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Enhancing the renewable energy payback period of a photovoltaic power generation system by water flow cooling

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ABSTRACT

A photovoltaic system which enjoys water flow cooling to enhance the performance is considered, and the impact of water flow rate variation on energy payback period is investigated. The investigation is done by developing a mathematical model to describe the heat transfer and fluid flow. A poly crytalline PV module with the nomical capacity of 150 W that is located in city Tehran, Iran, is chosen as the case study. The results show that by incresing water flow rate, EPBP declines first linearly, from the inlet water flow rate of 0 to 0.015 kg.s^{-1}, and then, EPBP approaches a constant value. When there is no water flow cooling, EPBP is 8.88, while by applying the water flow rate of 0.015 kg.s^{-1}, EPBP reaches 6.26 years. However, only 0.28 further years decreament in EPBP is observed when the inlet water mass flow rate becomes 0.015 kg.s^{-1}. Consequently, an optimum limit for the inlet water mass flow rate could be defined, which is the point the linear trend turns into approaching a constant value. For this case, as indicated, this value is 0.015 kg.s^{-1}.

Keywords:
Efficiency improvement way; Energy payback period; Parametric study; Photovoltaic (PV) technology; Water-flow cooling technique

1. Introduction

There is a strong tendency to replace the fossil fuels with renewable energies, which is motivated by the need to have safer, cleaner, and more available supply [1,2]. This reality could necessarily transition our built environment, such as office buildings and residential buildings, towards renewable energy sources [3,4]. As the concept of GEB (Generating Energy Buildings) has now becoming a reality in which a series of innovative technologies such as translucent vacuum insulation panels [5-7], smart vacuum insulated windows [8-25], vacuum-based PV integrated solar thermal collectors [26,27] and cooling mechanism [28], wind & wave energy systems [29], providing access

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and monitoring of the electric vehicles charging [30-34] with integration to microgrid [35] and utilising waste heat into electricity using thermoelectric [36-39] are the progress towards smart cities. It is evident from the aforementioned references that solar thermal energy and insulation technologies are playing major role in achieving the built environment sector towards net-zero energy.

As one of the most popular kinds of renewable energies, solar energy is predicted to play a serious role in the future [40]. However, the concepts of carbon capture-storage and progressive technologies of quantum-dot and organic solar cells and new materials [41,42] are going to speed up the notion of GEB [43]. Still, using PV modules offers a number of huge benefits that makes it favorable worldwide. It originates from the issues like being utilized in different scales, as well as low cost compared to other products to provide the electrical energy [44]. Among different types of PV technologies, the silicone based (Si-based) type is the most available type in the market. The main reason is the low cost of that compared to the other kinds.

Silicon modules typically convert around 20% of solar energy into electricity, and the rest is converted into heat. This heat causes the module temperature to rise. As the module heats up, its performance decreases and its efficiency decreases. Considering this point, cooling solar modules is one of the ways to increase efficiency. One of the common cooling methods is cooling the surface of the module by pouring water. Water has a high heat absorption capacity due to its high heat capacity and further reduces the surface temperature of the module.

The following is the research conducted in this regard:

Javidan and Moghadam [45] investigated the effect of cooling on the photovoltaic module by jet impingement cooling with water-acting fluid. They examined the number of nozzles and their diameters. Finding the optimal conditions, they found that the temperature of the solar module drops from 63.95 °C to 33.68 °C.

Shahverdian et al. [46] used water flow system for cooling the solar module. They optimized the hourly water flow and found that the difference in average cell surface temperature for a cooling system with an optimal flow rate compared to a system with a constant flow rate without cooling in the module was 16.63 °C and 54.07 °C, respectively.

Da Silva et al. [47] investigated the effect of water film cooling on the solar module and found that this method reduces the panel temperature by about 15 to 19%.

Luben et al. [48] Experimentally studied the cooling effect on a 240W polycrystalline module. In this research, cooling has been done by pouring water and also spraying it. The effect of this cooling on current and voltage has been seen.

Kabeel et al. [49] in an experimental study investigated the effect of cooling and using reflector on a photovoltaic solar module. The cooling method in this article is water flow as well as air blower. Experimental results show that the net power for the mode without cooling and using the reflector is 832 $Wh.day^{-1}$ and for the mode with reflector and air blower, with reflector and water flow and for the mode with reflector and air blower and water flow, it is 912, 1077 and 1010 $Wh.day^{-1}$.

Tashtoush and Oqool [50] experimentally investigated the effect of cooling by water flow. In this work, an attempt has been made to keep the temperature of the module at a specific temperature, which in this study is 35 °C, 37 °C, 39 °C, 41 °C, 43 °C and 45 °C, and to examine the amount of water consumption at each of these temperatures and the rate of increase in power.

Maj et al. [51] cooled down a 260 W module by dropping water. For their work, they identified 9 points on the solar module and observed the effect of cooling on the temperature of these points through thermal imaging and compared the power of the module in both cooling and non-cooling modes in different radiation.

Basrawi et al. [52] conducted experimental work in the laboratory to study the cooling of the photovoltaic solar module by water cooling. Cooling analysis was investigated in three ways: without module cooling, half surface and all cooled surface. This effect is observed on the parameters of temperature, current, voltage and power.

Nazetic et al. [53] analyzed the cooling effect by spraying water on the front and back of the module. In this work, they obtained the module temperature in the state without cooling and with cooling of the back and front, 54 °C and 24 °C, respectively.

Reviewing literature shows that although different energy-related important performance criteria of a PV system with water flow cooling have been investigated so far, only efficiency has been considered as a dimensionless index. In other words, other dimensionless performance indicators of such system have not been investigated. Therefore, and based on the indicated gap, in this study, energy payback period, as a recently developed concept is chosen, and the impact of changing water flow rate on that is investigated through the parametric study.

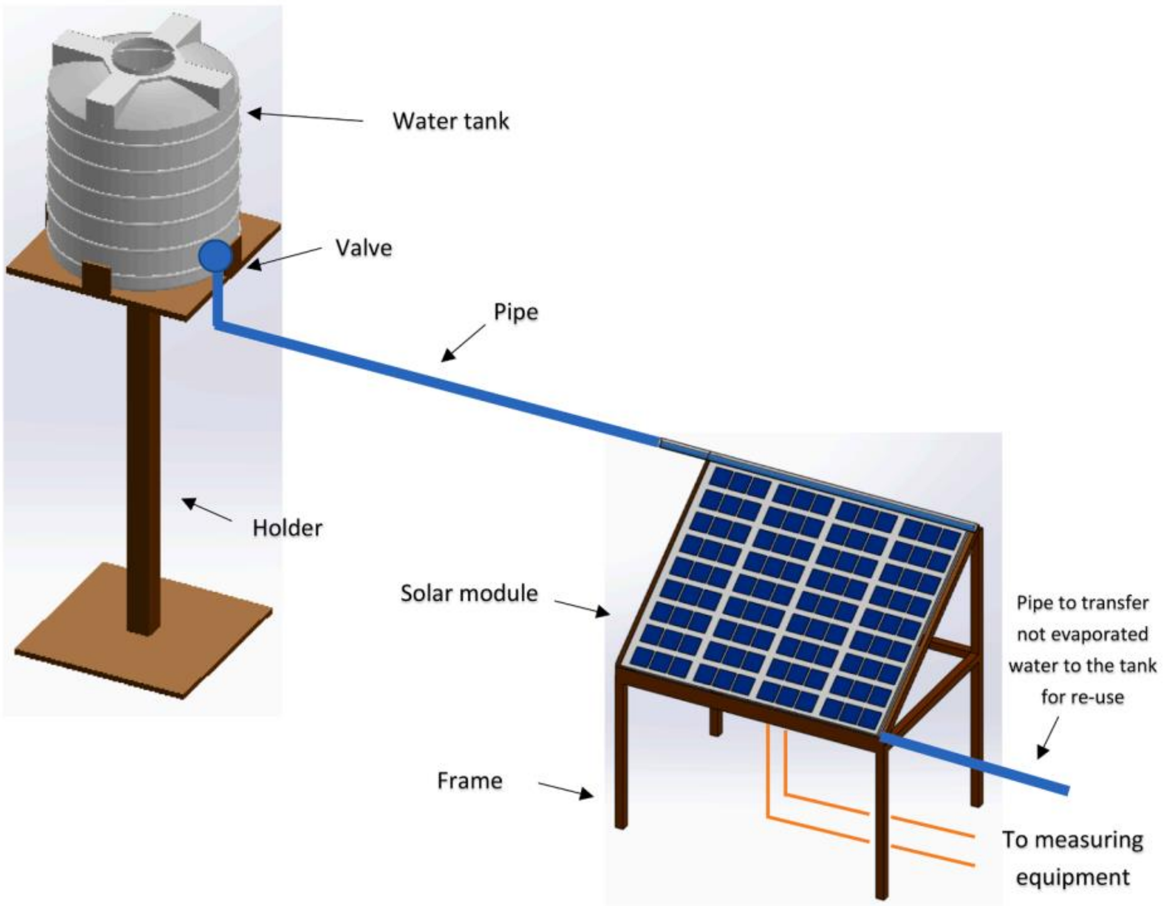

Fig. 1. The experimental setup employed in this study to record data [46]

2. The PV power generation system with water flow cooling

Fig. 1 introduces the studied PV power generation system. As observed, in this system, water flows on the surface of PV module and through absorbing the water, the PV module cools down, and a part of water is evaporated. The not evaporated water is returned to the tank for using again. The water flow rate could be controlled using a valve, while the tank, which keeps the water, is installed on a holder, same as the PV module.

3. Modelling

This part gives the details of modelling. Initially, in section3.1, description of modelling from heat transfer and fluid flow aspects is presented. Then, part 3.2 explains that how energy payback period is calculated.

3.1. Heat transfer and fluid flow

In this section, the modeling of water flow on a photovoltaic solar module is discussed. To achieve this, in the first part, the equations governing each layer are given and in the next part, the thermal resistances in each layer are discussed.

3.1.1. Energy balance equation

In this section, 6 layers of water, glass, upper EVA, silicon, bottom EVA and tedlar are modeled. The equations are extracted from the literature; including the previous studies of the research team [54,55].

a) Water layer

The upper layer is the water layer that flows on the solar module. In Eq.(1), the energy balance equation for this layer is written:

$$m_w c_{p,w} \frac{dT_w}{dt} = \alpha_w GA + \frac{T_g - T_w}{R_{conv-g,w}} - \frac{T_w - T_a}{R_{evap}} - \frac{T_w - T_a}{R_{conv\text{-}w,a}} - \frac{T_w - T_{sky}}{R_{rad-w,\mathrm{sky}}} + \dot{m}_w c_{p,w}(T_s - T_w) \tag{1}$$

Where m_w is the mass of water, $c_{p,w}$ is the water specific heat, T_w is the water temperature, t is the time, α_w is the water absorptivity, G is the irradiation, A is the area of module, T_g is the glass temperature, $R_{conv-g,w}$ is the convective thermal resistance between water and glass, T_a is the ambient temperature, R_{evap} is the evaporative thermal resistance, $R_{conv\text{-}w,a}$ is the convective thermal resistance between water and ambient, T_{sky} is the sky temperature and $R_{rad-w,\mathrm{sky}}$ is the radiative thermal resistance of water.

b) Glass layer

The next layer is the glass layer, whose energy balance equation is given in Eq.(2):

$$c_{p,g}\delta_g A\rho_g \frac{dT_g}{dt} = \alpha_g \tau_w GA - \frac{T_g - T_w}{R_{conv-g,w}} + \frac{T_{EVA1} - T_g}{R_{EVA1,g}} \tag{2}$$

Where $c_{p,g}$ is the glass specific heat, δ_g is the glass thickness, ρ_g is the glass density, T_g is the glass temperature, α_g is the glass absorptivity, τ_w is the water transitivity, T_{EVA1} is the upper EVA temperature and $R_{EVA1,g}$ is the conductivity thermal resistance between upper EVA and glass.

c) Top EVA layer

The energy balance of the upper EVA layer is seen in Eq. (3):

$$c_{p,EVA1}\delta_{EVA1} A\rho_{EVA1} \frac{dT_{EVA1}}{dt} = \frac{T_{PV} - T_{EVA1}}{R_{PV,EVA1}} - \frac{T_{EVA1} - T_g}{R_{EVA1,g}} \tag{3}$$

In above equation, $c_{p,EVA1}$ is the upper EVA specific heat, δ_{EVA1} is the upper EVA thickness, ρ_{EVA1} is the upper EVA density, T_{PV} is the silicon temperature and $R_{PV,EVA1}$ is the conductivity thermal resistance between upper EVA and silicon layer.

d) Silicon layer

The energy balance equation of the silicon layer, which is responsible for converting heat energy into electricity, is given in Eq.(4):

$$c_{p,PV}\delta_{PV} A\rho_{PV} \frac{dT_{PV}}{dt} = \alpha_{PV}\tau_g\tau_w GA - P_{ele} - \frac{T_{PV} - T_{EVA1}}{R_{PV,EVA1}} - \frac{T_{PV} - T_{EVA2}}{R_{EVA2,PV}} \tag{4}$$

Where $c_{p,PV}$ is the silicon specific heat, δ_{PV} is the silicon thickness, ρ_{PV} is the silicon density, , α_{PV} is the silicon absorptivity, τ_g is the glass transitivity, P_{ele} is the electricity production of module, T_{EVA2} is the bottom EVA temperature and $R_{EVA2,PV}$ is the conductivity thermal resistance between bottom EVA and silicon layer.

e) Bottom EVA layer

As Eq.(3) for the upper EVA layer is written for this layer:

$$c_{p,EVA2}\delta_{EVA2} A\rho_{EVA2} \frac{dT_{EVA2}}{dt} = \frac{T_{PV} - T_{EVA2}}{R_{EVA2,PV}} - \frac{T_{EVA2} - T_{Td}}{R_{EVA2,Td}} \tag{5}$$

In Eq.(5), $c_{p,EVA2}$ is the bottom EVA specific heat, δ_{EVA2} is the bottom EVA thickness, ρ_{EVA2} is the bottom EVA density, T_{Td} is the tedlar temperature and $R_{EVA2,Td}$ is the conductivity thermal resistance between bottom EVA and tedlar layer.

f) Tedlar layer

The energy balance equation of the substrate of a photovoltaic module, which is the ted layer, is shown in Eq.(6):

$$c_{p,Td}\delta_{Td} A\rho_{Td} \frac{dT_{Td}}{dt} = \frac{T_{EVA2} - T_{Td}}{R_{EVA2,Td}} - \frac{T_{Td} - T_a}{R_{conv-Td,a}} - \frac{T_{Td} - T_{gr}}{R_{rad-Td,gr}} \tag{6}$$

Where $c_{p,\mathrm{Td}}$ is the tedlar specific heat, δ_{Td} is the tedlar thickness, ρ_{Td} is the tedlar density, $R_{conv\text{-}Td,a}$ is the convective thermal resistance between tedlar and ambient, T_{gr} is the ground temperature and $R_{rad-Td,\mathrm{gr}}$ is the radiative thermal resistance of tedlar.

3.1.2. Thermal resistance

As mentioned above, this section deals with thermal resistance relationships.

a) Conductive thermal resistance

The conductive thermal resistance in the solar module is between the layers of glass, upper EVA, silicon, bottom EVA and tedlar, which is given in Eq.(7) in general.

$$R_{\mathrm{a,b}} = \frac{\delta_a}{2k_a A_a} + \frac{\delta_b}{2k_b A_b} \tag{7}$$

In the above equation, k is the thermal conductivity.

b) Convective thermal resistance

Eq.(8) is used to calculate the displacement thermal resistance.

$$R_{conv-g,w} = \frac{1}{h_{conv} A} \tag{8}$$

Where h_{conv} is the heat transfer coefficient which is given in Eqs (9) and (10).

$$h_{conv-g,w} = 0.332\, Re^{0.5} Pr^{0.33} \tag{9}$$

$$h_{conv-Td,a} = h_{conv-g,a} = 2.8 + 3U \tag{10}$$

c) Radiative thermal resistance

The radiative thermal resistance between the water layer and the air as well as the tedlar and the ground are given in Eqs (11) and (12), respectively.

$$R_{rad-w,sky} = \frac{1}{\sigma \varepsilon_w A(T_w^2 + T_{sky}^2)(T_w + T_{sky})} \tag{11}$$

$$R_{rad-Td,\mathrm{gr}} = \frac{1}{\sigma \varepsilon_{Td} A(\mathrm{T}_{Td}^2 + \mathrm{T}_{gr}^2)(\mathrm{T}_{\mathrm{Td}} + \mathrm{T}_{\mathrm{gr}})} \tag{12}$$

Where σ is the Stefan-Boltzmann and ε is the emissivity. In Eq.(11), T_{sky} is calculated as Eq.(13) .

$$\mathrm{T}_{\mathrm{sky}} = 0.0552 T_a^{1.5} \tag{13}$$

d) Evaporative thermal resistance

To calculate the heat transfer resulting from water evaporation, the evaporative thermal resistance must be determined, which is obtained according to Eqs. (14) to (17).

$$R_{evap} = \frac{1}{h_{evap} A} \tag{14}$$

$$h_{evap} = \frac{0.016(\mathrm{P_w} - \varphi P_{\mathrm{a}})}{T_w - T_a} \tag{15}$$

$$\mathrm{P_w} = \exp\left(25.317 - \frac{5144}{T_{\mathrm{w}}}\right) \tag{16}$$

$$\mathrm{P}_a = \exp\left(25.317 - \frac{5144}{T_a}\right) \tag{17}$$

Where φ is the relative humidity, and P is the partial pressure.

3.1.3. Electrical model

There are various methods and formulas for calculating the amount of electricity generated in the solar module. In one of these methods, holding the temperature of the solar module, the efficiency of the module is calculated, which is seen in Eq.(18), and then having the efficiency of the module, its power is calculated according to Eq.(19) [56].

$$\eta_{elec} = \eta_{ref}(1 - \beta_{\mathrm{ref}}(T_{PV} - T_{ref})) \tag{18}$$

$$P_{elec} = \eta_{elec} G A \tag{19}$$

3.2. Calculating the energy payback period

Energy payback period, which is shown by EPBP in this investigation, is defined by Eq. (20) [57]:

$$EPBP = \frac{E_{material\_to\_delivery}}{E_{PV}} \tag{20}$$

The numerator in Eq. (20) is the energy consumed during the process of preparing material to delivery to the end-user. In order to calculate this parameter, the information reported in [58] is utilized. The denominator is also the amount of electricity bought from the network in case there were not any PV technologies for power generation. It could be determined based on the governing equations presented in part 3.1.

4. Results and discussion

In this study, a 150 W poly crystalline module, produced by Yingly company is chosen as the studied module. It is assumed that this module is installed in city Tehran, Iran from January, which is the beginning of the year. The information about the module, as well as the location of the case study is completely found in the previous study of the research team [59].

The results are provided in Fig. 2. This figure demonstrates that by increasing the inlet water mass flow rate, the absorbed heat from the solar module goes up. Therefore, a higher amount of power is generated by the PV system. Therefore, the produced power in one internal, and as a result, the generated electricity by solar module [60] during a period has an upward trend. The amount of energy required for producing the installed capacity of a solar module is constant (the numerator in Eq. (20)). The more electricity is produced, the higher denominator is, which is accompanied by a lower EPBP.

As per Fig. 2, using water flow cooling leads to a considerable improvement in EPBP. When no cooling is utilized, EPBP is 8.88 years. By applying the water flow cooling it decreases and reaches 7.85 years when the inlet water flow rate is 0.005 $kg.s^{-1}$. An almost linear trend is observed until the inlet mass flow rate of 0.015 $kg.s^{-1}$, where EPBP 6.26 years. It is 29.50 and 20.25% lower than the corresponding values for the two previously indicated water inlet flow rates, respectively.

However, the linear trend changes and the decrease rate declines. The same increment in the mass flow rate, i.e., 0.010 $kg.s^{-1}$ results in only 0.28 years lower EPBP. In other words, EBPB reaches 5.98 years when the inlet water mass flow rate becomes 0.025 $kg.s^{-1}$. It indicates that the changes in the range of 0.005 to 0.015 $kg.s^{-1}$, i.e., 1.59 years (7.85-6.26), is 5.68 times bigger than the corresponding one in the range of 0.015 to 0.025 $kg.s^{-1}$ for the inlet water flow rate, which is 0.28 years.

The obtained outcome reveals that increasing the inlet water flow is reasonable only in the linear range, and after that, EPBP does not change significantly; only the water evaporation and water circulation cost have upward trends. Consequently, an optimum limit for the inlet water mass flow rate could be considered, which is around 0.015 $kg.s^{-1}$ for the investigated case study.

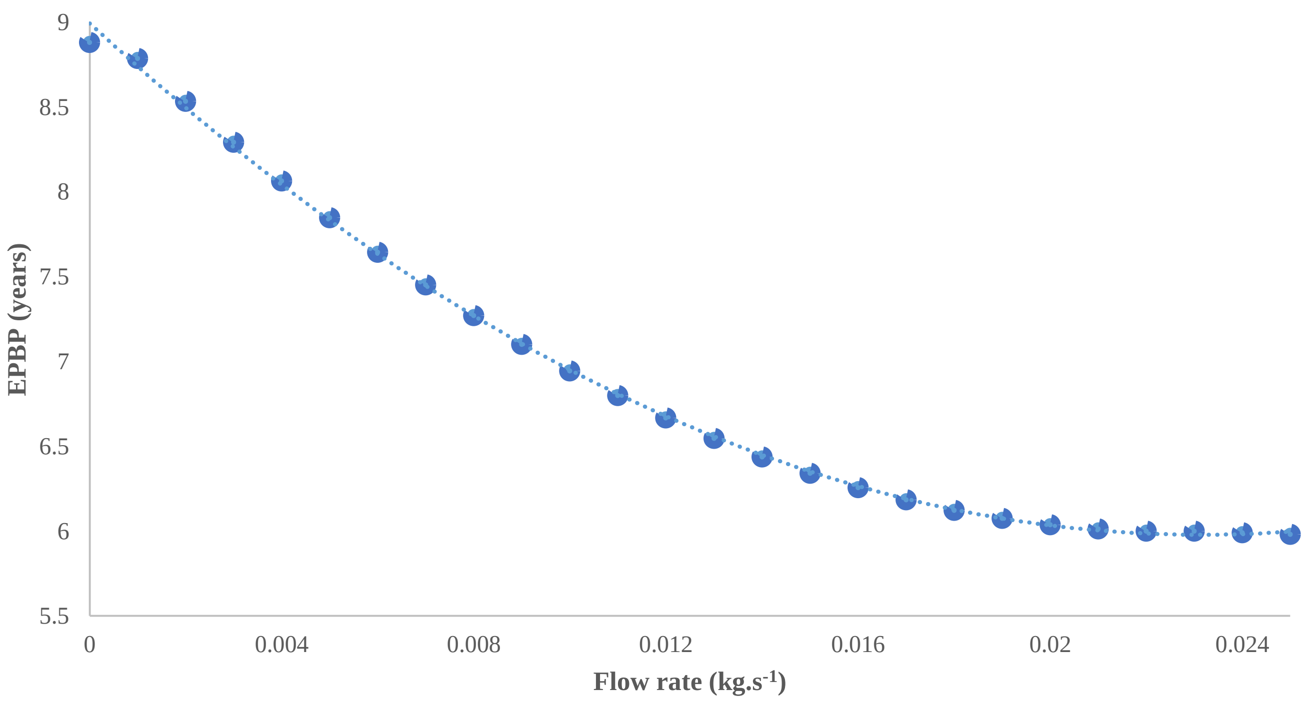

Fig. 2. Impact of water flow rate on EPBP

5. Conclusions

The impact of the inlet water mass flow rate on the energy payback period (EPBP) of a system with water flow cooling technology was found through conducting a parametric study. A 150 W poly crystalline module is considered to be installed in city Tehran, Iran. The system was simulated using a developed mathematical model. The results demonstrated that there was an optimum value for inlet water mass flow rate. It is the point the linear decrement turned into approaching a constant limit. For the investigated case-study the optimum value was found to be 0.015 kg.s^{-1}. Adjusting the water flow rate to the optimum condition offered the EPBP of 6.26 years.

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