



HAL
open science

Improving the efficiency of photovoltaic panels using air exhausted from HVAC systems: Thermal modelling and parametric analysis

Wassim Salameh, Cathy Castelain, Jalal Faraj, Rabih Murr, Hicham El Hage, Mahmoud Khaled

► To cite this version:

Wassim Salameh, Cathy Castelain, Jalal Faraj, Rabih Murr, Hicham El Hage, et al.. Improving the efficiency of photovoltaic panels using air exhausted from HVAC systems: Thermal modelling and parametric analysis. *Case Studies in Thermal Engineering*, 2021, 25, pp.100940. 10.1016/j.csite.2021.100940 . hal-03196809v2

HAL Id: hal-03196809

<https://hal.science/hal-03196809v2>

Submitted on 29 Jan 2025

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



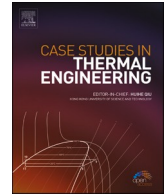
Distributed under a Creative Commons Attribution 4.0 International License



ELSEVIER

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: <http://www.elsevier.com/locate/csited>

Improving the efficiency of photovoltaic panels using air exhausted from HVAC systems: Thermal modelling and parametric analysis

Wassim Salameh^a, Cathy Castelain^b, Jalal Faraj^{c,d}, Rabih Murr^a, Hicham El Hage^a, Mahmoud Khaled^{c,e,*}

^a Energy and Thermo-fluid Group, Lebanese International University LIU, Bekaa, Lebanon

^b Laboratory of Thermal Energy of Nantes, LTEN, Polytech' Nantes, University of Nantes, Nantes, France

^c Energy and Thermo-fluid Group, International University of Beirut BIU, Beirut, Lebanon

^d Lebanese University, Faculty of Technology, Saida, Lebanon

^e University Paris Diderot, Sorbonne Paris Cité, Interdisciplinary Energy Research Institute (PIERI), Paris, France

ARTICLE INFO

Keywords:

Photovoltaic panel
Efficiency
Improvement
Exhaust air
Thermal modeling
Parametric analysis

ABSTRACT

The present work proposes the engagement of relatively cold air exhausted from Heating, Ventilating and Air Conditioning (HVAC) systems, that exist in structures such as residential commercial and industrial, to reduce the PV modules' operational temperature. To proceed, a thermal resistance model in steady state is developed along with its corresponding iterative procedure and calculations which are carried out for different configurations and scenarios. The thermal modeling was validated by comparing it to experimental measurement found in the literature. It was revealed that the PV modules' temperature can be reduced with increasing the mass flow rate of the exhaust air. However, the air mass flow rate depends on the cooling load need; which increases with increasing the cooling load. The efficiency of the PV has shown an increase from 11 to 18% when the cooling load increases from 0 to 160 kW for a solar radiation of 500 W/m². Moreover, there is an optimum height for the exhaust air duct for each cooling load that must be determined.

1. Introduction

Global warming, non-stable high prices of fossil fuel and pressure from legislatures to reduce air pollution have imposed on industries to promote renewable energy technologies and sustainable development [1-6]. The widely used technology is the solar photovoltaic (PV) cell capable to convert the solar radiation into electricity, hence, reducing the adverse anthropogenic impacts of fossil fuel use. The integration of the PV systems in buildings has become an important factor to achieve the zero energy performance [7-12].

One of the main obstacles that face using PV systems to produce electricity is overheating the PV modules due to excessive solar radiation and high ambient temperatures. High solar cell temperature can result in cell life degradation, lower energy conversion efficiency and even cell damage under extreme solar concentration [13-15].

* Corresponding author. Energy and Thermo-fluid Group, International University of Beirut BIU, Beirut, Lebanon.
E-mail address: mahmoud.khaled@liu.edu.lb (M. Khaled).

<https://doi.org/10.1016/j.csited.2021.100940>

Received 22 January 2021; Received in revised form 1 March 2021; Accepted 7 March 2021

Available online 19 March 2021

2214-157X/© 2021 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license

(<http://creativecommons.org/licenses/by/4.0/>).

Another problem that can be encountered during the solar-electric conversion of the PV system is the accumulation of dust at its upper surface. Mohandes et al. [16] investigated the performance of 500W Copper Indium Diselenide (CIS) PV system in UAE under the effect of temperature, humidity, and dust. During night time, the temperature is lower in desert areas resulting dew on the surfaces of solar systems and trap the smallest dust particles found in the air. The study concluded that a reduction of the output power of 10% during 5 weeks and 50% during 6 months can be stemmed due the dust accumulation [17,18].

Also, solar electric efficiency is effected by cell temperature. It was shown that there exist a drop of solar electric efficiency by 0.5% for an increase of cell temperature with 1 °C for crystalline silicon cells and by 0.25% for amorphous silicon cells [19,20]. However, controlling the operating temperature of the module, by collecting the heat accumulated from the PV, will enhance the overall efficiency. Furthermore, PV modules work well with high averages of global solar radiations and temperatures not exceeding the recommended operating temperature usually given by the PV manufacturer.

Different passive and active heat removal techniques have been used to maintain the PV operating temperature as near as possible to a temperature leading to a maximum efficiency.

Zhu et al. [21] presented a radiative cooling of the solar cells by placing a thin layer of silicon on the front surface of the PV. This thin material is transparent and colourless over wide range of solar wavelengths, but has a strong emissivity which generates a significant thermal radiation and results in the cooling of the solar cell radiatively by emitting the heat to the environment. The numerical results showed a decrease in the PV operating temperature by 18.3 K without any experimental validation. Another study of the passive cooling technique [22] suggested installing the PV panel on the top of canals or rivers to benefit from the evaporated water as a coolant. The authors suggested as a real application the installation of PV panels in the top of rivers or canals to use the evaporation of the water as the coolant. An increase of 7.3% of the generated power and a reduction of the surface temperature from 60 to 40 °C was achieved using a laboratory set-up.

The aforementioned techniques use liquid or air flow [23-26] at a lower temperature compared to the PV module in order to extract any developed heat and consequently ensure a cooler operating environment for the module. Abdolzadeh and Ameri [27] employed different cooling systems one of which is Photovoltaic Pumping Systems (PVPS). It was observed that a high decrease of operating temperature and high increase of the electrical efficiency, about 17%, was achieved by spraying part of the pumped water on the front of the cells. Wilson [28] used a zero-energy consumption system (without using a pump) in which the water flows by gravity. The study was performed experimentally and numerically. It was shown that the output energy was incremented by 12.8%. Yuan et al. [29] conducted a series of experiments to compare the performance of a conventional PV, water-pipe-based PV/T, and PV/T with micro-channel heat pipe array (MHPA). The electrical efficiency of the water-pipe-based PV/T, the PV/T with MHPA and the PV module ranged from 11.2% to 10%, 9.6%–7.7% and 8.6 to 7.0% respectively. Electrical performance of both, the water-pipe-based PV/T and the PV/T with MHPA was superior to its counterpart of the PV module. Tiwari et al. [30] derived an analytical expression for the temperature of solar cell and water and an overall thermal efficiency of an integrated photovoltaic and thermal solar (IPVTS) as a function of climatic and design parameters. The numerical computation has been considered for four configurations, unglazed with tedlar (UGT), glazed with tedlar (GT), unglazed without tedlar (UGWT) and glazed without tedlar (GWT). It was found that the efficiency of IPVTS system is higher when cooled with water than cooled with air for all configurations except GWT.

André et al. [31] demonstrated that the annual energy production of a PV power plant increased by 12%. They showed that the efficiency of the PV is affected by the cooling/heating thermal time constants and water ON/OFF time cycles. The PV annual production can be increased by 12%, reaching to 17% of increase peaks by optimizing the water flow and the ON/OFF cycles. Mingke et al. [32] developed a trifunctional photovoltaic–photothermic–radiative cooling system that converts the solar energy into electricity during the daytime and offer cooling energy during time through radiative cooling.

Moreover, a Phase Change Material (PCM) is also used as a heat remover from the PV. It is used on the back of the PV module to extract the excess of heat [33]. Hasan et al. [34] showed experimentally an enhancement of the electrical efficiency by 10% and 10.7% in Ireland and Pakistan respectively while using a PCM. Hachem et al. [19] compared experimentally the effect of using pure and combined PCM/copper/graphite on the performance of a PV panel. It was found that the electrical enhancement of the PV efficiency reached 5.8% by using the combined PCM.

The aforementioned numerical and experimental research attempts prove that cooling the PV module is a striking research subject. Therefore, numerical and experimental approaches will continue to develop energy and cost-effective cooling methods applicable for both new and existing PV plants. Nonetheless, it was shown that PV module cooled with water delivers higher efficiency than PV module cooled with air. However, the circulation of the water flow in the system to extract the heat from the PV requires a pump that necessitates an electric power to operate. This power reduces the amount of electrical power generated by the PV system. From an energy management point of view, it is recommended to use a system with zero energy consumption to cool the PV instead of using a system that operates from the output power of the module. Therefore, the proposed research concentrates on using the exhaust air of HVAC system to cool down the operating temperature of a PV module. One should be cognizant that the proposed system can be integrated in residential, commercial and industrial buildings where the exhausts air of HVAC exist or any other type of exhausted air. Also, the current work embraces a thermal resistance modeling in steady state along with its corresponding iterative procedure. Therefore, calculations are carried out for different configurations and scenarios. In addition, the thermal resistance takes into account all the layers of the PV module. The proposed thermal modeling will be compared to the experimental results obtained by Hachem et al. [19]. However the aim of this research is to benefit from the existing exhaust air of an HVAC system which has a lower temperature than the PVs' surface temperature without spending money on designing a cooling system. This active cooling concept doesn't require power consumption as the one using a pump. This system can also avoid the accumulation of the dust at the panel surface.

The originality of the present work resides in the following points:

1. It suggests a new system that permits to enhance the performance of Photovoltaic panels along with its associated thermal modelling and iterative procedure.
2. The material presented is important since the enhancement that the suggested system will provide is proven through an appropriate thermal modelling and parametric analysis.
3. This work provides useful system and modelling for photovoltaic solar energy community. This advantage will be by using the developed thermal modelling in any study using any active or passive cooling techniques. It also offers the possibility to study the effect of a wide range of parameters on the performance of the system, particularly when it comes to study the feasibility of new concepts.

This paper is organized as follows: section 2 describes the proposed system and its modeling. Section 3 presents the results and analysis of the model which are divided into two parts: parametric study to calculate the PV efficiency and optimization of the duct height. Finally, section 4 underlines the conclusions.

2. Proposed system and modeling

Fig. 1 portrays a schematic of the proposed system that will be employed to evaluate the effect of the exhaust air on the performance and efficiency of the photovoltaic panel. The goal of the proposed system is to reduce the operating temperature of the PV module.

HVAC systems condition the air temperature, humidity, and air quality for the comfort of the people inside a building. HVAC is classified into three main categories: All-Water, Water-Air and All-Air systems. In the all-air heating and cooling systems, both energy and ventilating air are carried out by ductwork between the furnace or air handler and the conditioned space. The lower left side of Fig. 1-a is a schematic showing the major elements providing energy to or removing energy from the airstreams passing through air handlers, typical of the central all-air commercial HVAC systems.

As it can be seen from Fig. 1, there are heating and cooling coils and associated fan responsible for exchanging energy between the water streams and the air to be supplied to the conditioned space. The heating coil receives hot water from a boiler by using a hot water pump and the cooling coil receives chilled water from a chiller by using a chilled water pump. These two systems act individually as ordered by the owner in summer cooling and in winter heating.

In general and in order to adopt compromises between comfort and economy, a fraction of the return air from the conditioned spaces (Fig. 1) will be exhausted and instead an amount of outdoor air will be mixed. This permits to have continuously fresh air entering the spaces and to reduce the amount of energy required to condition the supply air required completely from the outdoor air.

The entire setup is placed in an open surrounding.

The proposed system (Fig. 1-a) consists of using the exhaust air of an HVAC system to absorb the excess of heat from the PV module and improve the overall efficiency of the PV system. The operating temperature of the PV array will be reduced due to the heat transfer between the air flow and the lower surface of the PV system which usually have a high temperature. The forced convection of the exhaust air will increase the heat transfer from the lower surface of the PV.

The mass flow rate of the return air depends on the cooling load required for a space and can be calculated using the following relation:

$$\dot{m} = \frac{\dot{Q}_{cooling}}{i_r - i_s} \tag{1}$$

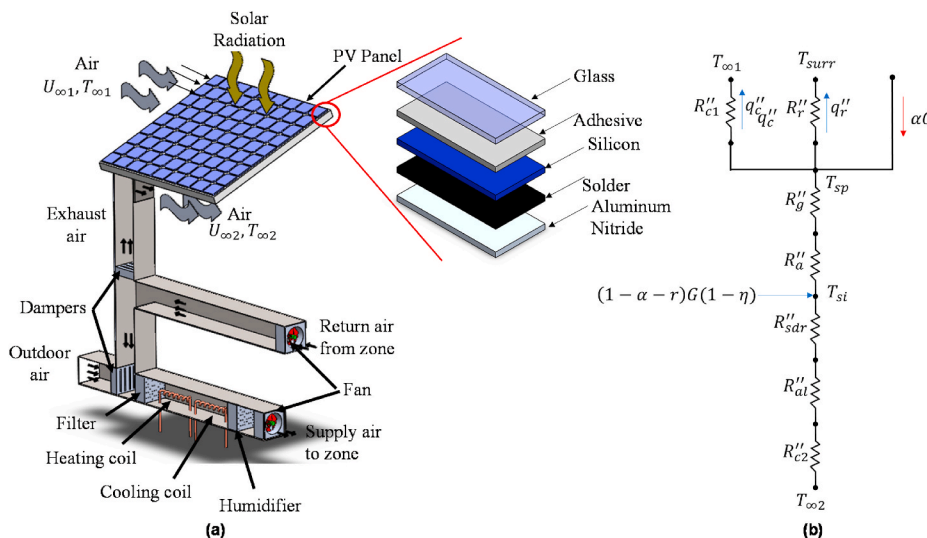


Fig. 1. Proposed system for cooling PV array and its corresponding thermal circuit.

Where \dot{m} is the mass flow rate the return air, $\dot{Q}_{cooling}$ is the cooling load of the conditioned space, i_r is the specific enthalpy of the air in the room, and i_s is the specific enthalpy of the supplied air. The indoor temperature and relative humidity are 24 °C and 50% respectively which corresponds to an enthalpy i_r of 48 kJ/kg. Then, with a typical value of the sensible heat factor of 0.8 and for a supply temperature of 13 °C, the enthalpy of supply air i_s is 32 kJ/kg.

The mass flow rate of the exhausted air is then considered equal to 20% of that of the return air.

The photovoltaic panel illustrated in Fig. 1-a consists from the top to the bottom of:

- A 3-mm-thick ceria-doped glass with a conductivity of $k_g = 1.4$ W/m.K.
- A 0.1-mm-thick optical grade adhesive with a conductivity $k_a = 145$ W/m.K.
- A *very thin* layer of silicon (negligible thermal resistance) within which solar energy is converted to electrical energy.
- A 0.1-mm-thick solder layer with a conductivity $k_{sdr} = 50$ W/m.K.
- A 2-mm-thick aluminum nitride substrate with a conductivity $k_{al} = 120$ W/m.K.

The solar-to-electrical conversion efficiency within the silicon layer depends on the silicon temperature T_{si} and is described by the following expression [19] where T_{amb} is the ambient temperature:

$$\eta = 0.1829 - 0.0028(T_{si} - T_{amb}) \tag{2}$$

Based on the thermal circuit (Fig. 1-b), the PV surface temperature (T_{sp}) and Silicon temperature (T_{si}) can be calculated by taking a system of nodes. The first is between the silicon temperature (T_{si}) and the surface temperature (T_{sp}), and the second one is between the surface temperature (T_{sp}) and the ambient air (upper surface). By taking the aforementioned system of nodes, the following two equations are obtained:

$$(1 - \alpha - r)G(1 - \eta) - \frac{(T_{si} - T_{\infty 2})}{R''_{sdr} + R''_{al} + \frac{1}{h_{con2}}} = \frac{T_{si} - T_{sp}}{R''_a + R''_g} \tag{3}$$

$$(1 - \alpha - r)G(1 - \eta) + \alpha G - \frac{(T_{si} - T_{\infty 2})}{R''_{sdr} + R''_{al} + \frac{1}{h_{con2}}} = h_{con1}(T_{sp} - T_{\infty 1}) + \varepsilon\sigma(T_{sp}^4 - T_{sur}^4) \tag{4}$$

where h_{con1} and h_{con2} are the convection coefficients at the upper and lower surfaces respectively, $T_{\infty 1}$ is the ambient air temperature and $T_{\infty 2}$ is the return air temperature, ε is the emissivity of the PV module (glass layer), σ is the constant of Boltzman, η is the PV efficiency, R''_a is the thermal resistance due to conduction in the adhesive, R''_g is the thermal resistance due to conduction in the glass layer, R''_{sdr} is the thermal resistance due to conduction in the solder, R''_{al} is the thermal resistance due to conduction in the aluminium nitride, and α and r are respectively the absorptivity and the reflectivity of the glass layer.

It is considered that 10% of the incident solar irradiation is absorbed at the top surface of the glass ($\alpha = 0.1$) while 83% of the solar irradiation is transmitted to and absorbed by the silicon (the remaining 7% is reflected away from the top surface of the glass ($r = 0.07$)). The PV system under investigation has a $L = 0.5$ m long and $W = 0.5$ m wide solar cell.

The convection heat transfer coefficients, in general, vary along the flow direction. The mean or average heat transfer coefficient for a surface is determined by averaging the local heat transfer coefficient over the entire surface. In order to calculate the heat transfer coefficient (at the lower or the upper surface), the type of the flow should be determined by calculating the Reynolds number:

$$Re = \frac{VL}{\nu} \tag{5}$$

Where V and ν are the velocity and the kinematic viscosity of the air stream and L is the length of the module. Once the Reynolds number is determined, the average heat transfer coefficient may be calculated by selecting the suitable relation for the average Nusselt number depending on the type of the flow; the average Nusselt number over the flat plate is [35]:

- For laminar flow:

$$Nu = \frac{hL}{k} = 0.453Re^{0.5}Pr^{0.33} \text{ with } \left\{ \begin{array}{l} Re < 5 \times 10^5 \\ Pr > 0.6 \end{array} \right\} \tag{6}$$

- For mixed flow:

$$Nu = \frac{hL}{k} = (0.37Re^{0.8} - 871)Pr^{0.33} \text{ with } \left\{ \begin{array}{l} Re < 10^8 \\ 0.6 \leq Pr \leq 60 \end{array} \right\} \tag{7}$$

Where Pr is the Prandtl number.

The average velocity of air at the upper surface of the PV panel V_1 is equal to the wind speed and the average velocity at the lower surface of the PV panel V_2 is equal to the average velocity of the return air at the exit of the exhaust duct which is calculated as follows:

$$V_2 = \frac{4\dot{m}}{\rho\pi D_h^2} \tag{8}$$

Where ρ is the air density and D_h the hydraulic diameter of the duct where the exhaust airflow exists that can calculated as follows:

$$D_h = \frac{4S}{P} = \frac{2(Hl)}{H+l} \tag{9}$$

The height of the exhaust duct H is taken equal to 0.1 m and the width l is 0.5 m (equal to the PV panel width).

The surface temperature is obtained in function of the silicon temperature by substituting Eq. 2 into 3 which yields to:

$$T_{sp} = T_{si} + \frac{(R''_a + R''_g)(T_{si} - T_{\infty 2})}{R''_{sdr} + R''_{al} + \frac{1}{h_{con2}}} - (R''_a + R''_g)(1 - \alpha - r)G[0.8171 + 0.0028(T_{si} - T_{amb})] \tag{10}$$

Then, the silicon temperature can be obtained in function of the surface temperature by substituting Eq (2) into Eq (4) and using then the developed form of Eq (4):

$$T_{si} = \frac{\frac{T_{\infty 2}}{R''_{sdr} + R''_{al} + \frac{1}{h_{con2}}} - (0.8171 + 0.1829\alpha - 0.8171r)G + 0.0028(1 - \alpha - r)GT_{amb} + h_{con1}(T_{sp} - T_{\infty 1}) + \epsilon\sigma(T_{sp}^4 - T_{sur}^4)}{-\frac{1}{R''_{sdr} + R''_{al} + \frac{1}{h_{con2}}} + 0.0028(1 - \alpha - r)G} \tag{11}$$

The silicon temperature T_{si} is obtained using an iterative method based on equations (10) and (11) as detailed below:

- 1) An initial temperature of the silicon is assumed equal to the ambient temperature;
- 2) The surface temperature is then calculated based on the assumed value of the silicon temperature and using equation (10);
- 3) A new value for the silicon temperature is now calculated based on the surface temperature obtained in 2) and using equation (11);
- 4) A relative error for the new calculated silicon temperature with respect to the assumed one is calculated and the system will converge when the difference between the assumed value and the calculated one reaches a minimum when varying the silicon temperature from the ambient temperature and 80 °C.

The newly suggested thermal modelling along with its associated iterative procedure are validated against experimental data obtained in [19]. Table 1 shows a comparison between theoretical temperatures of the surface (obtained with the suggested thermal modelling) and their experimental counterparts for two different configurations.

The results obtained using the proposed thermal modelling and the associated iterative procedure are neighbouring the results obtained from the two experimental configurations (relative errors of 7.8 and 7.0 are obtained). The error between the experimental and the proposed model can be attributed to several parameters such as:

- An error can be occurring while measuring the wind speed over the entire module since the average velocity will affect the average convection coefficient as well as the surface temperature.
- The accuracy of the thermocouple while measuring the surface temperature.
- The measured area (experimental) was taken for the whole PV. However, the area should be measured for each cell.
- The modelling considers that the airflows at the upper and lower surfaces of the PV panel are parallel to the surfaces which is not completely true in real conditions.

Since the values of the analytical temperatures are relatively correlated with their experimental counterparts (relative error less than 10%), the proposed model is considered to have sufficient accuracy to be employed to estimate in steady state conditions the surface temperature, the silicon temperature, and the output efficiency of the PV module to perform parametric analysis to obtain information about the potential of application of the new suggested concept.

3. Results and analysis

The results are divided into two parts. The first part is a parametric study to calculate the PV efficiency by varying the cooling load

Table 1
Comparisons between theoretical and experimental data [19] for the surface temperature.

Configuration	1	2
Wind speed upper Surface (m/s)	5	3
Wind speed lower Surface (m/s)	3	2
Irradiance (W/m ²)	790	763
Ambient temperature (°C)	32	28
Surface temperature Calculated (°C)	63.6	64.2
Surface temperature Experimental (°C)	59	60
Relative error (%)	7.8	7.0

for different solar irradiance (section 3.1). The second part is an optimization of the duct height for a selected cooling load (Sections 3.2, 3.3, and 3.4).

3.1. PV efficiency

After the validation of the thermal proposed model, a parametric study is completed by varying the cooling load of the HVAC system from 0 to 110 kW. The height of the exhaust duct (H) was taken as 0.1 m and the width (l) as 0.5 m. The length of the PV module was taken as 0.5 m. The ambient temperature is set at 25 °C while the exhaust air temperature is set to 22 °C. The wind speed at the upper surface was taken to be 2 m/s. As mentioned previously, the calculations are prepared iteratively by varying the silicon temperature from 25 to 80 °C. The convergence will take place when the difference between the assumed value and the calculated counterpart of the T_{si} reaches a minimum. Fig. 2 shows the efficiency improvement of the PV module by varying the cooling load from 0 to 160 kW and with the variation of the solar irradiance from 500 to 900 W/m².

The first point represents the PV efficiency without using the exhaust air flow (0 kW); it corresponds to a natural convection. On the other hand, the increase in cooling load of the HVAC system results in lower PV temperatures and increasing the output efficiency of the PV module. For the same cooling load, the efficiency decreases with increasing the solar radiation. Indeed, increasing the solar radiation by keeping the same cooling load (same cooling airflow capacity), will increase the temperature range of the PV panel absorbing more heat from the sun, and then the efficiency range of the PV panel. The efficiency increases from 0.08 to 0.18 with increasing the cooling load for a solar radiation of 700 W/m². The results show that the efficiency of PV remains constant when the cooling load reaches 90 kW. The temperature of the PV surface becomes very close to the temperature of the exhaust air.

Results in Fig. 2 show that there are three regions:

- Region 1: the efficiency of the PV panel increases slightly with increasing the cooling load from 0 to 30 kW, the flow is fully laminar over the rear plate of the PV panel. At this region the Reynolds number is lower than 5×10^5 .
- Region 2: the efficiency increases suddenly with a small variation of the cooling load from 30 to 40 kW. The increase of the efficiency is due to the perturbation in the flow that can be attributed to the transition between a fully laminar flow and slightly mixed flow.
- Region 3: the efficiency remains approximately constant at high cooling load (90 kW and above); the surface temperature reaches faster the temperature of the exhaust air due to the highly mixed flow regime over the rear surface of the PV panel.

At high cooling load the surface temperature reaches the temperature of the exhaust air faster than at low cooling load. The increase of the cooling load will result in a high decrease of the surface temperature and the flow will be highly turbulent. By increasing the cooling load with the same area of the duct, the surface temperature will be very close to the exhaust air temperature without any improvement of the efficiency. There is a waste of exhaust air at low temperature. This waste can be used to cool down more than one PV module. At this end, an optimization of the hydraulic diameter of the exhaust air duct must be completed for each cooling load to determine the minimum height of the exhaust air duct.

3.2. Hydraulic diameter optimization

To proceed with this optimization, the silicon temperature was calculated by varying the height of the exhaust air duct at different cooling loads. Fig. 3 shows the variation of the silicon temperature by varying the height of the exhaust air duct from 0.01 to 0.49 m and by varying the cooling load from 60 to 140 kW. The solar irradiance was taken constant and equal to 700 W/m².

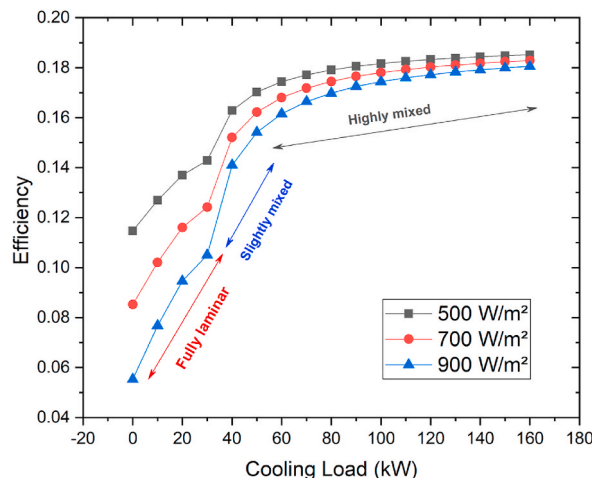


Fig. 2. PV's efficiency versus cooling load at different solar irradiance.

The results show that there are four regions:

- Zone 1: At small height of the exhaust air, the silicon temperature varies slightly. This is attributed to the fact that the airflow velocity is very high to cool down the back surface temperature of the PV. The waste in the amount of the exhaust air is very high.
- Zone 2: The silicon temperature increases with increasing the height of the exhaust air. The silicon temperature increases with decreasing the cooling load using the same height. At this region the height of the exhaust air duct can be selected while using the exhaust air system to cool down the operating temperature of a PV system.
- Zone 3: The temperature increases suddenly with a small variation of the exhaust air height. The increase of temperature is due to the perturbation in the flow that can be attributed to the transition between a mixed flow and a laminar flow (natural convection).
- Zone 4: The temperature remains approximately constant with increasing the height of the exhaust air. The flow becomes laminar and the PV is cooled due to natural convection.

The suitable height of the exhaust air duct must be selected at the end of the second region.

3.3. REYNOLDS number versus duct height

In the previous section, the sudden increase of temperature was attributed to the transition between a forced convection and a natural convection. Fig. 4 shows the variation of Reynolds number at the lower surface by varying the height of the exhaust air duct from 0.01 to 0.49 m and by varying the cooling load from 60 to 140 kW. The solar irradiance was taken constant and equal to 700 W/m².

The Reynolds number decreases with increasing the height of the duct. The Reynolds number increasing with increasing the cooling load since the mass flow rate of the exhaust air will increase. As mentioned previously, the results show that there are four regions:

- At small height (lower than 0.1 m) of the exhaust air, the exhaust velocity is very high having a Reynolds greater to cool down the back surface temperature of the PV. The silicon temperature varies slightly. The amount of air exhausted is very high.
- The Reynolds number decreases slightly with increasing the height of the exhaust air. At this region the height of the exhaust air can be selected while using the exhaust air system to cool down the operating temperature of a PV system.
- The flow is in a transition region between a mixed (around 5×10^5) and laminar flow.
- The flow becomes laminar at high height of the duct and the silicon temperature will remain constant.

3.4. PV efficiency versus duct height

Fig. 5 shows the variation of PV efficiency by varying the height of the exhaust air duct from 0.01 to 0.49 m and by varying the cooling load from 60 to 140 kW. The solar irradiance was taken constant and equal to 700 W/m².

The efficiency of the PV system decreases with increasing the height of the exhaust air. The results of the PV's efficiency versus exhaust air height at different cooling loads have a similar features as shown in Fig. 3. The results show that there are four regions. The dimension of the height should be selected from the second region. Otherwise, the increase of the cooling load will result in a high decrease of the surface temperature and the flow will be highly turbulent. The surface temperature will be very close to the exhaust air temperature without any improvement of the efficiency. In this case, a waste of exhaust air at low temperature is present. This waste can be used to cool down more than one PV module.

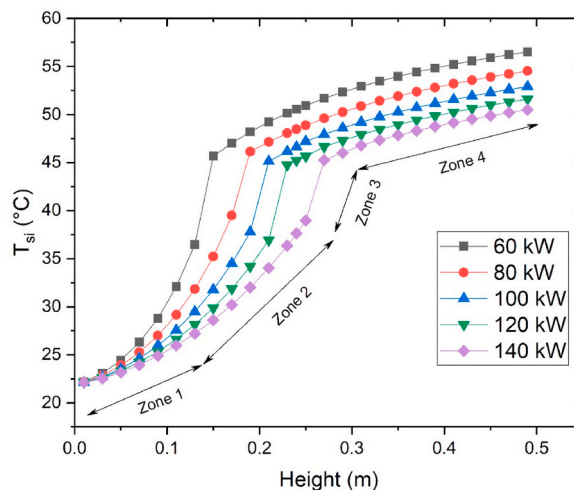


Fig. 3. Silicon temperature versus exhaust air height at different cooling loads.

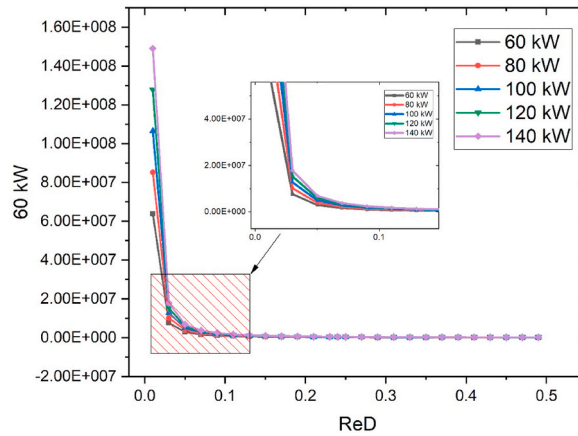


Fig. 4. Reynolds number versus exhaust air height at different cooling loads.

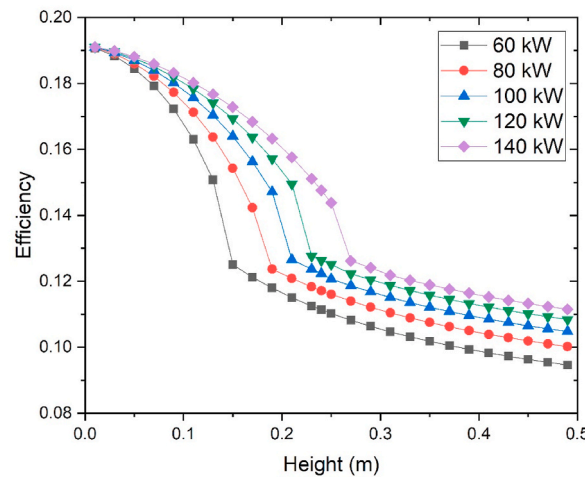


Fig. 5. PV's efficiency versus exhaust air height at different cooling loads.

4. Conclusions

The study presented that exhausted air of HVAC systems could be employed to reduce the surface temperature of PV modules installed within structures where exhaust air of HVAC systems or any other industrial system are available. The efficiency of the PV modules will be improved when its operating temperature is reduced. The efficiency of the PV has shown an increase from 11 to 18% when the cooling load increases from 0 to 140 kW.

At high cooling load, the surface temperature decreases suddenly due to the high heat transfer. However, a minimum height of the exhaust air duct must be selected to reduce the waste of air at low temperature or use a series of PV to be cooled with the same air duct.

As mentioned in the introduction, the dust accumulation disturbs the output power of the PV system; a modification of the proposed system can be used to cool down the operating temperature of the module and avoid the acclimation of dust. The modification is to divide the flow of the exhaust air into two parts; the first can flow over the lower surface and second over the upper surface. In this case, the flow over the upper surface of the PV will eliminate the accumulation of the dust. Moreover, the efficiency of the PV system may be enhanced by generating a turbulent flow at low Reynolds number by using a Vortex Generator.

This manuscript will be followed by a separate manuscript under preparation by the authors and will concern the optimization of the system performance taking into consideration several parameters such as placing the entire setup in a chamber or in an open surrounding, the position on the PV panel where the exhaust air that exits the chamber is blown, induced turbulence, blowing return or fresh air directly on the PV panel, and others.

Author statement

Wassim Salameh: Data curation; Formal analysis; Investigation; Methodology; Validation; Writing – original draft; Cathy Castelain:

Formal analysis; Investigation; Supervision; Writing – review & editing; Jalal Faraj: Formal analysis; Investigation; Supervision; Writing – review & editing; Rabih Murr: Formal analysis; Investigation; Supervision; Writing – review & editing; Hicham El Hage: Formal analysis; Investigation; Supervision; Writing – review & editing; Mahmoud Khaled: Conceptualization; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- [1] J. Blondeau, T. Museur, O. Demaude, P. Allard, F. Turoni, J. Mertens, Cost-effective flexibilisation of an 80 MWe retrofitted biomass power plants: improved combustion control dynamics using virtual air flow sensors, *Case Stud. Therm. Eng.* 21 (2020) 100680.
- [2] A. Inayat, H. Ang, M. Raza, B. Yousef, C. Ghenai, M. Ayoub, S. Gilani, Integration and simulation of solar energy with hot flue gas system for the district cooling application, *Case Stud. Therm. Eng.* 19 (2020) 100620.
- [3] C. Ghenai, M. Rasheed, M. Alshamsi, M. Alkamali, F. Ahmad, A. Inayat, Design of hybrid solar photovoltaics/shrouded wind turbine power system for thermal pyrolysis of plastic waste, *Case Stud. Therm. Eng.* 22 (2020) 100773.
- [4] S.H. Mun, J. Kang, Y. Kwak, Y.S. Jeong, S.M. Lee, J.H. Huh, Limitations of EnergyPlus in analyzing energy performance of semi-transparent photovoltaic modules, *Case Stud. Therm. Eng.* 22 (2020) 100765.
- [5] S. Vares, T. Häkkinen, J. Ketomäki, J. Shemeikka, N. Jung, Impact of renewable energy technologies on the embodied and operational GHG emissions of a nearly zero energy building, *J. Build Eng.* 22 (2019) 439–450.
- [6] T. Jafarinejad, M.B. Shafii, R. Roshandel, Multistage recovering ventilated air heat through a heat recovery ventilator integrated with a condenser-side mixing box heat recovery system, *J. Build Eng.* 24 (2019) 100744.
- [7] S. Thotakura, S.C. Kondamudi, J.F. Xavier, M. Quanjin, G.R. Reddy, P. Gangwar, S.L. Davuluri, Operational performance of megawatt-scale grid integrated rooftop solar PV system in tropical wet and dry climates of India, *Case Stud. Therm. Eng.* 18 (2020) 100602.
- [8] F.F. Ahmad, C. Ghenai, A. Hamid, O. Rejeb, M. Bettayeb, Performance enhancement and infra-red (IR) thermography of solar photovoltaic panel using back cooling from the waste air of building centralized air conditioning system, *Case Stud. Therm. Eng.* 24 (2021) 100840.
- [9] H.A. Kazem, Evaluation and analysis of water-based photovoltaic/thermal (PV/T) system, *Case Stud. Therm. Eng.* 13 (2019) 100401.
- [10] B. Ramkiran, C.K. Sundarabalan, K. Sudhakar, Performance evaluation of solar PV module with filters in an outdoor environment, *Case Stud. Therm. Eng.* 21 (2020) 100700.
- [11] S.M. Sultan, C.P. Tso, M.N. Ervina Efzan, A new method for reducing the performance evaluation cost of the photovoltaic module cooling techniques using the photovoltaic efficiency difference factor, *Case Stud. Therm. Eng.* 21 (2020) 100682.
- [12] S.M. Kiwan, A.M. Khlefat, Thermal cooling of photovoltaic panels using porous material, *Case Stud. Therm. Eng.* (2021) 100837.
- [13] W. Xiao, N. Ozog, W.G. Dunford, Topology study of photovoltaic interface for maximum power point tracking, *IEEE Trans. Ind. Electron.* 54 (2007) 1696–1704.
- [14] H. Patel, V. Agarwal, Maximum power point tracking scheme for PV systems operating under partially shaded conditions, *IEEE Trans. Ind. Electron.* 55 (2008) 1689–1698.
- [15] W. Salameh, A. Assi, C. Habshi, M. Khaled, Cooling PV Arrays Using the Return Air Flow of Air Conditioning Systems, the First International Ashrae Conference and Exhibition on Efficient Building Design, Beirut-Lebanon, 2014.
- [16] B.M.A. Mohandes, L. El-Chaar, L.A. Lamont, Application study of 500 W photovoltaic (PV) system in the UAE, *Appl. Sol. Energy* 45 (2009) 242–247.
- [17] M.J. Adinoyi, S.A. Said, Effect of dust accumulation on the power outputs of solar photovoltaic modules, *Renew. Energy* 60 (2013) 633–636.
- [18] W. Javed, et al., Characterization of dust accumulated on photovoltaic panels in Doha, Qatar, *Solar Energy* 142 (2017) 123–135.
- [19] F. Hachem, B. Abdulhay, M. Ramadan, H. El Hage, M. Gad El Rab, M. Khaled, Improving the performance of photovoltaic cells using pure and combined phase change materials – experiments and transient energy balance, *Renew. Energy* 107 (2017) 567–575.
- [20] E. Skoplaki, J.A. Palyvos, On the temperature dependence of photovoltaic module electrical performance: a review of efficiency/power correlations, *Sol. Energy* 83 (2009) 614–624.
- [21] Zhu Linxiao, Aaswath Raman, Ken Xingze Wang, Marc Abou Anoma, Fan Shanhui, Radiative cooling of solar cells, *Optica* 1 (2014) 32–38.
- [22] M. Ebrahimi, M. Rahimi, A. Rahimi, An experimental study on using natural vaporization for cooling of a photovoltaic solar cell, *Int. Commun. Heat Mass Tran.* 65 (2015) 22–30.
- [23] J. Ji, J. Han, T. Chow, H. Yi, J. Lu, W. He, W. Sun, Effect of fluid flow and packing factor on energy performance of a wall-mounted hybrid photovoltaic/water-heating collector system, *Energy Build.* 38 (2006) 1380–1387.
- [24] H.G. Teo, P.S. Lee, M.N.A. Hawlader, An active cooling system for photovoltaic modules, *Appl. Energy* 90 (2012) 309–315.
- [25] J.K. Tonui, Y. Tripanagnostopoulos, Improved PV/T solar collectors with heat extraction by forced or natural air circulation, *Renew. Energy* 32 (2007) 623–637.
- [26] S.R. Reddy, M.A. Ebadian, C.X. Lin, A review of PV-T systems: thermal management and efficiency with single phase cooling, *Int. J. Heat Mass Tran.* 91 (2015) 861–871.
- [27] M. Abdolzadeh, M. Ameri, Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells, *Renew. Energy* 34 (2009) 91–96.
- [28] E. Wilson, Theoretical and operational thermal performance of a ‘wet’ crystalline silicon PV module under Jamaican conditions, *Renew. Energy* 34 (2009) 1655–1660.
- [29] W. Yuan, J. Ji, Z. Li, F. Zhou, X. Ren, X. Zhao, S. Liu, Comparison study of the performance of two kinds of photovoltaic/thermal(PV/T) systems and a PV module at high ambient temperature, *Energy* 148 (2018) 1153–1161.
- [30] A. Tiwari, M.S. Sodha, Performance evaluation of hybrid PV/thermal water/air heating system: a parametric study, *Renew. Energy* 31 (2006) 2460–2474.
- [31] André F.A. Castanheira, João F.P. Fernandes, P.J. Costa Branco, Demonstration project of a cooling system for existing PV power plants in Portugal, *Appl. Energy* 211 (2018) 1297–1307.
- [32] Mingke Hu, Bin Zhao, Xianze Ao, Xiao Ren, Jingyu Cao, Qiliang Wang, Yuehong Su, Gang Pei, Performance assessment of a trifunctional system integrating solar PV, solar thermal, and radiative sky cooling, *Appl. Energy* 260 (2020) 114167.
- [33] M.R. Salem, M.M. Elsayed, A.A. Abd-Elaziz, K.M. Elshazly, Performance enhancement of the photovoltaic cells using Al₂O₃/PCM mixture and/or water cooling-techniques, *Renew. Energy* 138 (2019) 876–890.
- [34] A. Hasan, S.J. McCormack, M.J. Huang, B. Norton, Energy and cost saving of a photovoltaic-phase change materials (PV-PCM) System through temperature regulation and performance enhancement of photovoltaics, *Energy* 7 (2014) 1318–1331.
- [35] F. Incropera, D. Dewitt, T. Bergman, A. Lavine, *Fundamentals of Heat and Mass Transfer*, sixth ed., Wiley, 2007.

Nomenclature

\dot{m} : Mass flow rate kg/s
 i_r : Specific enthalpy of the air in the room kJ/kg
 i_s : Specific enthalpy of the supplied air kJ/kg
 kg : Glass thermal conductivity W/m.K
 ka : Aluminium thermal conductivity W/m.K
 ka : Adhesive thermal conductivity W/m.K
 η : Solar-to-electrical conversion efficiency
 h_{con1} : Convection coefficients at the upper surface (W/m².K)
 h_{con2} : Convection coefficients at lower surface (W/m².K)
 $T_{\infty 1}$: Ambient air temperature K
 $T_{\infty 2}$: Return air temperature K
 ε : Emissivity of the PV module
 σ : Constant of Boltzmann (W/m².K⁴)
 R''_a : Thermal resistance in adhesive K/W
 R''_g : Thermal resistance in glass K/W
 α : Absorptivity
 r : Reflectivity
 V : Velocity of air stream m/s
 ν : Viscosity of air stream m²/s
 L : Length of the module m
 Pr : Prandtl number
 ρ : Air density Kg/m³
 D_h : Hydraulic diameter of the duct m
 H : Height of the exhaust duct m
 l : Length of the exhaust duct m
 G : Solar irradiance W/m²