



Utilization of Solar PV Panel Arrays for Supply Part of Main Pumps Power Demand in a Typical Pumped Storage Hydro Power Plant

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Abstract

The small and medium scale pumped storage hydro power plants are very useful manner of power generation for safe supply of extra electrical power demand of some urban and rural areas during peak hours in many under development countries. But the electric power consumption of the main transfer pumps of these power plants, which usually work continuously about 12~16 hours on a daily basis, is a considerable amount of electric power that is usually supplied via the national cross country electrical power grid network. Usually, renewable energy sources utilization are more economic in "Hybrid" combination with other conventional electric power sources in under development countries. Otherwise, they have not significant chances to be utilized and effectively developed in these countries.

In this paper, a typical 1040 MW nominal capacity pumped storage hydro power plant, with a total main pumps power consumption of about 50 MW is studied for seeking opportunity for supply part of their electrical power demand via hybrid power generation of a series of solar PV panels (i.e., a small solar PV power plant) and simultaneous electrical power get from national cross-country power grid network.

This study resulted that about 12% of the main pumps power demand can be generated via a suitable design and proper arrangement of series of solar PV panel arrays.

Keywords: Pumped Storage; Hydro-Power Plant; Solar PV; Power Demand; DC; AC; Capital Investment Payback Period (IPP); Million Tons Oil Equivalent (MTOE).

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1. Introduction

Indeed, any successful sustainable power generation project shall include following criteria:

- Avoiding "Mega-Projects" which destroy the environment
- Insisting on "Discrete Power Generation" projects
- Implementing "Renewable Energy Resources" as far as applicable, especially in "Hybrid" and "Co-generation" systems
Meantime, the industry shall:
- Develop and produce "Energy Efficient"

products for society, and remove the old technology non-efficient systems & products

- Discover and make use of any proper opportunity for energy conservation purposes

In all of the above tasks, the "Conservation of Environment" shall be considered as the governing factor.

In this paper, a typical pumped storage hydro-power plant is studied for preliminary feasibility estimation to supply about 12% of its power demand of main pumps through construction of a solar PV power plant. The Siah Bishe pumped storage power plant is located at 36°13'04"N and

51° 18' 18" E in 125 km north of Tehran, as the aerial view shown in Fig.1.

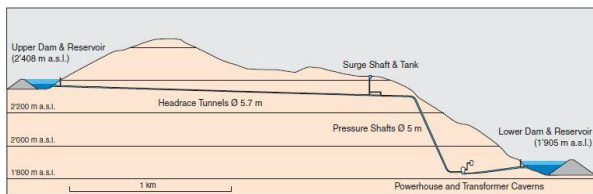


Fig. 1: Siah Bisheh Pumped Storage Power Plant.

The general specifications of Siah Bisheh pumped storage power plant is as following (Colenco Power Eng. AG, 2010):

- Upper Dam & Reservoir: Concrete Faced Rock fill Dam, Height 85 m,
- Crest Elevation +2410.14 m a.s.l.
- Dam Volume 1.4 million m³
- Reservoir live volume: 3.5 million m³
- Headrace Tunnels: Two Tunnels: L = 2015 m and 1973 m, Ø = 5.70 m, concrete lined
- Surge Tanks: one for each tunnel, surge range = 87 m
- Tanks: 2 x 23 m deep, 20 m wide, circular concrete tank
- Shafts: 2 x 65 m deep, Ø 6.5 m vertical shafts, concrete lined
- Pressure Shafts: Two Shaft: L = 2 x 760 m, Ø = 5 m, steel lined
- Shaft inclination 67°
- Design Flow: 2 x 130 m³/s in turbine operation
- 2 x 100 m³/s in pump operation
- Gross Head: Max. 520.8 m, Min. 470.8 m
- Powerhouse Cavern: L = 130.0 m, W = 22.0 m, H = 42.9 m
- 4 vertical Francis Turbines
- Turbine rated output: 4 x 260 MW = 1040 MW
- Transformer Cavern: L = 198 m, W = 14 m
- 4 connecting bus-bar galleries and vertical shafts
- Tailrace Tunnels: 2 tunnels Ø 6.0 m, concrete lined
- Lower Dam & Reservoir: Concrete Faced Rock fill Dam, Height 106.5 m
- Crest Elevation 1911.50 m a.s.l.

- Dam Volume 4.93 million m³
- Reservoir live volume: 3.6 million m³
- Construction Period: 2003 – 2009
- Estimated Construction Cost: 380 Million USD

The nominal peak capacity of this power plant is 1040 MW_e, and the electric power consumption of main water transfer pumps is about 50 MW_e. Although this may be about 5% of the nominal generated electric power of this plant, it may be more economic if a definite part of this consumed power can be supplied from a renewable power source, such as solar PV arrays. This means using a hybrid power generation system will be a proper reasonable approach to assist development of renewable sources of energy. Also, it bears in considerable saving of fossil fuels which are used in thermal power plants in somewhere to generate electricity, which a small part of it provides the power demand of main pumps of Siah Bishe pumped storage hydro-power plant. So, it causes to decrease greenhouse gases emission to the atmosphere, too.

The subject of “hybrid” power generation in Siah-Bisheh pumped storage hydro-power plant has been studied first time overall by Kalantari and et al. (Kalantari, et al, 2019, 5). This study indicates the Siah-Bisheh pumped storage hydro-power plant has a potential of saving energy for various combinations of energy feed. This means, it can save an amount of 158.658 MTOE for hybrid power generation with wind power, 274.335 MTOE with hybrid power generation with combined wind & solar PV power generation, and 115.677 MTOE with hybrid power generation with solar PV.

After this study, there was no major research study published in this field.

2. Design Basis

Fixed tilt ground mounted flat solar PV modules, having average efficiency of 19% will be considered as the design basis. Also, the geographic latitude of 36° N will be considered for calculation of total solar gain. The inverter efficiency for conversion of solar PV panel’s generated DC power to needed AC power is assumed to be 92%; this means the power loss of the conversion will be 8%.

Since the power consumption of the main pumps is 50 MW_e, we set the goal power generation capacity of the solar PV power plant as 12%, i.e., 6 MW_{AC}. Therefore, the nominal DC power generation capacity will be 6.52 MW_{DC} ≈ 6.6 MW_{DC}. This sets our design power capacity for

solar PV power plant.

2-1. Calculations

Case 1: Conservative Design Approach

Regarding the latitude of 38N, and assuming 50 ° inclination of PV panels to horizon, the mean total solar heat gain per square meter is given on a daily basis in Table 1 (Lunde, Peter J., 1980).

The above solar heat gain values are given for atmospheric clearance of 1.0. In order to have a realistic assumption, we assume the mean annual atmospheric clearance coefficient at site location be equal to 0.88. On the other hand, since the site is located at a mountainous area about 2500 meters above sea level, the availability of solar PV panels to generate electric power at 6 months of fall and winter is assumed to be 85%. It means, during these seasons the solar PV power plant generates about 25.5 days per month. As per Table 2, this will result the annual mean daily solar radiation gain at project site be equal to 19.0883 MJ/m².

Therefore, the actual average daily solar radiation gain per unit area (m²) for a panel surface with 50 ° inclination to horizon at site area will be obtained as shown in Table 2.

It is assumed the main pumps operate 12 hours daily. Since the needed total power demand for solar PV power plant is 6.6 MW_{DC}, the approximate net area solar PV panels will be about:

$$S = \frac{6.6 \times 12 \times 3600}{19.0883 \times 0.19} = 78615.5 \text{ m}^2$$

Each solar PV module has an overall surface of 1.99 m². Therefore, the needed quantity of solar PV modules is equal to:

$$78615.5 \div 1.99 = 39505$$

As the well-known rule of thumb, the approximate needed ground area for installation and utilization

of 47108 No's of 2.2 m² (and net surface area of 1.99 m²) solar PV panels will be equal to:
 $2 \times 39505 \times 2.2 = 173822 \text{ m}^2$

2-1-1. Economic Analysis

The 6.6 MW_{DC} solar PV power plant with a module efficiency of 19% construction costs consist of:

- Module price (NREL Report, 2022): Assuming \$0.30 /W_{DC}, it will be about 2'437'380 \$.
- Inverter price: Assuming \$0.048/W_{AC}, it will be about 389'981 \$.
- Structural fixed supports: Assuming \$8/m²_{panels}, it will be about 628'924 \$.
- Electrical works: Assuming \$10/ m²_{panels} + \$73'000, it will be about 937'455 \$.
- Installation rental equipment: Assuming \$4/m², it will be about 829'101 \$.
- Direct installation labor: Assuming 1 \$/m² for all civil works, and 4 \$/m² for all electrical works, it will be about: 1'036'376 \$.
- Sum of taxes, contingency, and overhead costs: it would be about 750'000 \$.
- Construction permit fees, inter-connection, testing and commissioning costs: Assuming \$0.02/W_{AC} + \$ 209'466, it will be about 332'566 \$.
- Transmission line: Assuming \$260'000/mile, for 1.72 miles of this plant, it will be equal to 448'084 \$.
- Developer overhead costs: will be about \$800'150.
- Therefore, the total estimated construction costs for this 6.6 MW_{DC} solar PV power plant is equal to: 8'590'017.

**Table 1. Mean total daily solar radiation gain
(The mean monthly value is equal to 23.5016 MJ/m²)**

Month/ Total Solar Heat Gain	Jan.	Feb.	Mar.	Apr.	May	June
MJ/m ²	23.06	25.17	25.94	24.19	22.36	21.29
Month/ Total Solar Heat Gain	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
MJ/m ²	21.64	23.13	24.87	25.10	23.34	21.93

**Table 2. Mean actual daily solar radiation gain
(The design mean monthly value will be equal to 19.0883 MJ/m²)**

Month/ Total Solar Heat Gain	Jan.	Feb.	Mar.	Apr.	May	June
MJ/m ²	17.25	18.83	19.40	21.28	19.67	18.73
Month/ Total Solar Heat Gain	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
MJ/m ²	19.04	20.35	21.88	18.77	17.46	16.40

The current tariff of Iran Energy Ministry for purchase of renewables generated electricity is about \$0.0625/kWh_{AC}. This means, for 5 MW_{AC} solar PV generated electric power of about 6 hours daily utilization, it will be equal to:

$$5000 \times 0.0625 \times 6 = 1875 \text{ \$/day}$$

And annually will be about:

$$1875 \times 365 = 684375 \frac{\$}{\text{year}}$$

It simply means that by construction a 6.6 MW_{DC} solar PV power plant with a module efficiency of 19%, the capital investment payback period would be about:

$$IPP = 8590017 \div 684375 = 12.5 \text{ year}$$

Therefore, this project will be economically feasible and it will be a reasonable project to plan and execute it.

Regarding the local site conditions, it would be necessary to design and install automatic or semi-automatic solar PV panels washing/ cleaning system. This would avoid due solar PV panel fouling power losses, which usually is about 10%. By doing this, the capital investment payback period would be a little more than 150 months, say 180 months, which is still economically feasible project. A typical washing/ cleaning system is shown in Fig. 2.



Fig. 2. A semi-automatic solar pv panel washing/ cleaning machine.

Also, regarding the site mountainous area, it would be preferred to construct the solar PV power plant in a trapezium layout, as is shown in Fig. 3.

It would be better to limit the maximum ground slope of solar PV power plant to 18-20°, in order to avoid extra costs of structural steel supports construction and installation. Otherwise, the construction and installation costs of structural

steel supports of the solar PV arrays will be increased considerably.



Fig. 3. A trapezium layout of solar pv panels.

Case 2: PVSYST Software Design Approach

A preliminary design of this solar PV power plant is also run in PVSYST Software. The brief results of this preliminary design are shown in Fig. 4.

It is observed that there is a definite discrepancy between the calculations and the output of PVSYST software. This discrepancy, which has caused to increase the size, and apparently, the construction costs of the solar PV plant is due to our conservative assumptions. At first, we imposed a reduction of 0.12 on the atmospheric clearance factor, as mentioned in clause 2.1. Indeed, this can be considered as an excessive conservative assumption because actually in elevations above 1000 meters from sea level, the net solar energy gain flux per unit area will be considerably more than the values presented for sea level. The second conservative parameter introduced in our calculations is the “availability” of the solar PV plant. We have assumed that in six months of year the availability of plant (see clause 2.1) is reduced to 85%. Therefore, the average mean daily solar energy gain value is reduced from 23.5016 MJ/m² to 19.0883 MJ/m², i.e. a 19% reduction. The result of superposition of these two factors: 0.19 + 0.12 = 0.31 %, which is exactly in compliance with the obtained results. In addition, the efficiency of the solar PV panels was assumed as 19%, instead of the existing norm value of 21%. Some may believe these conservative assumptions will result an “over-design” of the size and construction costs of this solar PV plant.

For this case, if we follow the analysis result of PVSYST software, we have to reduce the total surface of solar PV panels to about 63’852 m², and quantity of the required solar PV panels will reduce to 32’086 cells. The total needed ground area will be about 141’178 m².

The total construction costs of this solar PV plant will be reduced to about 7 million USD, and a capital return payback period of 10 years, which is in compliance with the common construction costs of solar PV plants in this scale.

It is assumed the main pumps operate 12 hours daily. Since the needed total power demand for solar PV power plant is 6.6 MW_{DC}, the approximate net area solar PV panels will be about:

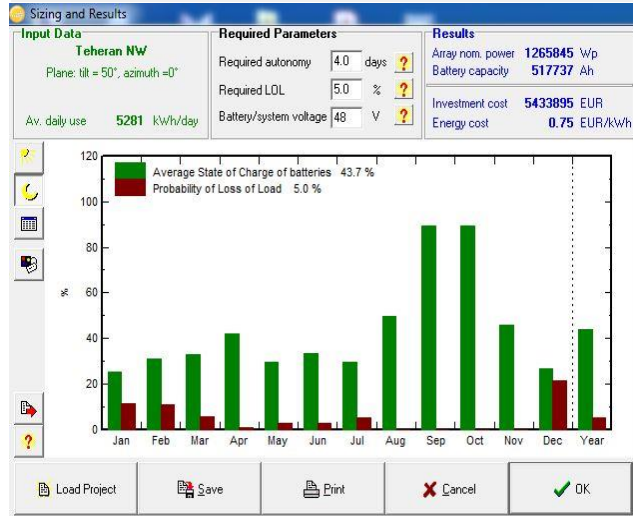
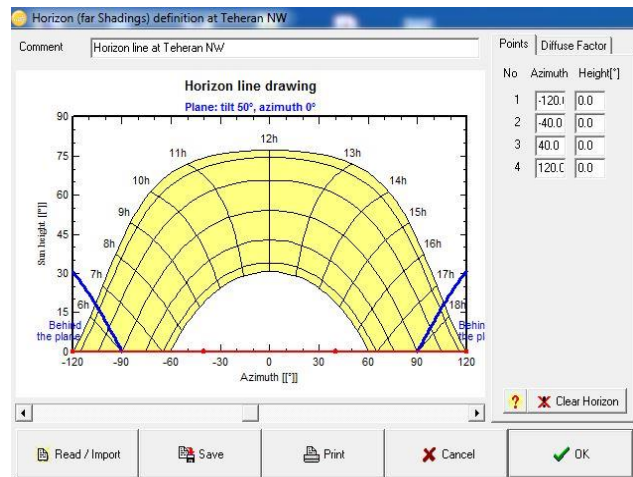
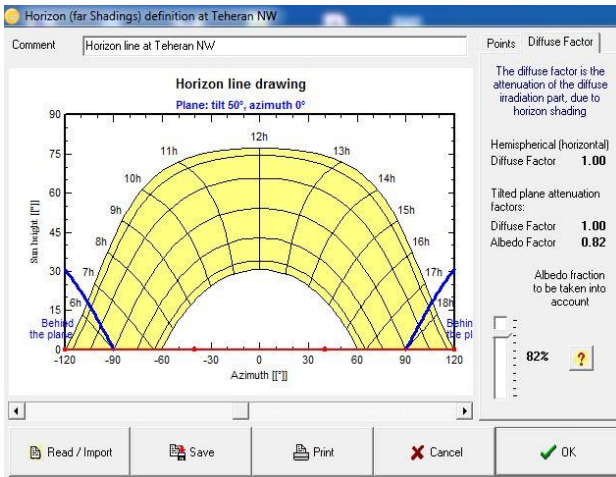
$$S = \frac{6.6 \times 12 \times 3600}{23.5016 \times 0.19} = 63852 \text{ m}^2$$

Each solar PV module has an overall surface of 1.99 m². Therefore, the needed quantity of solar PV modules is equal to:

$$63852 \div 1.99 = 32086$$

As the well-known rule of thumb, the approximate needed ground area for installation and utilization of 47108 No's of 2.2 m² (and net surface area of 1.99 m²) solar PV panels will be equal to:

$$2 \times 32086 \times 2.2 = 141178 \text{ m}^2$$



Sizing and Results

Input Data: Teheran NW, Plane: tilt = 50°, azimuth = 0°

Required Parameters: Required autonomy 4.0 days, Required LOL 5.0%, Battery/system voltage 48 V

Results: Array nom. power 1265045 Wp, Battery capacity 517737 Ah, Investment cost 5433895 EUR, Energy cost 0.75 EUR/kWh

	Incid.	PV avail.	Demand	Excess	Missing	SOC	Pr. LOL	Fuel
	kWh/m ² .day	kWh	kWh	kWh	kWh	%	%	liter
Jan.	5.2	162173	163708	0.0	18853.	25	11.5	12569.
Feb.	5.5	154655	147865	0.0	15794.	31	10.7	10529.
Mar.	5.6	172724	163708	0.0	8722.5	33	5.3	5815.0
Apr.	5.6	171619	158427	0.0	801.3	42	0.5	534.2
May	5.6	174616	163708	0.0	4472.9	30	2.7	2961.9
June	5.7	172109	158427	0.0	4408.0	33	2.8	2938.6
July	5.6	177163	163708	0.0	8301.8	29	5.1	5534.5
Aug.	6.2	193085	163708	0.0	0.0	50	0.0	0.0
Sep.	6.5	198541	158427	12335.	0.0	89	0.0	0.0
Oct.	5.9	184671	163708	11061.	0.0	89	0.0	0.0
Nov.	5.5	167408	158427	0.0	0.0	46	0.0	0.0
Dec.	4.7	148229	163708	0.0	32343.	26	21.4	21562.
Year	5.6	*81750	*27534	23396.	93698.	44	5.0	62465.

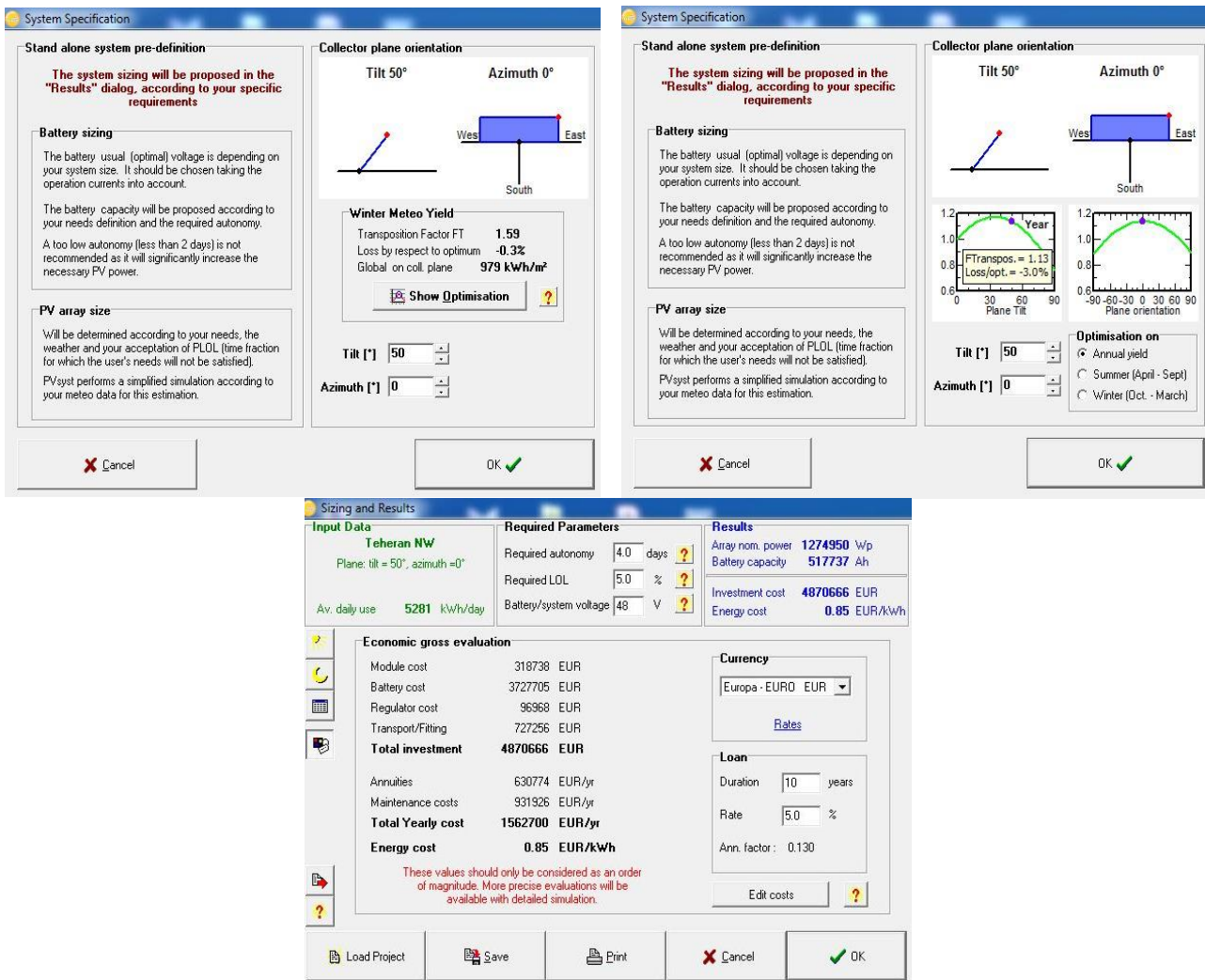


Fig. 4. PVSYST Software Preliminary Design Output.

2-1-2. Economic Analysis

The 6.6 MW_{DC} solar PV power plant with a module efficiency of 19% construction costs consist of:

- Module price (NREL Report, 2022): Assuming \$0.30 /W_{DC}, it will be about 1'980'000 \$.
- Inverter price: Assuming \$0.048/W_{AC}, it will be about 316'800 \$.
- Structural fixed supports: Assuming \$8/ m²_{Panels}, it will be about 510'816 \$.
- Electrical works: Assuming \$10/ m²_{Panels} + \$73'000, it will be about 711'520 \$.
- Installation rental equipment: Assuming \$4/m², it will be about 564'712 \$.
- Direct installation labor: Assuming 1 \$/m² for all civil works, and \$4 \$/m² for all electrical works, it will be about: 705'890 \$.
- Sum of taxes, contingency, and overhead costs: it would be about 550'000 \$.
- Construction permit fees, inter-connection, testing and commissioning costs: Assuming \$0.02/W_{AC} + \$ 209'466, it will be about 341'466 \$.

- Transmission line: Assuming \$260'000/mile, for 1.4 miles of this plant, it will be equal to 364'000 \$.
- Developer overhead costs: Assuming \$650'000.
- Therefore, the total estimated construction costs for this 6.6 MW_{DC} solar PV power plant is equal to: 6'695'204 \$.

The current tariff of Iran Energy Ministry for purchase of renewables generated electricity is about \$0.0625/kWh_{AC}. This means, for 5 MW_{AC} solar PV generated electric power of about 6 hours daily utilization, it will be equal to:

$$5000 \times 0.0625 \times 6 = 1875 \text{ \$/day}$$

And annually will be about:

$$1875 \times 365 = 684375 \frac{\$}{\text{year}}$$

It simply means that by construction a 6.6 MW_{DC} solar PV power plant with a module efficiency of 19%, the capital investment payback period would be about:

$$IPP = 6695204 \div 684375 = 9.78 \text{ year} \\ = 117 \text{ months}$$

Therefore, this project will be economically feasible and it will be a reasonable project to plan and execute it.

Regarding the local site conditions, it would be necessary to design and install automatic or semi-automatic solar PV panels washing/ cleaning system. This would avoid due solar PV panel fouling power losses, which usually is about 10%. By doing this, the capital investment payback period would be a little more than 117 months, say 144 months, which is still economically feasible project.

3. Conclusion and Recommendations

This study shows that design & construction of a 6.6 MW_{DC} solar PV power plant to supply 12% of electric power demand of main water transfer pumps of Siah Bishe pumped storage hydro-power plant is an economically feasible project, having a capital investment payback period of about 12 years. In this conservative study, both the high class, high grade, high quality (US Origin and European Brands) and high price of main components of solar PV power plant has been selected, and the availability factor of solar PV power plant during autumn and winter has been reduced to 85%. On the other hand, the annual atmosphere clarity coefficient has been assumed as 0.88, which may be seemed somehow low. Also, the power loss in inventor has been assumed as 8%, and the solar PV modules efficiency has been assumed as 19%, while it is about 21% at the existing market. Therefore, this conservative preliminary design may actually yield more electric power to the pumps, and the capital investment payback period be shorter than 12 years. This solar PV power plant is expected to have a lifetime of about 15-25 years, depending on systems quality and the implemented O&M procedures and actions. Proper regular scheduled & random inspection of the solar PV panels and other main equipment of this solar PV power plant is extremely important, in order to avoid any probable technical failure of solar PV panels, or intrusion of broken parts of solar PV panels in to soil and pollute the site ambient soil & environment. Although the site may have a good potential for Wind Turbine project, regarding the site mountainous location and difficulty to take appropriate scheduled necessary maintenance operations, using Wind Energy Converter (Wind Turbine) is not recommended for this site.

On the other hand, the environmental impacts of the construction of this solar PV plant shall be

exactly analyzed by due engineering teams and taken in to consideration adequately. Most of the land used for larger utility-scale solar facilities, depending on their location, can raise concerns about land degradation and habitat loss. This is the case even if abandoned industrial, fallow agricultural, or former mining sites are used. Total land area requirements vary depending on the technology, the topography of the site, and the intensity of the solar resource. Estimates for utility-scale PV systems range from 14'164 to 40'468 square meters per megawatt, while estimates for Concentrated Solar Power Plants (CSP) facilities are between 16'187 and 66'773 square meters per megawatt (UCS, 2013). Just as with the production of energy from all other sources, in one way or another solar energy production has a water footprint, defined as the total volume of freshwater used to produce energy and the services consumed by the production process.

Water consumption for solar generation varies by technology and location. For our purposes, water consumption is defined as the amount of water that is "evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment" (F. R. Spellman, 6).

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Biography



Aref Mohammadzadeh Novin is a retired senior Mechanical/ Energy engineer. He received his BSc. in mechanical engineering in Feb. 1991 from the central Branch of Islamic Azad University in Tehran, and MSc. degree in Energy Engineering (Renewables Energy) in Feb. 2018 from the Science and Research Branch of Islamic Azad University in Tehran. His total work experience has been about 35 years in various industries. His personal study and research interest field is Renewable Energies and Environment. Some of his previously issued papers are available in Iran Civilica, and abroad in Academia websites.
