Cost-effectiveness of the Combination of Solar Panel and Cooling System for Achieving Higher Efficiency

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Abstract

Solar energy is an important renewable energy source. Solar panels are rapidly developing due to material availability, flexibility and economic viability. The efficiency of existing panels is limited due to many factors such as weather, environment, location and lack of investment. To achieve maximum efficiency, solar panels are designed to and installed in specific areas designated as solar zones with high global horizontal irradiation. Research shows that the efficiency of solar panels decreases when the temperature increases. This paper will present the efficiency impact of high temperatures on each type of solar panel, and conclude a desired operating environment for solar panels. Furthermore, the paper will illustrate the working of a water cooling system for solar panels (combined system). The outcome of the research in this paper will have great educational value to engineering education, researchers and students taking courses in renewable energy.

Keywords

Solar energy, photovoltaic and solar thermal systems, solar panel efficiency.

Introduction

Solar energy is an ideal renewable energy compared to traditional non-renewable energy. Solar energy has its advantages due to its widespread use, low contamination and flexibility. Photovoltaic (PV) panel efficiency is mainly impacted by the solar irradiance, which means photovoltaic module gains an ideal efficiency in low latitude area. However, PV overheating causes the cell to lose efficiency. PV module cannot absorb all the energy from sunlight and can only convert solar irradiation to electricity within 10-15% efficiency[1]. The rest of irradiation is transformed into thermal energy and absorbed by the PV module. When the PV module temperature increases, the electric resistance of PV module increases as well, which decreases the efficiency of PV module.

The cooling system is an ideal method to maintain temperature and efficiency of PV panels. The paper will analyze the energy cost for the cooling system including active and passive types. Furthermore, the cooling system can be used as hot water supplication or air conditioning system for green buildings (passive house).

Temperature impact on the photovoltaic module

The photovoltaic module is formed of basic cells. The solar cell is modeled and presented in Figure 1, [2]

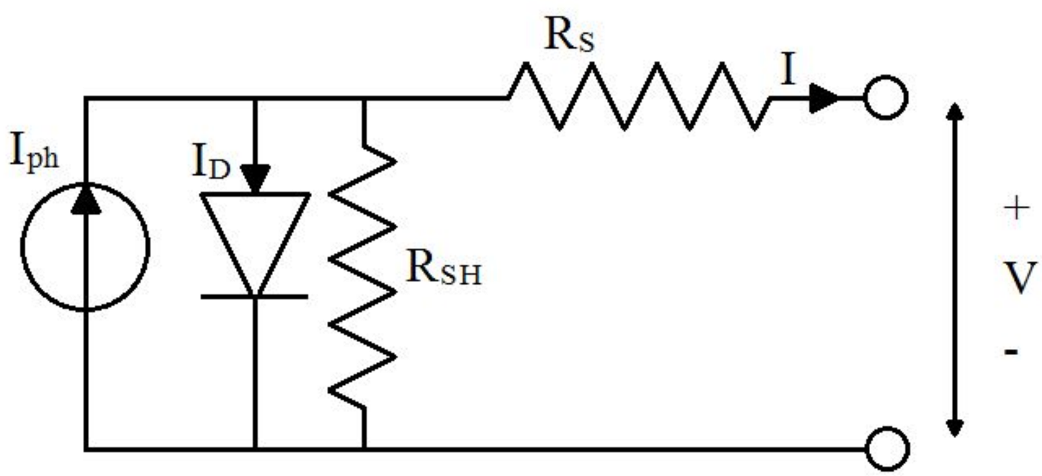

Figure 1 Single Solar cell model

I_{ph} shows the source current generated by the cell. Solar cell works as a diode with I_D current in nighttime or connected to external large supply of electricity. The cell has series resistance (R_S) and diode's internal shunt resistance (R_{SH}). The net current I is given by:

$$I = I_{ph} - I_D = I_{ph} - I_o\left\{\exp\left[\frac{e(V + IR_S)}{kT_C}\right] - 1\right\} - \frac{V + IR_S}{R_{SH}} \quad (1)$$

Usually, the shunt resistance R_{SH} is much larger than load resistance R_S, the net current I is simplified as:

$$I = I_{ph} - I_D = I_{ph} - I_o\left[\exp\left(\frac{eV}{kT_C}\right) - 1\right] \tag{2}$$

Where

k = Boltzmann's gas constant, = 1.381 × 10^{-23} J/K;

T_C = absolute temperature of the cell (K);

e = electronic charge = 1.602 × 10^{-19} J/V;

V = voltage imposed across the cell (V);

I_o = dark saturation current (A).

The dark saturation current I_o is determined by temperature (approximately doubles per 10°C increase in temperature[3]). As the temperature increases, PV cell generates less net current and causes the efficiency of the solar cell to decrease.

Temperature impact on the efficiency of photovoltaic module

When a photovoltaic module is cooled by heat dissipation to the ambient air, it reaches an energy balance:

$$(\tau\alpha)G_t = \eta_e G_t + U_L(T_C - T_a) \tag{3}$$

For the glazing-cover transmittance τ, and plate absorptance α, 0.9 can be used as the value of τα with minor approximation error.[4] The heat loss coefficient (U_L) consists of radiation loss and convection loss from PV panel to ambient temperature T_a. Under nominal operating cell temperature (NOCT) condition, (Irradiation: $G_{t,NOCT}$=800 W/m^2, ambient temperature: $T_{a,NOCT}$= 20°C, wind speed: W_{NOCT}= 1m/s) and without load (η_e=0), Eq. (3) changes:

$$(\tau\alpha)G_{t,NOCT} = U_L(T_{NOCT} - T_{a,NOCT}) \tag{4}$$

When combining Eq. (3) and Eq. (4), the PV module temperature T_C can be given by:

$$T_C = (T_{NOCT} - T_{a,NOCT})\left[\frac{G_t}{G_{t,NOCT}}\right]\left[1 - \frac{\eta_e}{(\tau\alpha)}\right] + T_a \tag{5}$$

As temperature coefficient β is given, the equations above can be used to calculate the efficiency at a specific cell temperature:

$$\eta_e = \eta_R[1 - \beta(T_C - T_{NOCT})] \tag{6}$$

Where

β= temperature coefficient (per k^{-1})

η_R= reference efficiency

It also can be given by:

$$\eta_e = \eta_R\left[1-\beta_R\left(T_C - T_R\right)\right] \tag{7}$$

When the absolute temperature of the cell increases, the efficiency of photovoltaic module decreases.

Power temperature coefficient of photovoltaic cells

On the market, 80 percent of product is crystalline silicon,[5] The rest 20 percent of product is thin-film PV, the temperature impact on the PV efficiency is shown in Table 1.

Table 1 Efficiency and temperature coefficient of typical photovoltaic cells

Type	Efficiency	Temperature coefficient (minus)
Crystalline silicon		
Monocrystalline silicon cells	14-15%	0.4-0.5%/°C[6.7]
Polycrystalline silicon cells	13-15%	0.4-0.45%/°C[8,9]
Amorphous silicon	6-7%	0.2%/°C[7,8]
Thin-films		
Cadmium Telluride	19.60%	0.25-0.35%/°C[5,10]
Copper Indium Gallium Selenide	21.70%	0.3-0.4%/°C[5,11]

Crystalline module is more stable, commonly used and suited to building-constrained space.[3] Thin-films have better efficiency and low temperature coefficient especially in hot climates. Combined with a cooling system, the temperature of photovoltaic panel is maintained in an acceptable level. It is known that PV with high efficiency will benefit more from the cooling system.

Cooling system design

The cooling systems are divided into two types: a) air cooling system and b) water cooling system. Natural or forced air cooling system is the air circulation with low cost and more suitable in high latitude areas. Figure 2 presents the design of air cooling system.

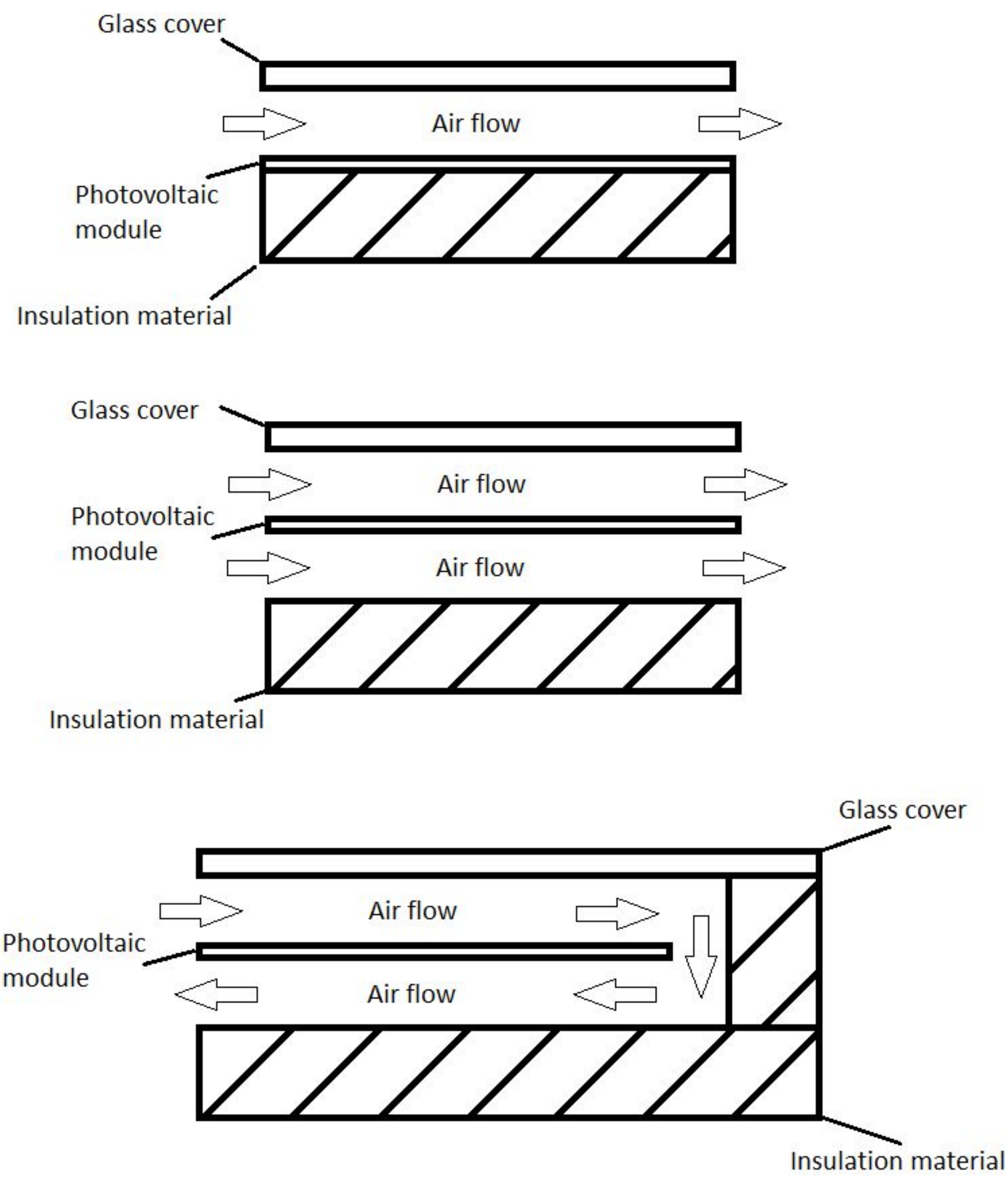

Figure 2 Design of air cooling system

When the ambient temperature difference is higher than 20°C, the air cooling system is not effective[12]. In low latitude countries, for more than 6 months, the ambient temperature difference is higher than 20°C.[5] Therefore, the water cooling system is the more effective choice for countries located in lower latitude.

Compare to air cooling systems, water cooling systems are more complicated. To prevent PV module from water erosion, the back surface of PV module is installed with a heat exchanger to transfer thermal energy. Figure 3 presents the design of the water cooling system.

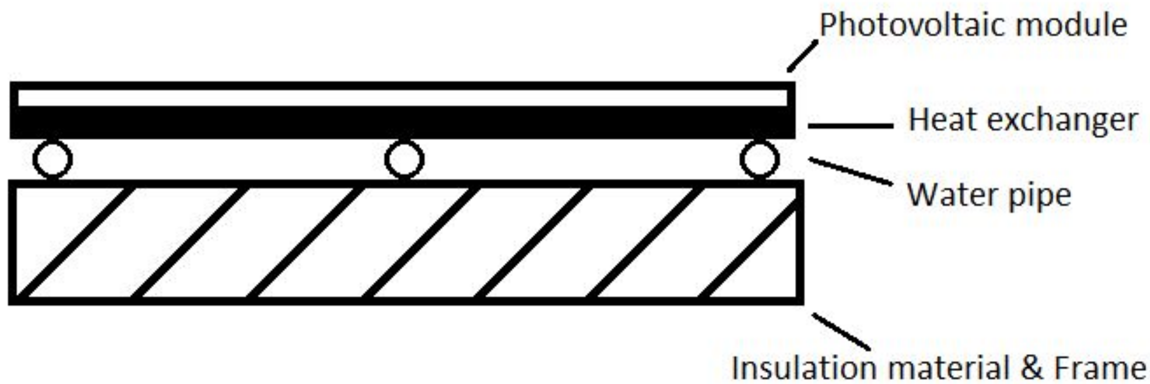

Figure 3 Design of water cooling system

Water cooling system types

According to the capacity and sizes of the PV system, the water cooling systems are designed smaller sizes for domestic usage and larger sizes for commercial or industrial buildings. Smaller size water cooling systems operate by thermosyphon effect (without pump), which maintains 3-5 m^2 PV panels and they work effectively.[12] Figure 4 presents the design of the cooling system. The water storage tank is located at a higher level to avoid reverse operation during the night.

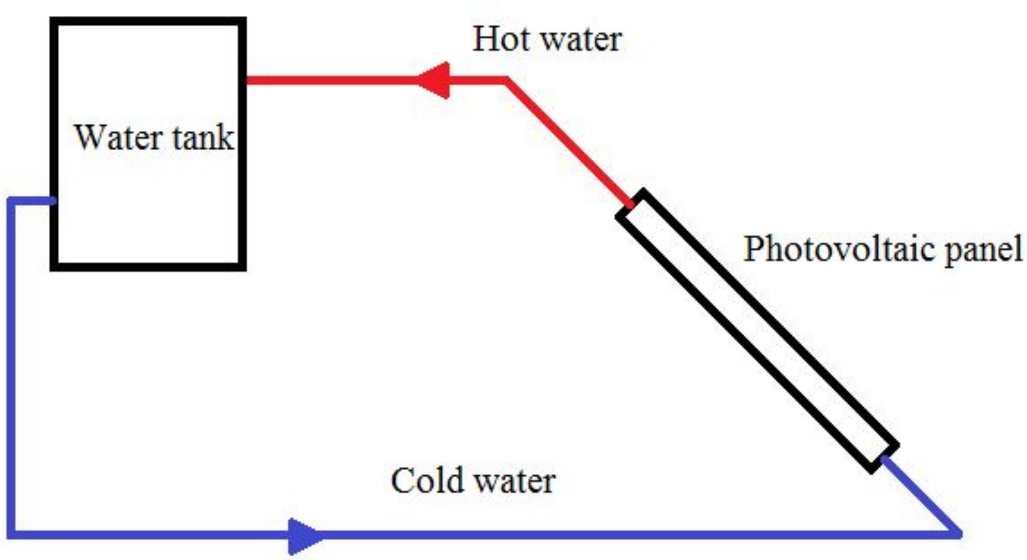

Figure 4 Design of small size water cooling systems (thermosyphon)

The large size water cooling system connects to the water system of the building, which provides an auxiliary hot water supply for building usage. It maintains 30-50 m^2 photovoltaic panels and they work effectively.[12] Figure 5 presents the design of the cooling system.

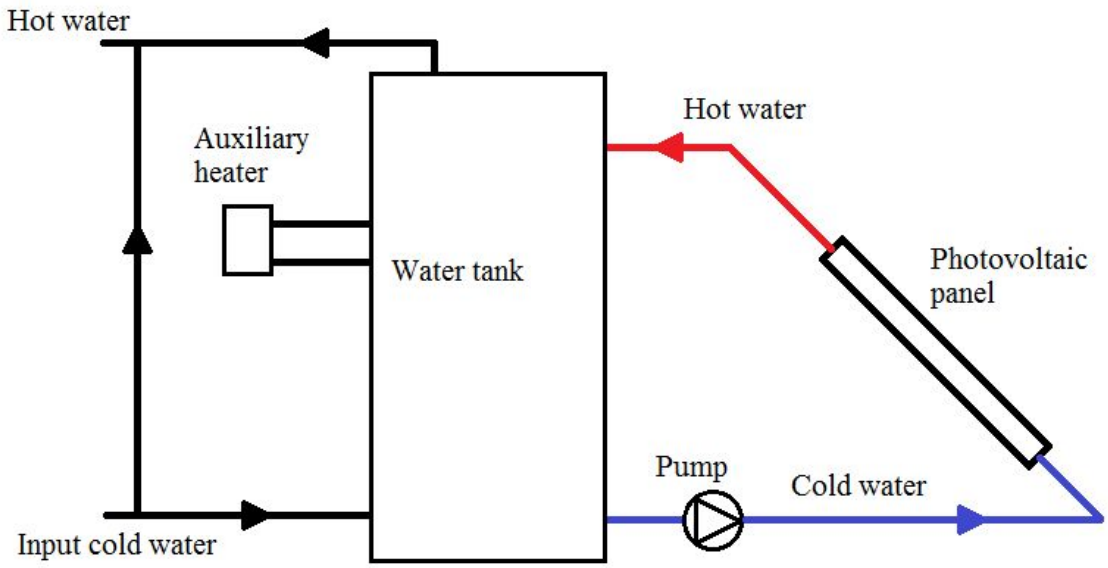

Figure 5 Design of large size water cooling systems

Photovoltaic and thermal hybrid system

Cooling systems are a desirable method not only to maintain the photovoltaic module's temperature in a low level but also to achieve high efficiency. Compared to the traditional type of photovoltaic panel, the initial investment and maintenance still need be considered. It is significant to regain the thermal energy from coolant water and benefit the economics of the cooling system. Photovoltaic and thermal hybrid (PV/T) systems are a new method to provide electricity and hot water for buildings.

Effectiveness analysis hybrid system

Transient Systems Simulation Program (TRNSYS) is a transient systems simulation with an analysis function for modular structure[13], Kalogirou *et al*.[14] applied the TRNSYS simulation with PV/T hybrid systems in Cyprus, and Huang *et al*.[15] illustrated a PV/T systems with TRNSYS simulation in Taiwan.

The paper uses TRNSYS software to design a solar hybrid system. The software will simulate the hybrid systems under given conditions (weather data, photovoltaic characteristic, water consumption, etc.) and analyze electricity output and thermal energy output. Another photovoltaic panel model will be designed to compare the output analysis of two models, and illustrate the economic availability of hybrid systems.

Parameter of TRNSYS

The paper focuses on crystalline silicon PV panels. 6 types of solar PV panels are used in the software to illustrate the difference of cell efficiency and temperature coefficient. The parameter of PV panels is shown in Table 2.

Table 2 Parameter of photovoltaic panel

Type	Efficiency	Temperature coefficient (minus)	Working temperature(°C)	Reference
Monocrystalline silicon cells				
Type 1	0.15	0.0041	25	16
Type 2	0.11	0.003	25	17
Type 3	0.13	0.004	25	18
Type 4	0.12	0.0045	25	19
Polycrystalline silicon cells				
Type 1	0.11	0.004	25	18
Amorphous silicon				
Type 1	0.08	0.0026	25	20

The paper uses TMY2 data as an input parameter to determine weather data (temperature, wind velocity, beam radiation, sky diffuse radiation, etc.)[21]. The paper uses three city's weather data for simulation: Tampa, FL (United States), Boise, ID (United States) and Guangzhou (China). The model runs 12 months to simulate an annual performance of hybrid systems. The major design parameters of hybrid system model are shown in Table 3.

Table 3 Parameter of hybrid systems

Component	Description	Value
PV/T	Module area	$50m^2$
	Collector Slope	45°
	Packing Factor	1
	Collector plate emittance	0.9
	Fluid Thermal Capacitance	4.19kJ/kg.K
	Number of glass covers	1
Pump	Maximum flow rate	200kg/hr
	Maximum power	240kJ/hr
Water tank	Volume	$1m^3$

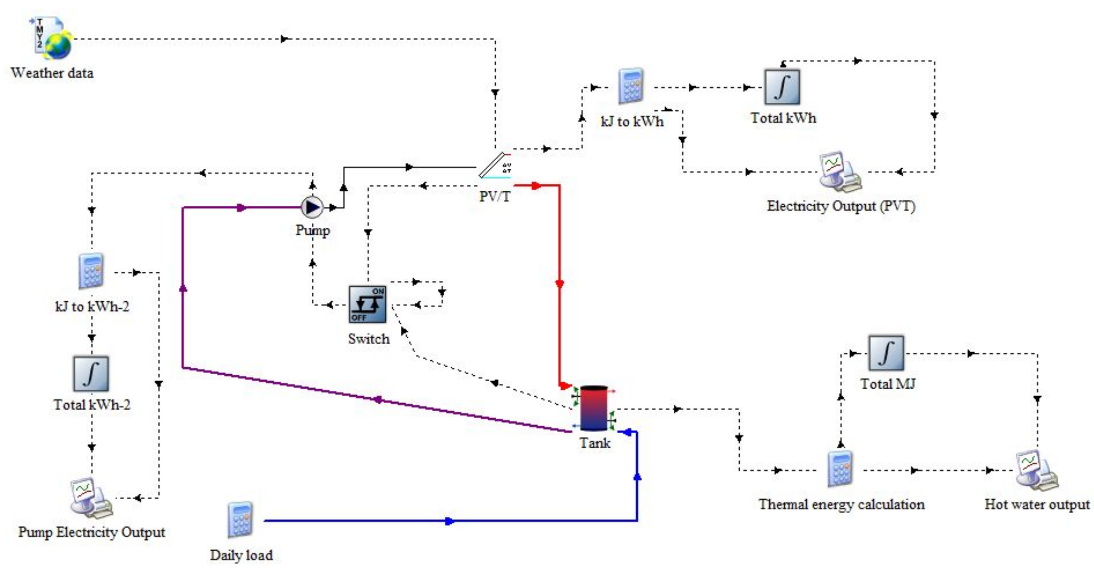

Figure 6 The PV/T hybrid design in TRNSYS

Output analysis

In the study, the software plots the total energy gain from thermal energy and electricity.

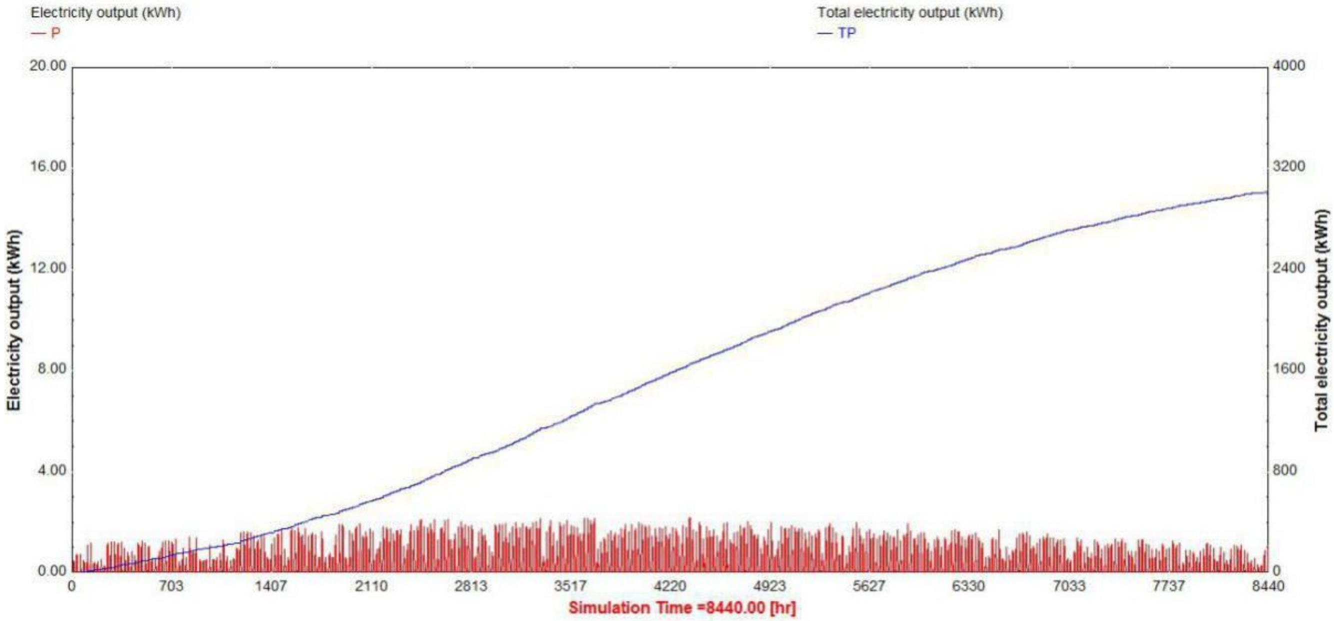

Figure 7 Electricity output analysis from TRNSYS

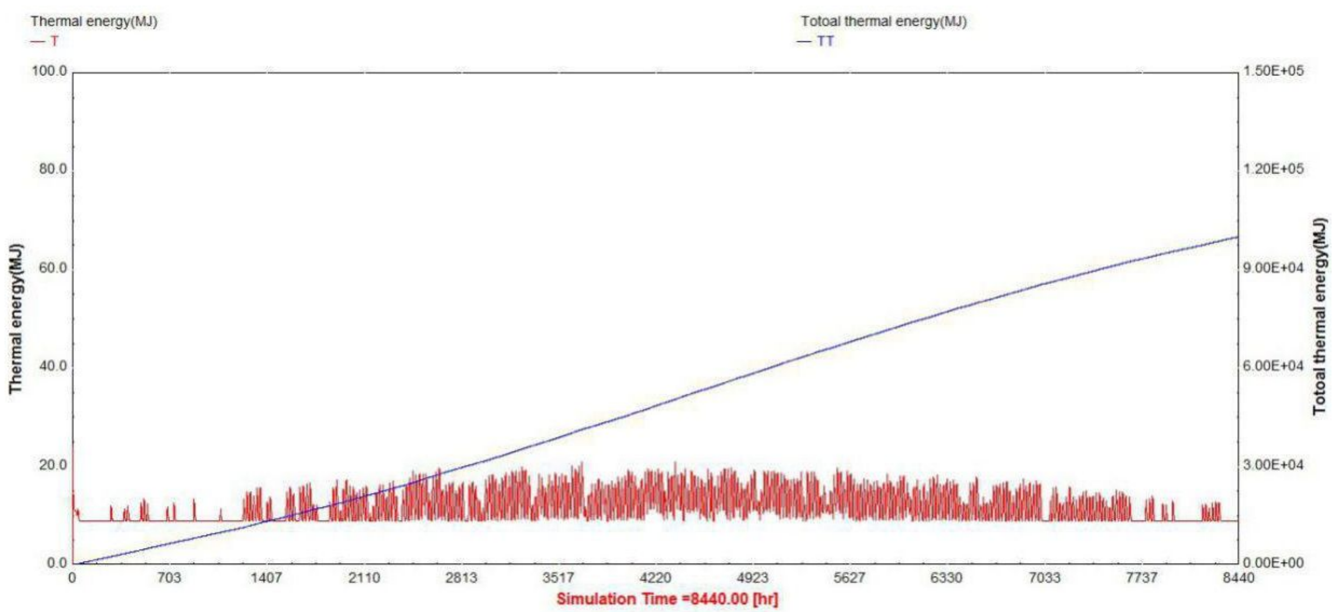

Figure 8 Thermal energy output analyses from TRNSYS

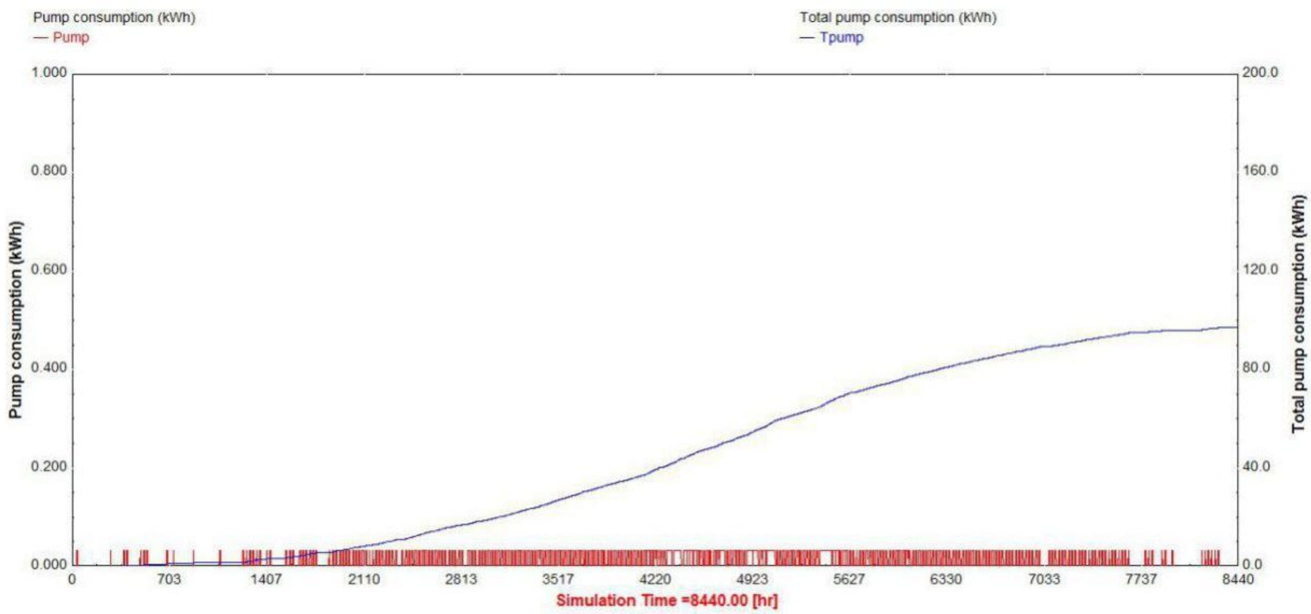

Figure 9 Pump energy consumption output analyses from TRNSYS

The energy analyses of 3 cities are shown in Table 4, 5 and 6.

Table 4 the energy analysis of PV/T hybrid system in Tampa, Florida

Cell Type	Thermal energy Q (kWh)	PV/T electrical energy (kWh)	Pump energy consumption (kWh)	Electricity loss (%)
Monocrystalline silicon cells				
Type 1	29792.5	4063.1	124.1	3.05%
Type 2	30148.2	3095.3	125.3	4.05%
Type 3	30005.9	3522.1	125.1	3.55%
Type 4	30037.4	3258.6	125.3	3.85%
Polycrystalline silicon cells				
Type 1	30268.1	3077.5	125.5	4.08%
Amorphous silicon				
Type 1	30367.9	2216.3	125.6	5.67%

Table 5 the energy analysis of PV/T hybrid system in Boise, Idaho

Cell Type	Thermal energy Q (kWh)	PV/T electrical energy (kWh)	Pump energy consumption (kWh)	Electricity loss (%)
Monocrystalline silicon cells				
Type 1	25483.6	3673.2	51.4	1.40%
Type 2	25700.4	2690.1	52.8	1.96%
Type 3	25609.9	3185.1	52.4	1.65%
Type 4	25670.1	2946.9	52.5	1.78%
Polycrystalline silicon cells				
Type 1	25709.3	2697.4	52.7	1.95%
Amorphous silicon				
Type 1	25874.6	1955.6	53.4	2.73%

Table 6 the energy analysis of PV/T hybrid system in Guangzhou,China

Cell Type	Thermal energy Q (kWh)	PV/T electrical energy (kWh)	Pump energy consumption (kWh)	Electricity loss (%)
Monocrystalline silicon cells				
Type 1	27909.2	3126.5	134.9	4.31%
Type 2	28146.8	2277.9	135.9	5.97%
Type 3	27820.8	2710.2	135.2	4.99%
Type 4	28228.7	2512.8	135.5	5.39%
Polycrystalline silicon cells				
Type 1	28093.9	2295.2	135.9	5.92%
Amorphous silicon				
Type 1	28392.0	1654.3	137.2	8.29%

When the cooling system is added to the photovoltaic panel, the surface temperature of the photovoltaic panel maintains in an acceptable level. In PV/T system, the temperature coefficient of photovoltaic can be ignored. Photovoltaic efficiency is considered as vital factor in choosing photovoltaic panels. For the total system, pump electricity consumption depends on the thermal energy gain. Natural wind cooling becomes negligible when the active cooling system is installed. The PV/T system will produce optimum results in a geographical area with windless and high solar radiation. Since the electricity generation cost of PV panels has reached a low level (18-43 cents per kWh)[22], when combining two systems, it can achieve a better economic cost.

Hybrid system for green house

Green house (passive house) is a concept that requires little energy to maintain heating or cooling. The passive house follows these requirements: [23]

Annual specific space heat demand ≤ 15kWh/m^{2}a

If applicable, the cooling demand ≤ 15kWh/m^{2}a

Heat or cooling load ≤ 10W/m^2

Primary energy demand ≤ 120kWh/m^{2}a

Airtightness $n_{50} \leq 0.6\ h^{-1}$

Summer climate criterion $h_{(\geq 25°C)} \leq 10\%$

Passive houses are always built in German-speaking areas and Scandinavia.[24] Many studies have shown the solar technology's application in passive houses.[25, 26] The hybrid system provides electricity and heat energy to meet passive house's heat and cooling load. Passive houses have a better performance with combined hybrid system. Solar panels absorb radiation heat when installed on the roof to cover solar direct radiation and be extended to provide an overshadow on the building facade. This decreases the solar heat income in summer and prevents the passive house from overheated. In the winter, the hybrid system provides an extra isolation on the roof and reduces the heat loss from the passive house, and the cooling system is also used to provide hot water. High temperature caused by high solar radiation is an obstacle for green house design in low latitude area. The hybrid system can be attached on the passive house to modify temperature influence. The high electricity generation from PV panel can meet the electricity requirement, and thermal energy is also used for dehumidification and hot water supply.

Conclusion

Compare to normal solar panels, the PV/T hybrid system is an ideal system not only to maintain solar panels with a desirable efficiency, but also provide a decent thermal supply for the buildings. Based on TRNSYS software results, it is still cost-effective to use the cooling system despite the electricity consumption for the operation of the pump. As the cooling system absorbs heat from PV panel, a higher radiation on the PV panels can provide more thermal energy for the cooling system. Combining ultra-high concentration of photovoltaic panels with an efficient cooling system is an ideal design for the future.

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