power plants.

3-2 Evaporation reduction

Covering part of the dam reservoirs has shown to be an effective way of reducing water evaporation. Furthermore, by changing the heat balance due to the reflection of the part of the solar energy from the PV panels, the evaporation rate will be reduced from the entire reservoir's surface (Durkovic´ and Đurišic´, 2017) . For the five selected dams, the monthly evaporation is calculated using the simplified Penman's model and shown in Fig. 6. As can be seen, the maximum evaporation occurs in July for Doosti and Karkheh Dams. In July, the water level in Doosti and Karkheh dams decreases more than 400 mm which is an average of 14 mm/day. For all dams, the monthly evaporation in November, December, January, and February is less than 100 mm with December having the smallest rate. The maximum and minimum total water evaporation in the selected year is 2742 mm and 1686 mm which are related to the Karkheh and Aras dams, respectively.

Fig. 7 shows the yearly increase in the available volume of water behind the selected dams after building FSPV under five coverage scenarios. Due to some energy reflection from the platform, k in Eq. (12) is assumed to be 0.6. As expected, building FSPV on the Karkheh reservoir can provide a vast amount of water annually by preventing evaporation. However, to make the results more meaningful, the evaporation reduction is divided by the adjustable volume of water (AVW) for each dam. AVW refers to the capacity of the dam to fulfill the downstream demands.

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As can be seen, Aras and Doosti dams have the highest ratio for all coverage scenarios which indicates the significance of implementing FSPV to prevent evaporation. Theoretically speaking, covering 80% of Aras Dam with FSPV could potentially satisfy 18.9% of the downstream demands.

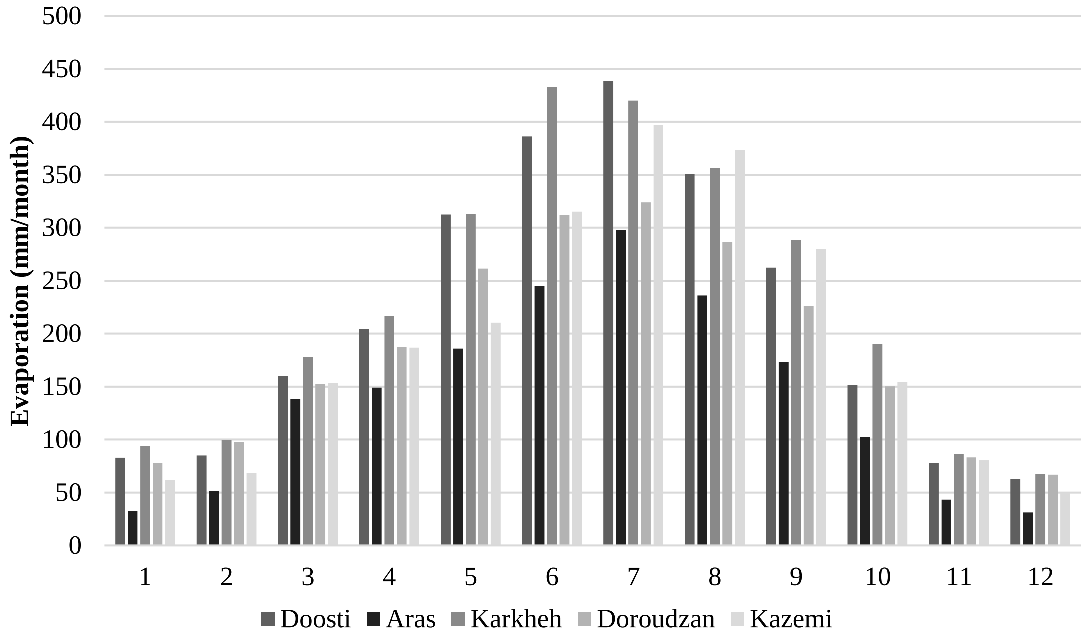

Fig. 6. Monthly evaporation of the selected dams.

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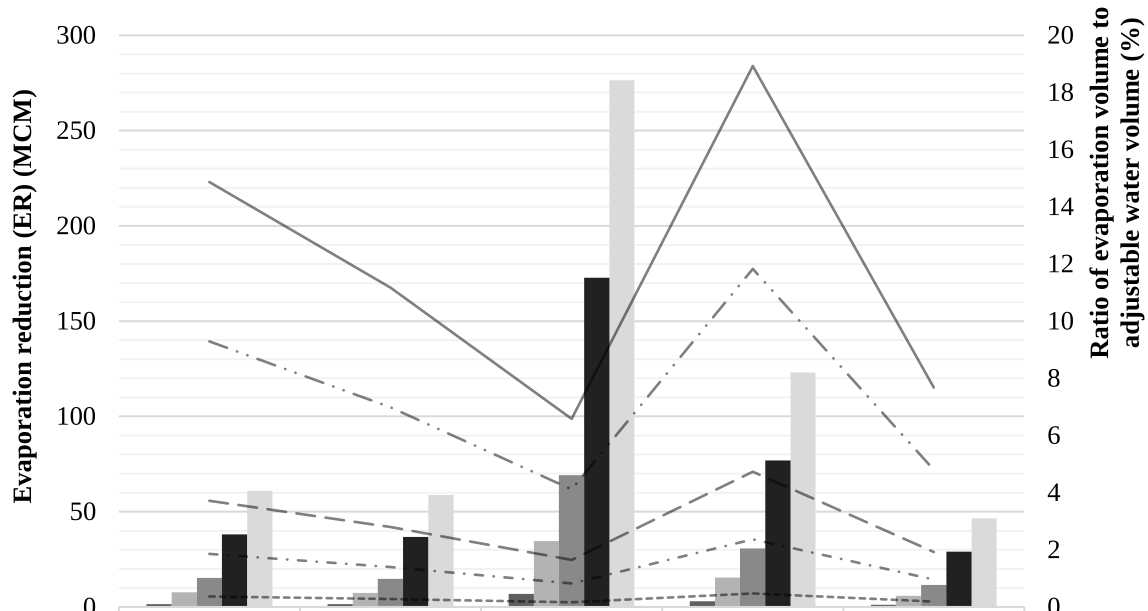

		Doosti	Doroudzan	Karkheh	Aras	Kazemi
ER	2%	1.524	1.469	6.911	3.076	1.161
	10%	7.620	7.345	34.554	15.378	5.804
	20%	15.240	14.690	69.109	30.756	11.609
	50%	38.099	36.725	172.772	76.891	29.022
	80%	60.959	58.760	276.435	123.025	46.435
EA (%)	2%	0.372	0.279	0.165	0.473	0.192
	10%	1.859	1.396	0.823	2.366	0.959
	20%	3.717	2.793	1.645	4.732	1.919
	50%	9.293	6.982	4.114	11.829	4.797
	80%	14.868	11.171	6.582	18.927	7.675

Fig. 7. The annual increase in the available volume of water in the selected reservoirs after building FPVP (left axis) and the ratio of evaporation volume of each dam to the corresponding adjustable water volume (EAR) (right axis)

3-3 *Economic Aspects*

3-3-1 Cost-Benefit Analysis Results

Regarding the second step of the proposed economic analysis workflow (Fig. 3) and based on Eq. (14), Table 5 shows the results of the four components of the investment costs (the invertor cost $C_{invertor}$, the panel cost C_{panel}, the floating structure cost $C_{structure}$, and the installation cost $C_{installation}$), the annual benefit, and the required years for returning total investment costs.

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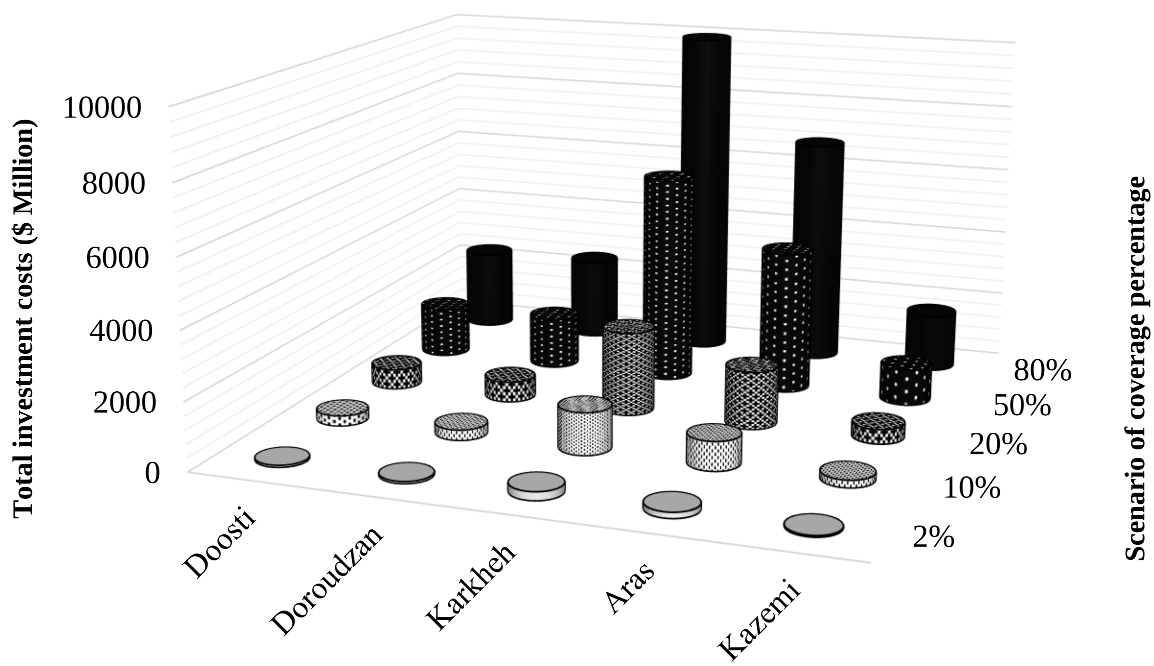
Table 5
The components of investment costs (USD Million) for the FSP scenarios of the case studies

Case study	FSP coverage percentage scenario	Invertor cost	Panel cost	Floating structure cost	Installation cost	Annual benefit	Years required for returning investment
Doosti	Sc.1:2%	6.19	31.34	14.57	8.18	9.38	6
	Sc.2:10%	30.93	156.70	72.87	40.91	46.92	6
	Sc.3:20%	61.86	313.39	145.75	81.81	93.84	6
	Sc.4:50%	154.66	783.48	364.37	204.53	234.60	6
	Sc.5:80%	247.45	1253.57	582.99	327.25	375.36	6
Doroudzan	Sc.1:2%	6.33	32.05	14.90	8.37	10.41	6
	Sc.2:10%	31.63	160.24	74.52	41.83	52.06	6
	Sc.3:20%	63.26	320.48	149.04	83.66	104.13	6
	Sc.4:50%	158.15	801.19	372.60	209.15	260.31	6
	Sc.5:80%	253.04	1281.91	596.17	334.65	416.50	6
Karkheh	Sc.1:2%	25.56	129.48	60.22	33.80	35.80	7
	Sc.2:10%	127.79	647.39	301.08	169.00	179.02	7
	Sc.3:20%	255.59	1294.78	602.15	338.01	358.05	7
	Sc.4:50%	638.96	3236.96	1505.39	845.02	895.12	7
	Sc.5:80%	1022.34	5179.13	2408.62	1352.03	1432.19	7
Aras	Sc.1:2%	17.53	88.81	41.30	23.18	21.78	8
	Sc.2:10%	87.71	444.34	206.65	116.00	108.96	8
	Sc.3:20%	175.42	888.68	413.29	231.99	217.92	8
	Sc.4:50%	438.55	2221.69	1033.23	579.98	544.80	8
	Sc.5:80%	701.69	3554.71	1653.16	927.97	871.69	8
Kazemi	Sc.1:2%	4.44	22.48	10.46	5.87	5.95	7
	Sc.2:10%	22.19	112.40	52.28	29.34	29.73	7
	Sc.3:20%	44.38	224.81	104.55	58.69	59.46	7
	Sc.4:50%	110.94	562.02	261.38	146.72	148.65	7
	Sc.5:80%	177.51	899.24	418.20	234.75	237.84	7

As can be inferred from Table 5, for all scenarios, among the four items of the investment costs, the highest cost is related to the panels and then the floating structure. The lowest cost was obtained for the invertor. Furthermore, the required time for returning the investments is estimated to be between 6~8 years depending on the annual benefit and the amount of the investments. It is expected that the costs of items in the investment part will increase by increasing the area covered by the FSPV system.

The total investment costs (IC_{tot}) was calculated using Eq. (14) and the results are illustrated in Fig. 8. Moreover, the corresponding O&M costs (OMC) are represented in Fig. 9.



	Doosti	Doroudzan	Karkheh	Aras	Kazemi
2%	60.28	61.64	249.05	170.83	43.24
10%	301.41	308.22	1245.27	854.69	216.21
20%	602.82	616.44	2490.53	1709.38	432.42
50%	1507.04	1541.10	6226.33	4273.45	1081.06
80%	2411.27	2465.76	9962.12	6837.52	1729.70

Fig. 8. The total investment costs ($ Million) for the FSPV scenarios of the case studies.

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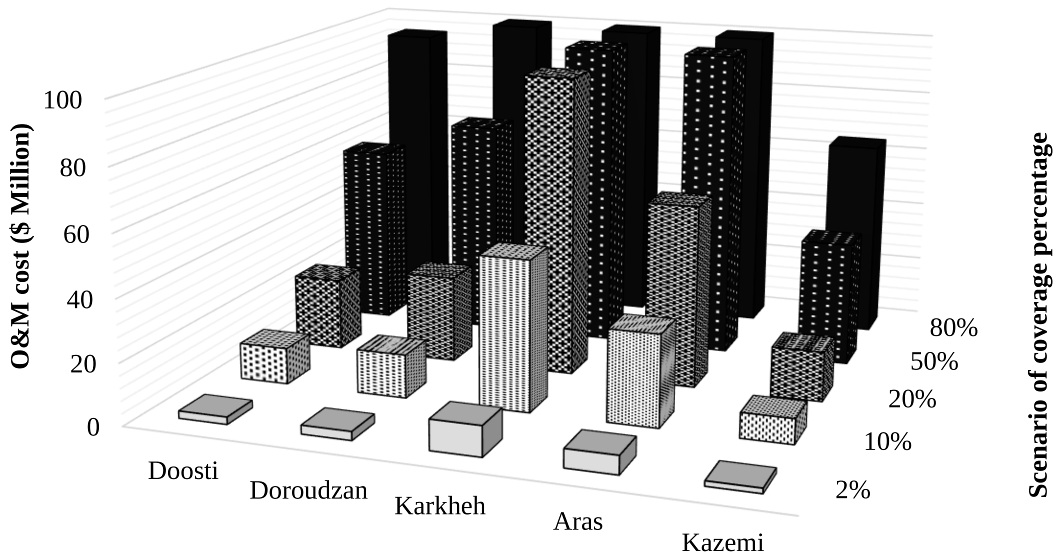

	Doosti	Doroudzan	Karkheh	Aras	Kazemi
2%	2.36	2.83	9.72	5.91	1.61
10%	11.79	14.14	48.62	29.59	8.07
20%	23.57	28.28	97.24	59.18	16.15
50%	58.93	70.70	243.10	147.96	40.37
80%	94.28	113.12	388.96	236.74	64.60

Figure 9. The O&M costs ($ Million) for the FSP scenarios of the case studies

As can be expected from Figs. 8 and 9, the total investment and O&M costs is increased by the rise of the area covered by the FSPV systems. The highest investment and O&M costs are related to Karkheh water infrastructure as it has the largest reservoir area among the case studies in the NWL and thus needs more material for FSPV coverage including the panel, the floating structure and installation items. Furthermore, because of the higher energy produced in this dam, the higher invertor cost is required.

3-3-2 Sensitivity Analysis on Economic Results

Regarding the steps 3 and 4 of the economic analysis process (Fig. 3), the overall energy production cost for each FSPV scenario of the water infrastructures is calculated based on Eq. (13).

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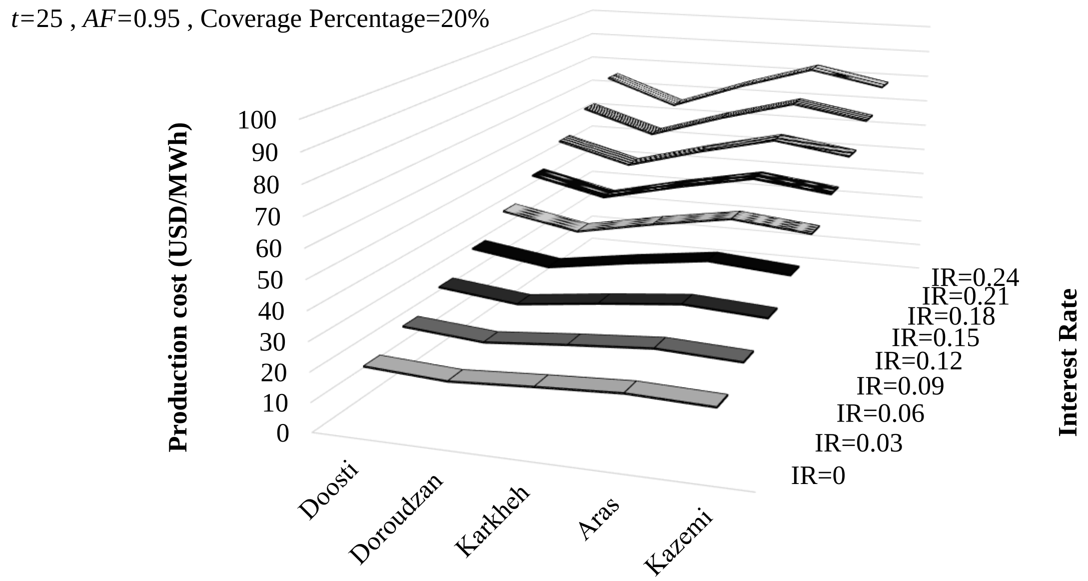
The results are analyzed with respect to the variations of the effective economic factors such as the interest rate, the availability factor, and the exploitation period for the FSPV scenarios. Fig. 10 shows the overall energy production costs (EPC) for the 20% coverage percentage in the conditions of t =25, AF =0.95 based on the variations of the interest rate (IR):

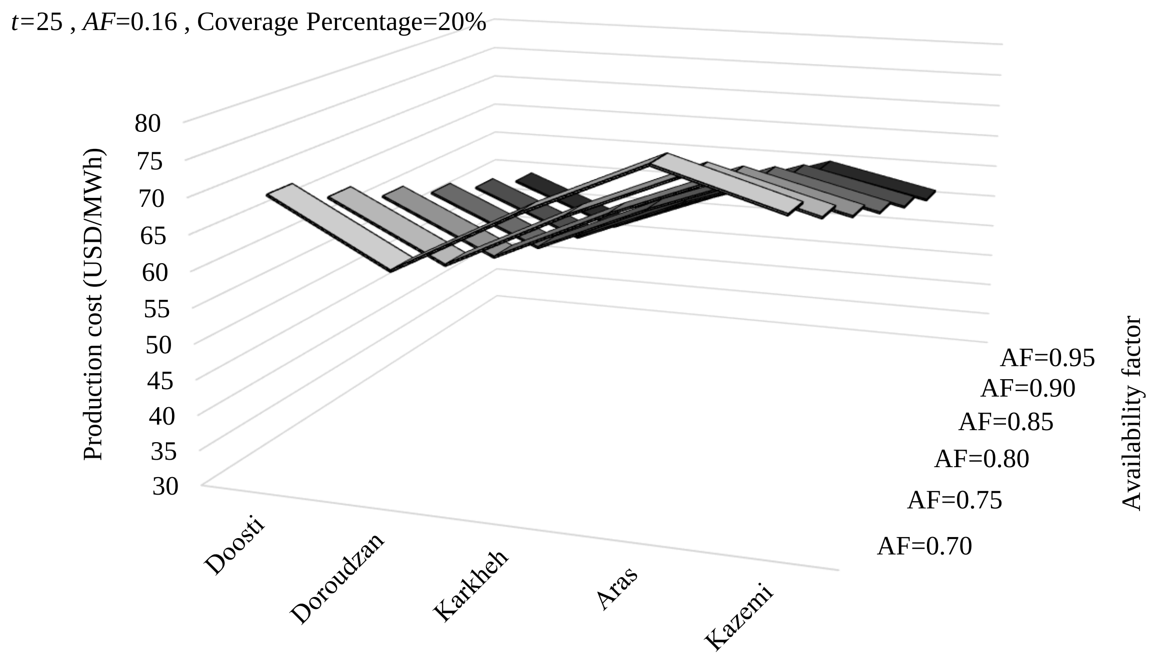


	Doosti	Doroudzan	Karkheh	Aras	Kazemi
IR=0	20.77	19.18	20.78	22.16	21.27
IR=0.03	25.46	23.18	25.48	27.46	26.19
IR=0.06	31.06	27.95	31.09	33.78	32.05
IR=0.09	37.41	33.36	37.45	40.95	38.70
IR=0.12	44.32	39.26	44.37	48.76	45.94
IR=0.15	51.65	45.50	51.71	57.03	53.60
IR=0.18	59.24	51.97	59.31	65.61	61.56
IR=0.21	67.02	58.60	67.10	74.39	69.70
IR=0.24	74.91	65.33	75.00	83.30	77.96

Fig. 10. The variations of energy production costs based on the interest rate values

It is revealed that the increase in the interest rates caused a significant rise in the energy production cost for the FSPV system. Indeed, if the higher internal rate of return is requested, the higher cost is required for producing electrical energy by the FSPV system. According to the results, the private or public investor could investigate the economic justification for such an investment. As can be seen, among the studied water infrastructures, the case study of Aras with considerable reservoir area and the least annual sunny days has the highest energy production cost.

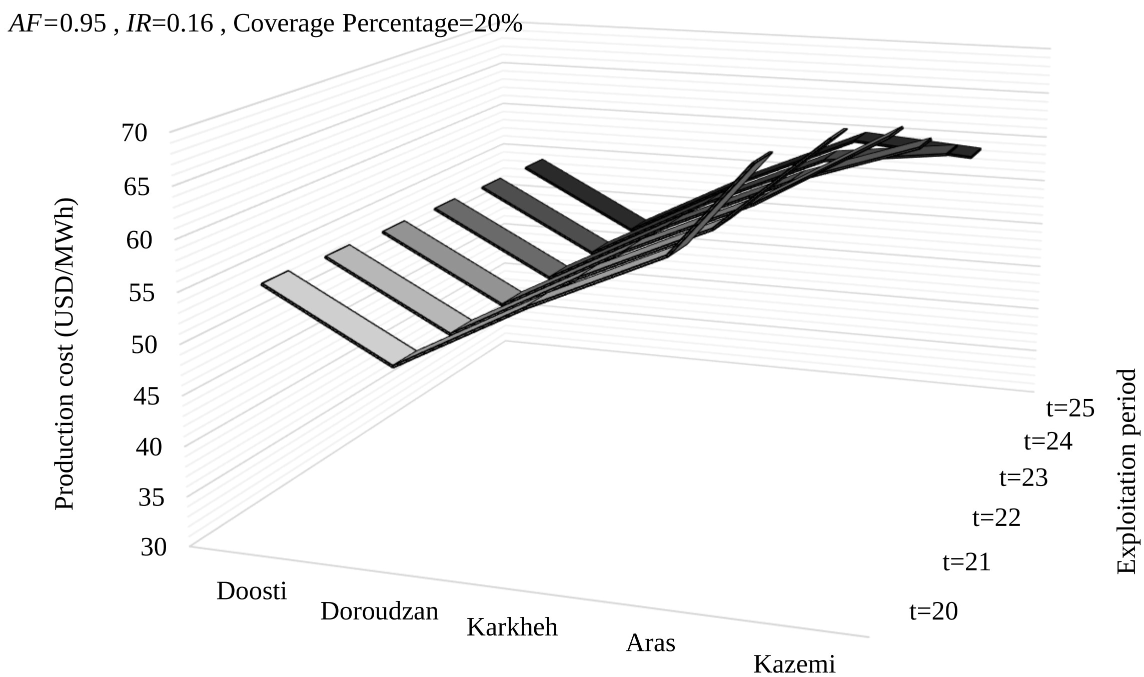
In Fig. 11, the overall energy production costs (EPC) for the 20% coverage percentage in the conditions of t =25 and IR =0.16 are presented based on variations of the availability factor (AF). As can be seen, the availability of the grid and the existence of desirable conditions for the FSPV panel during the exploitation period lead to a lower price for producing electrical energy.



	Doosti	Doroudzan	Karkheh	Aras	Kazemi
AF=0.70	69.92	61.07	70.01	77.67	72.74
AF=0.75	65.93	57.67	66.01	73.16	68.56
AF=0.80	62.43	54.69	62.51	69.21	64.90
AF=0.85	59.35	52.06	59.42	65.73	61.67
AF=0.90	56.61	49.72	56.67	62.63	58.80
AF=0.95	54.15	47.63	54.22	59.86	56.23

Fig. 11. The variations of energy production costs based on the availability factor values.

The overall energy production costs (EPC) for the 20% coverage percentage in the conditions of AF=0.95 and IR =0.16 are represented in Fig. 12 based on the variations of the exploitation period (t). It can be seen that the increase of the exploitation period caused a negligible decrease in the energy production cost, except the Kazemi dam. In this case, increasing the exploitation period leads to a considerable decrease in the energy production cost.



	Doosti	Doroudzan	Karkheh	Aras	Kazemi
t=20	55.41	48.70	55.47	61.28	76.34
t=21	55.07	48.42	55.14	60.90	71.92
t=22	54.78	48.17	54.85	60.58	68.05
t=23	54.54	47.96	54.60	60.30	64.63
t=24	54.33	47.79	54.40	60.06	61.60
t=25	54.15	47.63	54.22	59.86	58.88

Fig. 12. The energy production costs based on the variation of the exploitation period.

3-4 Environmental Issues

Since there is no FSPV power plant built on the studied dams yet, the average total life cycle energy input is considered as 183×10^{6} MJ in the context of the cradle to grave procedure

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based on the previous studies in the Asia (Fu et al. 2015; Palanov 2014). Table 6 shows the energy payback time for each of dams under different coverage scenarios.

Table 6
The energy payback time for the FSP scenarios of the case studies

	EPBT (Year)				
	Doosti	Aras	Karkheh	Doroudzan	Kazemi
2%	0.776	0.309	0.188	0.647	1.133
10%	0.155	0.062	0.038	0.129	0.227
20%	0.078	0.031	0.019	0.065	0.113
50%	0.031	0.012	0.008	0.026	0.045
80%	0.019	0.008	0.005	0.016	0.028

According to the Table 6, the EPBT range of variation for Kazemi dam is 1 years (about 0.03~1.13) which is the widest range among the case studies. The highest EPBT is corresponded to Kezemi dam, and it is followed by the Doosti, Doroudzan and Aras dams, respectively. Installing FSP systems in the Karkheh dam area is highly recommended, where it takes less than 0.2 years to pay back the energy consumed during its lifecycle stages. According to the results, wherever in Iran the FSPV system is installed, the EPBT would be less than its lifespan (here less than 1.5 year). Thus, regarding to the energy payback point of view, the development of these systems in Iran is practical and beneficial.

The effect of FSPV systems on GHG emission reduction is an important environmental issue. In this context, values for G (tCO_2/MWh) and β (dimensionless) were estimated as 0.65 and 0.13, respectively (World Bank, 2020). The annual reduction of CO_2 emissions is shown in the Table 7.

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Table 7
The reduction of CO_2 emissions on selected dams

	G_t (ktCO_2)				
	Doosti	Aras	Karkheh	Doroudzan	Kazemi
2%	173.126	434.437	714.233	207.708	118.613
10%	865.629	2173.545	3571.164	1038.541	593.064
20%	1731.258	4347.089	7142.328	2077.082	1186.128
50%	4328.146	10867.723	17855.821	5192.705	2965.320
80%	6925.033	17388.356	28569.313	8308.328	4744.512

According to the results, the installation of floating PV systems can significantly contribute to reduction of greenhouse gas emissions at least 118 ktCO_2 annually at 2% reservoir surface coverage.

In the context of eutrophication, the Doroudzan dam has the highest potential because of having the highest solar radiation and this is followed by Doosti and Karkheh dams which are threatened by algal blooms. Aras and Kazemi dams have the least value for eutrophication potential. Therefore, installing PV systems can highly affect the eutrophication status and protect water quality from excessive algae growth in the Dorudzan dam.

Sustainable development would eventually lead to an increase in demand for more environmental-friendly processes, infrastructures and products. Thus, environmental evaluation of FSPV systems as an infrastructure using renewable energy is essential, especially in arid and semi-arid areas.

4. Conclusions

Photovoltaic (PV) energy, owing to its ubiquity and efficiency, is one of the world's most promising renewable energies. However, due to solar radiation, surface water resources are considerably subjected to extreme evaporation. Over the past 10 years, a new technology called floating PV has attracted much interest because of its eco-environmental advantages, particularly when it comes to large-scale installing on dams' lakes and reservoirs. This system protects the huge amount of water resources from evaporation and generate sustainable electrical energy from solar energy, simultaneously. Having developed an energy path focusing on the increased use of renewable energy, Iran has a tremendous opportunity to install floating solar photovoltaic (FSPV) plants with over 1300 water reservoirs under operation, implementation, and study that will protect fertile property, mitigate greenhouse gas pollution, and minimize water evaporation levels. This study first provides a comprehensive literature review on the application of FSPV and then evaluates the technical, economic and environmental potential of installing FSPV plants in important water infrastructures in Iran, namely Aras, Karkheh, Doosti, Doroudzan and Shahid Kazemi dams.

According to the present study, installing FSPV plant over one square kilometer of the lake's surfaces of the selected dams could annually generate 194~257 GWh of electrical energy. Given the fact that the per capita annual electricity consumption in Iran is 2727 kWh, the results show that covering only one square kilometer of each dam with floating solar panels could meet the electricity needs of, on average, about 90,000 people. One of the most beneficial ecological consequences of the development of FSPV is the reduction in water evaporation. This system if implemented on the selected dams covering for instance 10% of each lake, would save up to collectively 70.7 MCM water per year which meets the annual domestic water demands of a city with one million residents. In addition, regarding with the economic evaluation results, the energy production cost is calculated based on the four items of invertor, panel, structure and installation costs at 20~85 ($/MWh) depending on the coverage percentage of the reservoirs' area, interest rate, availability factor, and exploitation period. Furthermore, the economic outcomes indicate that the investment costs for energy production return in 6 to 8 years. In terms of environmental advantages, results indicated that the least EPBT value is for Karkheh dam as the most desirable case, where it takes less than 0.2 years to pay back the energy consumed during its lifecycle stages. The proposed FSPV would contribute to a reduction of CO_2 emission more than 118 ktCO_2 annually.

The study conducted here is a preliminary effort to highlight the significance of installing FSPV on Iran's reservoir surfaces based on the most important governing factors and other aspects will need to be thoroughly explored in future works. Also, a comparative economic analysis between the investment costs for water supply as much as the evaporated volume form the reservoirs and the investment costs for installing the FSPV system could be a subject for future studies. In addition, a detailed investigation should be undertaken into all possible electrical links, including the possibility of integrating FSPV with hydroelectric power plants. In conclusion, FSPV is opening up a new investment path, where many factors lead to the reduction of costs and the enhancement of the environment.

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