*Energy Equip. Sys./ Vol. 5/No.2/ June 2017/211-218*

ENERGY EQUIPSYS

Energy Equipment and Systems

http://energyequipsys.ut.ac.ir
www.energyequipsys.com

# Theoretical analysis of reservoir-based floating photovoltaic plant for 15-khordad dam in Delijan

**Authors**

**Sina Azami** [a*]
**Maziyar Vahdaty** [b]
**Farschad Torabi** [c]

[a] Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129, Turin, Italy

[b] Department of Mechanical Engineering, Mazandaran University of Science and Technology, Babol, Iran

[c] Mechanical Engineering Faculty, Energy Systems Group, KNToosi University of Technology, Tehran, Iran

## ABSTRACT

*The current study presents the design features and photovoltaic requirements of a floating photovoltaic plant (FPVP) whose purpose is to reduce the evaporation from the surface of a water reservoir while generating electricity. A summary of the energy budget method is also introduced to calculate the rate of evaporation from the water reservoir behind 15-Khordad dam. The top of the reservoir has a surface area about 1.59 km² but only 2% of it has been covered with the proposed FPVP with a stated capacity of 1.45 $MW_{dc}$. The study proves that covering even a small percentage of the reservoir's surface has a significant effect on the amount of water saved annually. Finally, the average water saved monthly due to FPVP, the electricity generated by the system in the first year, and the $CO_2$ balance of the facility are calculated based on meteorological data of Delijan.*

*Article history*:

Received : 18 January 2017
Accepted : 3 April 2017

**Keywords:** FPVP , Water Reservoir, Energy Budget.

## 1. Introduction

Water scarcity and greenhouse gas emission due to fossil-fuel combustion are considered major challenges facing the Middle Eastern countries. In 2014, Iran ranked eighth among the top 10 emitting countries by producing 556.1 million tonnes of $CO_2$, according to IEA [1]. Hydrological analysis also confirms that per-capita renewable water resources in MENA are among the lowest in the world, and projects that the situation will worsen in future (Fig.1) (Immerzeel et al. [2]).

In recent years, renewable energy sources have been growing rapidly all over the world. Solar energy is considered one of the most promising alternatives due to its ubiquity and sustainability. Solar energy is freely and enormously available throughout the world, especially in the Middle East and Africa (MENA) region (Kumar et al. [3]). The most common way to use solar energy is through photovoltaic (PV) systems. Floating solar plants generate more electricity than ground-mount and rooftop systems because of the cooling effect of water. They also reduce reservoir evaporation and algae growth by shading the water. The floating platforms are 100% recyclable. They are made from medium-density polyethylene (MDPE), which can withstand ultraviolet rays and corrosion.

*Corresponding author: Sina Azami
Address: Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129, Turin, Italy
E-mail address: sina.azami@studenti.polito.it

### Abbreviations

| | |
|---|---|
| FPVP | Floating Photovoltaic Plant |
| POA | Plane of Array |
| MENA | Middle East and North Africa |

### Symbols

| | |
|---|---|
| C | The specific heat of water |

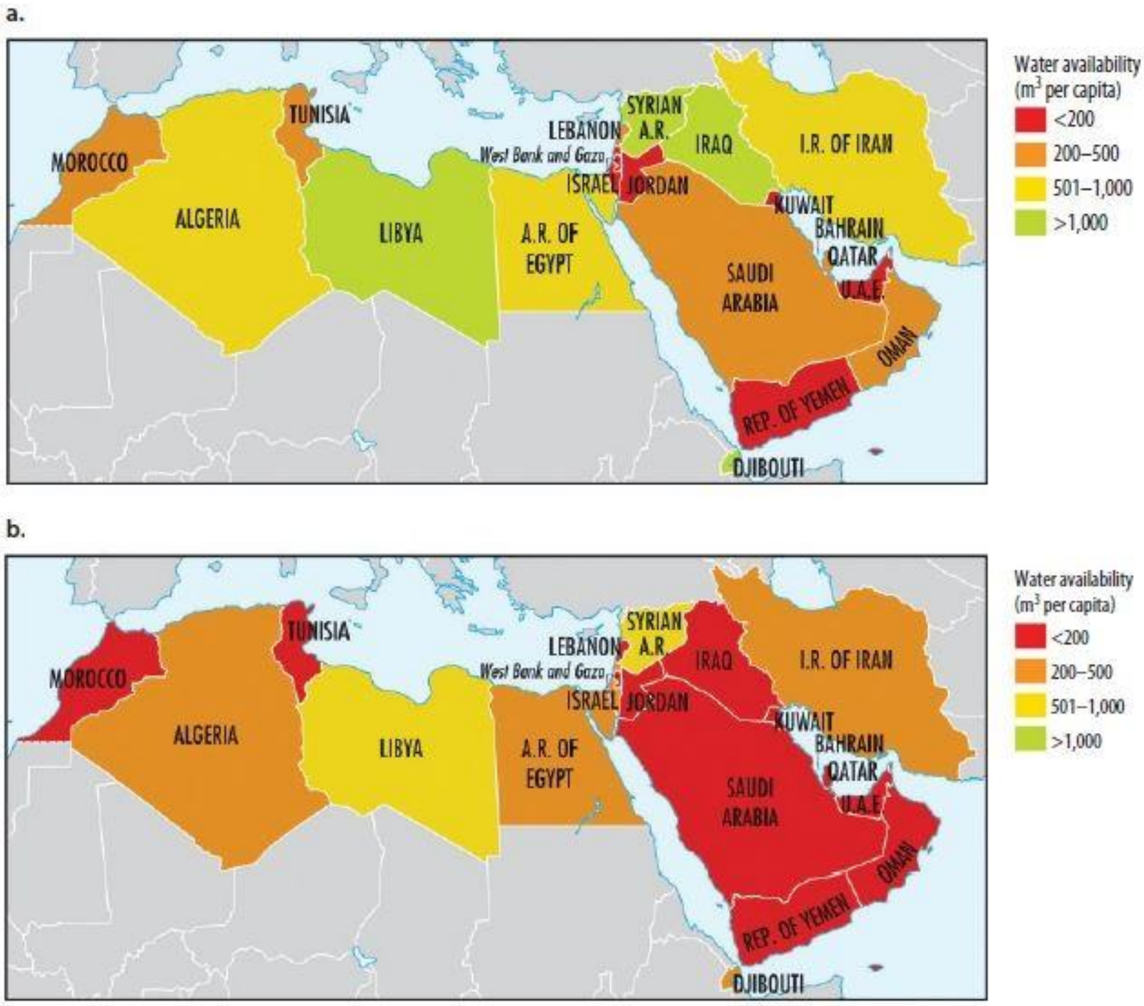


**Fig.1**.a. Average water stress by country, 2000–09
b. Average water stress by country, 2020–30

| | |
|---|---|
| E | rate of evaporation |
| F | heat flux |
| G | conducted heat |
| H | flux of sensible heat |
| N | change in the energy stored |
| Rg | global irradiance |
| Tb | temperature of the arbitrary base |
| Ts | temperature of the evaporated water |
| X | total cost of floating PV system |
| Y | total annual cost saving of PV system |
| $\lambda$ | latent heat of vaporization |
| $\beta$ | Bowen ratio |

In this study, a dual-purpose FPVP was found to produce zero-emission electricity as well as prevent high surface-water evaporation within 15-Khordad dam's reservoir in Delijan.

## 2. Location specification

15-Khordad dam is located in Delijan city, Markazi province, Iran. It is situated on the 33°59 N latitude. It channels the water drained from the Golpaiegan basin to this city. The dam's useful water volume is 165 million cubic meter with an estimated total surface area of 1.59 $km^2$. With the average daily insolation of 5 $kWh/m^2$, Delijan is a suitable place to harvest clean solar energy by means of PV systems. On the other hand, the water reservoir suffers from high surface evaporation, mainly due to solar irradiation, which leads to degradation of its water quality. Hence, FPVPs can guarantee electricity production and the prevention of surface-water vaporization of reservoirs in arid and semi-arid areas like Delijan.

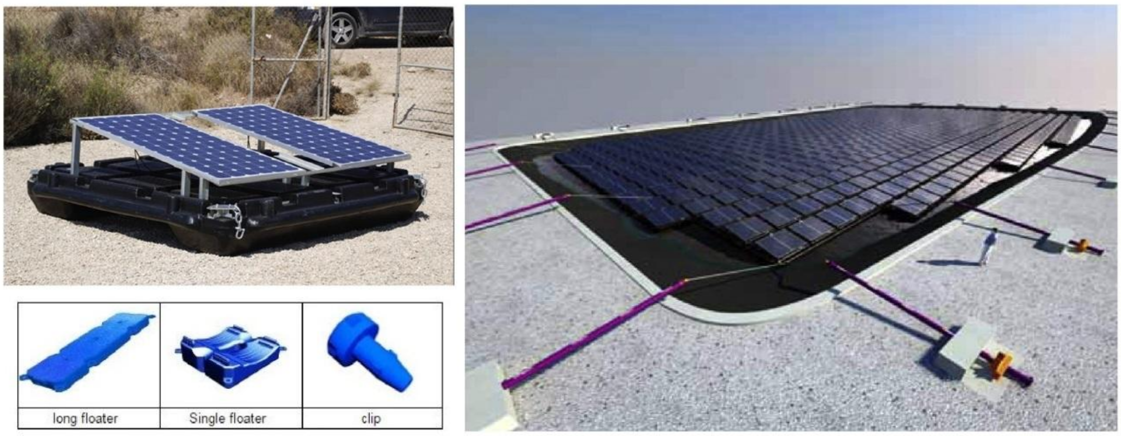


**Fig.2.** Components of an FPVP retrieved from Ferrer-Gisbert et al. [4]

## 3. System design requirement

The FPVP is a new concept. No commercial deployments have been made and only a few demonstrator projects have been undertaken worldwide (Trapani et al. [5]). From the structural point of view, the system consists of the following principal elements (Fig. 2):

- Floating platform (pontoons) and clips: These guarantee the buoyancy and stability of the electricity-generating system. These are made from MDPE by rotational moulding. Each platform supports two PV panels. Flexible couplings and clips allow the pontoons to move in relation to one another so that the system can adapt to different water levels.
- PV module support structure: This must be able to withstand the weight of the PV modules and transmit wind forces across the pontoons to the anchoring system at the perimeter.
- Solar PV module: This is a mono-crystalline PV with an area of 1.643 $m^2$ containing 60 cells. The maximum nominal power of the module is 250 $W_{DC}$ and the nominal efficiency is claimed to be 15.2%. Nearly all metals corrode over time. Hence, alternatives to standard aluminium frames and mounts, such as polymer-made frames, are needed.
- Inventers, cables, and connectors: Electricity is drawn from the solar array and transported to land. High temperature resistance, and robust, waterproof cables and junction boxes have to be used to provide long service. The proposed FPVP has three converters with maximum direct current power of 500 kW each.

## 4. The energy budget method

In this paper, the energy budget method was used to calculate the rate of evaporation from the water surface. This approach estimates the evaporation from a waterbody as the energy component needed to close the energy budget when all the remaining components of the budget of the waterbody are known, that is, it is the residual component (Finch and Calver [6]). The energy associated with evaporation is of two categories: first, the amount of heat to convert liquid water into water vapour (vaporization) and, second, the energy of the water vapour molecules carried from the waterbody (advection). The evaporation rate based on the energy budget for a waterbody is given by:

$$E = \frac{R_g + N + F_{in} - F_{out} + F_P - G}{\lambda\,(1+\beta) + c\,(T_s - T_b)} \qquad (1)$$

where $E$ is the evaporation rate in mass units. In Eq.1, the Bowen ratio ($\beta$) is defined as the ratio between the sensible and latent heat fluxes, which can be expressed as:

$$\beta = \frac{H}{\lambda\,E} \qquad (2)$$

where $H$ is the flux of sensible heat (the energy used to warm the atmosphere in contact with the water, which is then convected upwards). Over the oceans, the ratio varies from 0.1 in low latitude to 0.45 at $70°N$ and 0.23 at $70°S$ based on the study of J M Lewis [7]. Consequently, the estimated value of the Bowen ratio for Delijan dam was set to 0.15.

By suitable selection of an averaging period, it is sometimes possible to neglect the $F_{in}$, $F_{out}$, and $G$ terms. Indeed usually, the energy content of a waterbody is chiefly governed by the exchange of energy through the surface rather than the inflows and outflows and the water–substrate interface (Henderson-Sellers [8]). In the case of this study, the volumes of water flowing in and out of the waterbody were small compared to the overall volume and the temperatures were close to the temperature of the waterbody. Thus, the last five terms in the numerator of Eq.(1) can often be neglected. Finally, if $T_s$ would be equal to $T_b$, the energy budget was given by what is called the "reduced energy budget equation":

$$E = \frac{R_g}{\lambda(1+\beta)} \quad (3)$$

## 5. Saved-water audit

Based on the energy budget method and equations described in the previous section, the volume of the water saved monthly due to the FPVP on 15-Khordad dam's reservoir was calculated over a year (Table 1 and Fig.3). It is worth mentioning that two months, December and January, were excluded mainly due to the amount of precipitation and low ambient temperature. As it was expected, the calculations demonstrated that during June and July, the rate of evaporation was the maximum and, consequently, the volume of water saved increased significantly.

The amount of water prevented from evaporation annually by covering only 31,565 m$^2$ (2%) of the reservoir surface is 16,500 m$^3$.

**Table 1.** Monthly average $R_g$ value, rate of evaporation, and water saved for Delijan

| Month (Jan & Dec are excluded) | $R_g$ (W/m$^2$) | $E$ (kg/m$^2$s) | Saved Water (m$^3$) |
|---|---|---|---|
| February | 141.5 | 5.13E-05 | 1050 |
| March | 198.2 | 7.18E-05 | 1470 |
| April | 241.8 | 8.76E-05 | 1790 |
| May | 264.5 | 9.58E-05 | 1960 |
| June | 296.3 | 1.07E-04 | 2200 |
| July | 294.5 | 1.07E-04 | 2180 |
| August | 258.5 | 9.37E-05 | 1920 |
| September | 222.3 | 8.05E-05 | 1650 |
| October | 174.6 | 6.33E-05 | 1290 |
| November | 133.3 | 4.83E-05 | 988 |
| **Total** | | | **16500** |

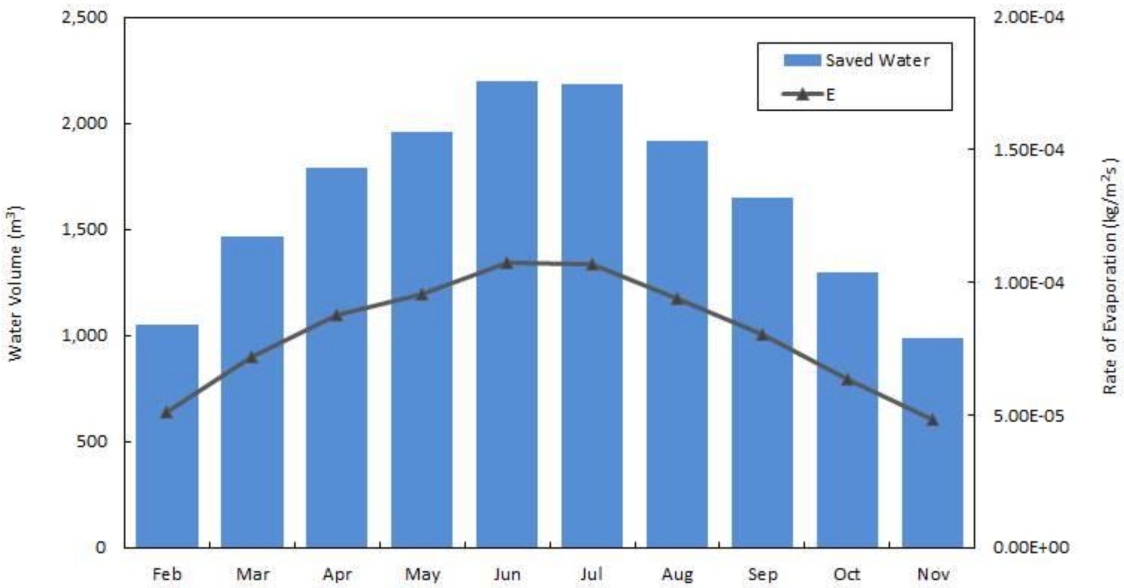


**Fig.3.** Estimated evaporation rate and water saved in some months of a year

## 6. Energy production and carbon footprint assessment

The dynamic simulation of the solar system is carried out using the System Advisor Model (SAM) software, which defines the eliminate it hourly output data of the solar field and a close view of an arbitrary week in late May and the beginning of June (Fig.4). The desired PV field output is set to 1.45 MWe with a total module area of 9,513 $m^2$ and DC-to-AC ratio of 1.10. The PV array orientation is set to face the south, and the optimum tilt angle of 30 is selected based on the latitude of Delijan city. In all, 386 strings in parallel and 15 modules per string form the PV field. The monthly energy production of the plant and POA solar irradiation are represented in Table 2. The system annual output is 2,831,196 kWh (including losses), and the performance ratio and capacity factor values for the plant are 0.81 and 18.7% respectively.

**Table 2.** FPVP energy production for a year

| Month | POA total radiation ($kWh/m^2$) | System energy (AC)(kWh) |
|---|---|---|
| January | 137 | 172493 |
| February | 122 | 150572 |
| March | 175 | 212521 |
| April | 183 | 215014 |
| May | 187 | 214972 |
| June | 195 | 217934 |
| July | 204 | 225343 |
| August | 195 | 217531 |
| September | 183 | 207311 |
| October | 168 | 198977 |
| November | 142 | 174012 |
| December | 131 | 164783 |
| **Total** | | **2,831,196** |

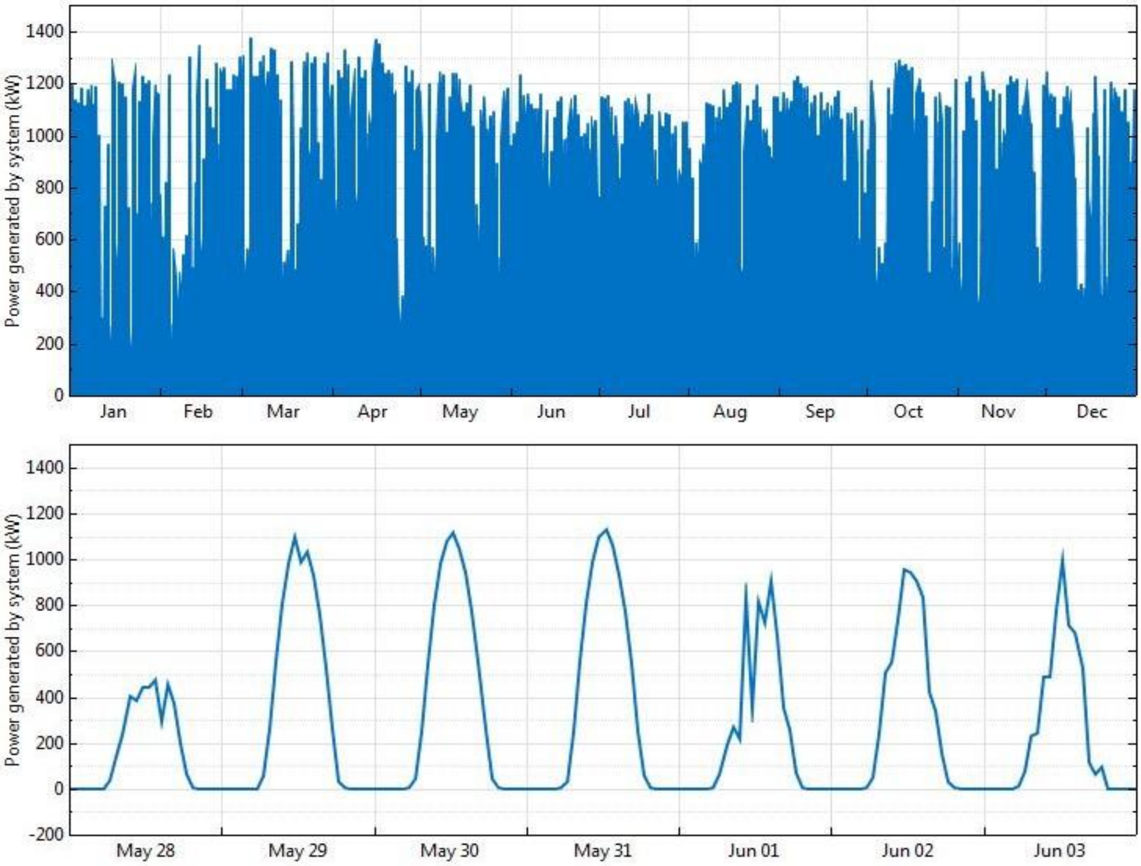


**Fig.4.** Annual time series of power generated by the system (including one arbitrary week in detail)

To assess the environmental improvements provided by the FPVP, this section performs a first approach by means of the carbon dioxide equivalent emissions. The key distinguishing element of the FPVP is that besides the quantification of the potential net loss of $CO_2$ from the installation of renewable energy technology, the environmental effects of reducing water evaporation must also be considered in the $CO_2$ balance.

According to the International Energy Agency (IEA) [9], the $CO_2$ emissions from the generation of a kW in Iran were at 536 gram $CO_2$/kWh for 2009. Thereby, the potential $CO_2$ saved by the FPVP for a service life of 20 years reaches 25,598.8 t for a given year, depending on the water sources. An average estimate of 1 kWh/$m^3$ is used for the water reservoir in this study. Therefore, the energy saved from the reduction of water evaporation, calculated for the lifetime of the project, resulted in a value of 26,204.5 t $CO_2$.

Table 3 presents the list of processes that emit $CO_2$ during manufacturing, installation, and transportation of conventional PV arrays (Trapani and Millar [10]).

In addition to the data summarized in Table 3, the FPV technology must record the carbon footprint of the polymeric floating module. The embodied carbon for the size of the floating module resulted in a value of 23.1 kg $CO_2/m^2$. Finally, the total carbon footprint of the FPV installation reached 137.7 kg $CO_2/m^2$, which, for the whole PV field, resulted in $CO_2$ emissions of 1819.6 t.

The calculation of the $CO_2$ balance over the lifetime of the FPVP, set at 20 years, enables us to conclude a carbon saving of 42,593.8 t $CO_2$.

## 7. Economic viability and payback period calculation

Table 4 illustrates the economic viability of the proposed FPVP. The total cost of the

**Table 3.** Embedded carbon in monocrystalline installations

| Process | Mono-crystalline PV (kg $CO_2/m^2$) |
|---|---|
| Manufacturing process | 51.1 |
| PV panels | 20.1 |
| Inverter | 2.3 |
| Balance of system (BOS) | 2.3 |
| Capital inputs | 18.4 |
| Structural support | 19.9 |
| Transportation | 0.53 |
| **Total** | **114.63** |

**Table 4.** An estimation of the entire system cost

| Concepts | Values |
|---|---|
| Cost estimation: floating system | |
| Total floating module (€/$m^2$) | 35 |
| Power (Wp/$m^2$) | 97 |
| Cost estimation: foundation & elastic joints | |
| Elastic joints (€/Wp) | 0.05 |
| Pilot foundation (€/Wp) | 0.07 |
| Foundations + elastic joints (€/Wp) | 0.11 |
| Total floating system (€/Wp) | 0.59 |
| Cost estimation: PV installation & electrical equipments | |
| Inventers (€/Wp) | 0.12 |
| PV panels (€/Wp) | 0.65 |
| Wiring (€/Wp) | 0.03 |
| Monitoring (€/Wp) | 0.02 |
| Security system (€/Wp) | 0.04 |
| Engineering (€/Wp) | 0.05 |
| Health and safety (€/Wp) | 0.02 |
| Quality control (€/Wp) | 0.01 |
| Total PV installation (€/Wp) | 0.94 |
| **Total Cost FPVP (€/Wp)** | **1.53** |

FPVP, including the floating system, PV installation, electrical equipment, and foundation is estimated to be 1.53 (€/Wp).

The payback period can be defined as:

$$Payback\ period = \frac{X}{Y} \tag{4}$$

where $X$ and $Y$ are the total cost of the FPV system with all auxiliary equipment, and the total annual cost savings after the installation of the PV system respectively. The annual energy production of the plant is 2,371,456 kWh. Iran's Ministry of Power guaranteed a revenue of 0.15 (€/kWh) for 20 years for this project. With 10% of the total revenue covering the plant's expenditures, the payback period becomes 10.2 years. Although the payback period is almost doubled in the case of the FPVP, the annual amounts of saved water and $CO_2$ are significant enough to make the system interesting for Middle Eastern countries suffering from water shortage.

## 8. Conclusion

Technical and economic analysis has shown the technical feasibility of the FPVP concept in Delijan, Iran. The study demonstrated that the FPVP on 15-Khordad dam's water reservoir generates 2,371,456 kWh/year of renewable energy while saving 16,500 $m^3$ of water annually. In short, the results from the calculations are highly satisfactory in meeting the main objectives of the study: near-zero-emission electricity generation and saving water from intense evaporation. The annual PR of 0.81 is also a very promising value. Additionally, significant $CO^2$ savings calculated over the lifetime of the FPVP stress the environmental benefits. By exploring Iran's potential to generate solar energy, it can be concluded that solar energy will play an increasingly important role in Iran's energy basket in future. That is because reducing the dependence on fossil fuels and addressing environmental issues are turning into serious debates within the country.

In short, there is great potential for the installation of floating solar-panel electricity-generating plants to improve the water and energy balances in arid and semi-arid zones with limited water resources, as it is the case in most of the central and southern regions of Iran.

## References

[1] Based on IEA Data from [CO2 Emissions from Fuel Combustion] © OECD/IEA[2016], www.iea.org/statistics,Licence: www.iea.org/t&c.

[2] Immerzeel W.W., Droogers P., Terink W., Hoogeveen J., Hellegers P., Bierkens M., Van Beek R., Middle-East and Northern Africa Water Outlook. World Bank Study, FutureWater Report 98(2011).

[3] Arun Kumar V., Rashmitha M., Naresh B., Bangararaju J., Rajagopal V., Performance Analysis of Different Photovoltaic Technologies. In, Proceedings of the 2013 International Conference on Advanced Electronic Systems(ICAES) (2013) 978-14799–1441-8/13/$31.00 © IEEE.

[4] Ferrer-Gisbert C., Ferrán-Gozálvez J., Redón-Santafé M., Ferrer-Gisbert P., Sánchez-Romero F.J., A New Photovoltaic Floating Cover System for Water Reservoirs, Renewable Energy (2013) 60:63-70.

[5] Trapani K., Millar Dean L., Smith H., Novel Offshore Application of Photovoltaic in Comparison to Conventional Marine Renewable Energy Technologies, Renewable Energy (2013)50:879-888.

[6] Finch J., Calver A., Methods for the Quantification of Evaporation from Lakes, Oxfordshire,OX10 8BB UK (2008).

[7] Lewis J. M., The Story Behind the Bowen Ratio, National Severe Storms Laboratory, Norman, Oklahoma (1995) 76(12).

[8] Henderson-Sellers B., Calculating the Surface Energy Balance for Lake and Reservoir Modeling, A Review, Reviews of Geophysics (AN AGU JOURNAL) (1986) 24(3): 625–649.

[9] Based on IEA Data from [CO2 Emissions from Fuel Combustion] © OECD/IEA[2009], www.iea.org/statistics, Licence: www.iea.org/t&c.

[10] Trapani K., Dean L., Proposing Offshore Photovoltaic (PV) Technology to the Energy Mix of the Maltese Islands, Energy Convers Manage (2013)67:18-26.

## Appendix A. System loss diagram

The loss diagram of the proposed floating PV plant is presented below to address the energy balance of the entire system. Assumed losses are illustrated specifically for each section and finally, the annual energy of the system is calculated accordingly.

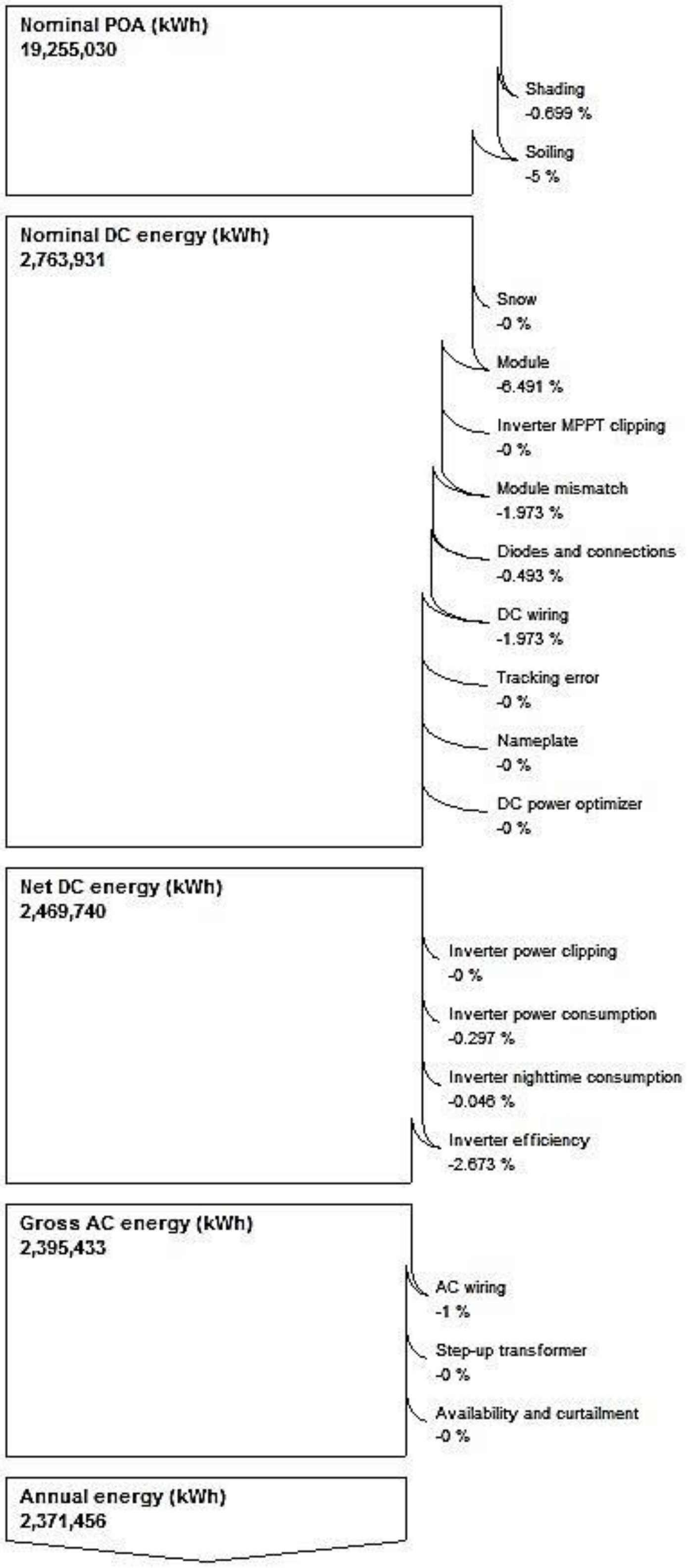


**Fig.A.1.** FPVP loss diagram