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Numerical Study of Integrated Solar Photovoltaic-Thermal Module with a Refrigeration System for Air Conditioning and Hot Water Production under the Tropical Climate Conditions of Singapore

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Thermal systems of buildings in the tropics are highly energy intensive. In this study, a novel integrated solar photovoltaic-thermal-refrigeration (PVTR) system used to produce hot water and air conditioning in the tropical climate conditions of Singapore was analyzed. A dynamic simulation model was formulated for the analysis. Mathematical models were developed for the PV sandwich attached with a solar flat plate collector and for the main components of the refrigeration system. Thorough investigation of the electrical and thermal performances of the system were conducted through analysis of coefficient of performance (COP), cooling capacity, water temperature and heat capacity in water heater, photovoltaic (PV) module temperature and photovoltaic efficiency. The results show that attractive electrical and thermal performance can be achieved with a maximum annual cooling COP of 9.8 and a heating COP of 11.3. The PV efficiency and power saving were 14% and 53%, respectively. The annual cooling, heating and PV energy produced were 9.7 MWh, 15.6 MWh and 1.6 MWh, respectively. The financial payback period of the system was 3.2 years and greenhouse gas emission (GHG) reduction annually was 12.6 tons of CO₂ equivalents (tCO₂e).

Keywords: photovoltaic; solar energy; thermal energy; refrigeration; heat pump

1. Introduction

Thermal systems in buildings, including heating, ventilation and air conditioning (HVAC), are integral parts of modern life. Unfortunately, they consume a huge amount of energy globally. In 2010, their use in residential and commercial buildings alone consumed almost 20% of the total global energy demand. This demand is expected to grow by about 80% by 2050¹. In tropical countries, like Singapore, the figure is

significantly higher. Singapore's National Environmental Agency (NEA) reported that air conditioning and water heating respectively consume 36.7% and 20.9% of household electricity in the country². In terms of general buildings in Singapore, air-conditioning consumes 50% of total electricity³. Considering that most of the electricity in Singapore is still produced from fossil fuel with CO₂ emission of 0.42 kg per kWh produced⁴, it is important to find a solution to lower the energy consumption of thermal

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appliances, especially air-conditioners and water heaters, in Singapore, in particular, and the tropics, in general.

Photovoltaic (PV) technology is now widely used for electricity generation. However, PV modules are relatively inefficient in terms of solar-to-electricity conversion ratio. Less than 20% of the solar energy absorbed is converted into electricity while the rest is dissipated as heat. Previous studies have found that this problem can be reduced by keeping the PV cell temperature low⁵. This can be done by air cooling or, more often, water cooling. The heat extracted from the PV cells can then be used for space heating or domestic hot water supply, resulting in an integrated photovoltaic-thermal (PVT) module. A possible design configuration is shown in Fig. 1. Aste *et al.* found that their air cooled PVT module had thermal efficiencies of between 20–40% and electrical efficiencies of 10%⁶, while that of Kim *et al.* had thermal and electrical efficiencies of 22% and 15%, respectively⁷. Joshi and Tiwari investigated the performance of a hybrid PVT parallel plate air collector was investigated under four different climatic conditions⁸. The results showed energy and exergy efficiencies of 55–65% and 12–15%, respectively. Tonui and Tripanagnostopoulos found that the use of forced air convection and fins can increase the efficiency of PV modules to 30%⁹. Kim *et al.* found that by using heat-recovery ventilator, the efficiency of PVT can reach 38%¹⁰.

Fig. 1. Sectional view of a photovoltaic-thermal (PVT) module

As compared to air cooling, water cooling provides a better cooling performance due to the higher heat capacity of water¹¹. Moharram *et al.* found a 12.5% increase in solar cell efficiency for a decrease of 100°C in cell temperature¹². Salih *et al.* used a water spray instead of a film over the PV panels and observed improvements in efficiency with an average thermal efficiency of 17.8%¹³. Tabaei *et al.* included a booster reflector in addition to the water film cooling concept

and observed almost 50% improvement in power generation¹⁴. Dubey and Tay studied two different configuration of water cooled PVT collectors under the tropical conditions of Singapore¹⁵. In the PV module that was encapsulated with mono-crystalline Si solar cells and integrated with a tube-and-sheet type thermal collector, the average thermal and PV efficiencies were 40.7% and 11.8%, respectively. In the PV module that was encapsulated with multi-crystalline Si solar cells and integrated with a parallel-plate type thermal collector, the average thermal and PV efficiencies were 39.4% and 11.5%, respectively. Yazdanifard *et al.* carried out a numerical simulation of water-based flat plate PVT system with and without glass cover¹⁶. Laminar and turbulent regime were considered during analysis. It was observed that the total energy and exergy efficiency increased with increasing solar radiation and packing factor. Othman *et al.* designed a hybrid PVT system with combined air and water as the heat removal medium¹⁷. Transparent PV panel was used and mounted on the top of designed system. The electrical efficiency achieved was 17% and thermal efficiency accomplished was 76%. The above studies conclude that the overall efficiency of a PVT collector is notably higher than both the photovoltaic efficiency of a PV module and the photothermic efficiency of a solar thermal collector.

We shall now discuss about solar energy usage for heating/cooling systems. The most common methods to use solar energy for thermal systems are either to use PV to power a compressor in a vapor compression refrigeration (VCR) system¹⁸ or to use solar collectors to provide heat for a sorption refrigeration system^{19–21}. More recently, however, PVT modules coupled with a refrigeration system have been gaining attention too²². In such system, a VCR-only system or a combination of sorption and VCR system can employed^{23–24}. Here, the compressor is powered by the PV panel while the PVT module itself also serves as the evaporator of the refrigeration system. The evaporator cooling effect lowers the solar cell working temperature and improves the photovoltaic efficiency. This arrangement can give an even better performance as compared to air or water cooled systems²⁵. Moreover, the solar thermal energy absorbed by the evaporator may increase the coefficient of performance (COP) of the refrigeration system. In their study, Qu *et al.* investigated a solar PVT integrated dual-source heat pump water heater in Shanghai, China²⁶. They found that the PVT panel

operating temperature can be decreased by up to 45°C, and the electrical conversion efficiency yielded a surplus of 10.3%. Hawlader et al. designed and tested performance of a solar assisted heat pump for dryer and water heater under the climate conditions of Singapore²⁷. The COP value reached 5.0 and the solar fraction was above 60%. Xu *et al.* built an integrated PVT-heat pump system and tested it in Nanjing, China²⁸. The refrigerant was R134a and parabolic concentrators were used to reflect the sunlight on the PV module. Hot water was produced at the condenser. Their experiments showed that the system achieved an averaged COP of 4.8 with an output electrical efficiency of 17.5%. In another paper, Xu *et al.* investigated the effect of modifying the geometry of collector / evaporator from round copper tubes to a multi-port flat extruded aluminum tubes²⁹. They found that the modified collector/evaporator design increased the COP by 7%, thermal efficiency by 6% and electrical efficiency coefficient by 2%.

The survey showed that most of the studies on integrated PVT-refrigeration (PVTR) systems are focused on heating mode. However, in tropical regions like Singapore, cooling (particularly for air conditioning) is the primary requirement throughout the year while hot water is also needed for usage in buildings. Traditionally, these are provided separately by electric-powered air conditioners and water heaters/boilers. In this study, an integrated PVTR system that provides simultaneous air-conditioning and water-heating is proposed. This system is expected to have the following advantages as compared to the traditional air conditioning systems and water boilers:

- Requires less to no electrical power input, because energy is from solar power. This also reduces carbon footprint of the system.
- More compact, because one system can produce both air conditioning and water heating.
- The integrated PVT module is more efficient as compared to a traditional PV panel.

It is the objective of this study to investigate the performance of an integrated PVTR system to provide simultaneous air conditioning and water heating in the tropical conditions of Singapore. The study was carried out numerically with previously validated mathematical models. In addition to the system's performance, cost and environmental impact analyses were also carried out to evaluate the feasibility of the proposed system.

2. Proposed System

The proposed PVTR system produces electricity, hot water and air conditioning at the same time by integrating solar PVT and VCR systems. Electricity is produced by the PV cells, while the refrigeration system produces hot water at its condenser and air conditioning (cooling) at a section of the evaporator through a fan coil unit (FCU). At the same time, the refrigeration system also cools the PVT modules to optimize their performance. The system, therefore, had the following main components: 1) a PVT/evaporator, 2) a compressor, 3) a water-heater/condenser, 4) an expansion device, and 5) a fan coil unit (FCU). A schematic diagram of the proposed system is shown in Fig. 2. The expansion device is an expander that can recover the refrigerant's expansion power³⁰. This power is the used to offset the compressor load.

Fig. 2. Schematic diagram of the proposed PVTR system for air conditioning and water heating

As solar radiation absorbed by the PV cells is converted into electricity, the corresponding solar thermal energy is transferred to the refrigerant flowing in the tubes beneath, evaporating the refrigerant. This keeps the temperature of the PV cells low to optimize its efficiency. The evaporated refrigerant is then compressed in the compressor to increase its temperature and pressure. This refrigerant then enters the condenser where its heat is transferred to the water through a heat exchanger. The hot water is then channeled for use by the occupants of the building. Meanwhile, the refrigerant leaves the condenser into the expansion device, where its temperature and pressure decrease. This low temperature refrigerant then flows into the FCU to provide cooling for the designated air-conditioned room.

The PVT module used in the analysis here was of the tube and sheet type. The PV part comprised layers of glass, ethylene-vinyl-acetate (EVA), solar cells and tedlar. The thermal part comprised copper tubes and an absorber sheet. The copper tubes had diameters of 8 mm. The entire PVT module was encased in an aluminum metallic box with 35 mm glass wool insulation below the absorber sheet to reduce bottom energy losses. The effective area of the whole module was 8 m².

3. Mathematical Model

To analyze the proposed PVTR system, a dynamic simulation model was formulated by coupling an existing VCR model³⁰ with an existing dynamic PVT module model³¹⁻³². In this model, heat was assumed to be conducted mainly in the vertical direction at the PVT modules and the system was in quasi-steady state. The relevant VCR equations are shown in Eqs. (1-4), while those for the PVT modules are in Eqs. (5-10). Definitions of parameters used are expressed in Eqs. (11-19). Values of the design parameters used in this study are tabulated in Table 1, following those from Duffie and Beckman³³ and Tiwari³⁴.

Vapor compression refrigeration (VCR) system equations:

- Cooling (evaporator) / heating (condenser) loads:

$$\dot{Q}_{load} = \dot{m}(enth_{ref,o} - enth_{ref,i}) \quad (1)$$

- Net electrical power consumption:

$$\dot{W}_{net} = \dot{W}_{compressor} - \dot{E}_{expander} - \dot{E}_{PV} \quad (2)$$

- Coefficient of performance (COP):

$$COP_{C/H/Combined} = \frac{\dot{Q}_{load,C/H/Combined}}{\dot{W}_{net}} \quad (3)$$

Photovoltaic-thermal (PVT) module equations:

- Rate of thermal energy collected from the collector:

$$\dot{Q}_{u,c} = A_c F_R \left(h_{p2} (\alpha \tau)_{m,eff} I(t) - U_L (T_{fi} - T_a) \right) \quad (4)$$

- Electrical energy produced by the PV modules:

$$E_{PV} = \eta_{sc} \times N_m \times A_m \times I(t) \quad (5)$$

- Energy balance at the solar cells of the PV module:

$$\begin{aligned} & \tau_g \alpha_{sc} \beta_{sc} I(t) W dx \\ &= \left[\left(U_{tc,a} (T_{sc} - T_a) + U_T (T_{sc} - T_{bs}) \right) W dx \right. \\ & \quad \left. + \eta_{sc} \beta_{sc} I(t) W dx \right] \quad (6) \end{aligned}$$

- Energy balance at the back surface of the tedlar sheet:

$$\begin{aligned} & h_T (T_{bs} - T_f) W dx \\ &= \tau_g \alpha_T (1 - \beta_{sc}) I(t) W dx + U_T (T_{sc} - T_{bs}) W dx \quad (7) \end{aligned}$$

- Energy balance of refrigerant flowing below the PV module:

$$\begin{aligned} & F' h_T (T_{bs} - T_f) W dx \\ &= \dot{m}_f C_f \frac{dT_f}{dx} dx + U_b (T_f - T_a) W dx \quad (8) \end{aligned}$$

- Flat plate collector efficiency:

$$F' = \frac{1}{\frac{W \times U'_L}{\pi D h} + \frac{W \times U'_L}{C_{bond}} + \frac{W}{D + (W - D) F}} \quad (9)$$

- Flow rate factor:

$$F_R = \frac{\dot{m}_f C_f}{A_c U_L} \left[1 - \exp \left(- \frac{A_c U_L F'}{\dot{m}_f C_f} \right) \right] \quad (10)$$

Parameters³³⁻³⁴:

$$F = \frac{\tanh[m(W - D)]/2}{[m(W - D)]/2} \quad (11)$$

$$m = \sqrt{\frac{U'_L}{K \delta}} \quad (12)$$

$$U_L = \frac{U_{iT} \cdot h_T}{U_{iT} + h_T} + U_b \quad (13)$$

$$U_{iT} = \frac{U_{tc,a} \cdot U_T}{U_{tc,a} + U_T} \quad (14)$$

$$U_{tc,a} = \left[\frac{1}{h_o} + \frac{L_g}{K_g} \right]^{-1} \quad (15)$$

$$U_T = \frac{K_T}{L_T} \quad (16)$$

$$U_b = \frac{K_{ins}}{L_{ins}} \quad (17)$$

$$h_o = 2.8 + 3V \quad (18)$$

$$h_{p1} = \frac{U_T}{U_{tc,a} + U_T} \quad (19)$$

$$h_{p2} = \frac{h_T}{U_{tT} + h_T} \quad (20)$$

Table 1. Design parameters of the integrated PVTR cooling and heating system

Parameter	Value	Parameter	Value
A_c	8 m ²	U_b	0.84 W/m ² K
C_f	4190 J/kg K	U_L	5.81 W/m ² K
F'	0.956	U_T	150 W/m ² K
F_R	0.948	U_{tT}	6.81 W/m ² K
h_T	45 W/m ² K	$U_{tc,a}$	7.14 W/m ² K
h_{p1}	0.954	V	1.5 m/s
h_{p2}	0.854	W	0.125 m
K	204 W/m K	δ	0.002 m
K_g	1.0 W/m K	α_{sc}	0.90
K_{ins}	0.042 W/m K	α_T	0.50
K_T	0.033 W/m K	β_{sc}	0.80
L_g	0.003 m	β_o	0.0045
L_{ins}	0.05 m	η_o	0.15
L_T	0.00022 m	τ_g	0.96
$\dot{m}$	0.02 kg/s

Fig. 3. Meteorological data of Singapore

Validations of the models can be found in Refs. 30-32, showing good agreements between simulation and experimental data. For example, discrepancies between predicted and measured COPs obtained with the model were less than 5% in most cases tested³⁰, while discrepancies between simulated and measured hot

water temperatures were less than 5°C in the range of operating conditions studied³².

Performance analysis of the proposed integrated PVTR system was carried out under the tropical climate conditions of Singapore. Meteorological data were averaged out over the years to obtain the hourly variation of solar radiation and ambient temperature³⁵. The averaged wind velocity for Singapore climate was considered as 1.5 m/s in the simulation. The hourly variations of averaged solar intensity and ambient temperature are shown in Fig. 3.

MATLAB computer programming code was used to solve the equations and REFPROP database³⁶ was employed to supply the fluid properties. Mechanical efficiencies of the compressor and expander were considered as 75% and 50%, respectively. R1234yf was chosen as the working fluid. The benchmark condensing temperature was 50°C. The evaporating temperature of the refrigerant was 5°C while the refrigerant temperature at the inlet of the PVT module was 15°C. The corresponding temperature-entropy diagrams are shown in Fig. 4.

Fig. 4. Temperature-entropy diagrams of the PVTR

4. Results and Discussion

In this study, the benchmark system had a condensing temperature of 50°C. The benchmark hourly variations of the refrigerant temperature at various points (compressor inlet, compressor outlet, condenser, evaporator (FCU) and inlet of PVT), ambient temperature and the PV efficiency are shown in Fig. 5. As the time moved closer to noon, the refrigerant temperatures, particularly at the compressor inlet and outlet, increased. They then decreased again after noon time. This trend indicates that refrigerant temperatures followed the solar irradiation intensity closely. The PV efficiency curve mirrored that of the refrigerant temperature. It decreased as the refrigerant temperature increased, and vice versa. The PV efficiency of the benchmark system varied from 14.5% to 12.9% with an average value of 13.6%.

The effects of variation in condensing temperature were studied by observing the performance of the system at condensing temperatures of 50°C, 60°C and 70°C. The corresponding hourly cooling and heating COPs are shown in Fig. 6. At noon, when solar irradiation was highest, the system had maximum COPs at all three

condensing temperatures because of the maximum electrical power produced by the PV modules, hence reducing the net power consumption. Maximum cooling and heating COPs were obtained at condensing temperature at 50°C, which were 14.4 and 16.5, respectively. These are significantly higher as compared to a conventional VCR system, where its cooling COP is typically around 3.4.

Fig. 5. Benchmark system's data

(a)

(b)

Fig. 6. Hourly variations of: (a) cooling and (b) heating COPs

The hourly variations of electrical power saving for compressor at three different condensing temperatures is shown in Fig. 7. The PVTR system is able to save an average of 53% of electrical power. It can be seen that as the condensing temperature decreases, the

percentage power saving increases. Maximum saving is obtained during the peak demand of cooling due to the maximum PV production.

Fig. 7. Electrical power saving

Daily data of total cooling, heating and PV power produced and electrical power consumed by the system at three different condensing temperatures are shown in Fig. 8. The figure shows that as the condensing temperature increases, the cooling and heating production is also increased but the COP of system decreases due to an increase in the compressor power.

Fig. 8. Daily performance data

The performance of the PVTR system was then simulated on annual basis by considering the monthly averaged solar radiation and ambient temperature of Singapore climatic condition. Based on the meteorological data, monthly variation of coefficient of performances (COP) of PVTR system and percentage of energy savings were calculated. Fig. 9(a) shows the monthly variation of cooling, heating, and combined COP and the electrical power savings of PVTR system when compared with a normal vapor compression cycle (VCR). It can be seen that COP of VCR is significantly lower as compared to that of the PVTR system. The monthly variations of cooling, heating and PV power production as compared to power consumed in the system are shown in Fig. 9(b). The monthly variations of the available solar radiation per m² and ambient temperature are also shown in the same figure. It can be seen that the production of cooling, heating and PV power follows the available amount of solar irradiation.

Fig. 9. Monthly performance data

The annual results of energy produced (MWh) at three different condensing temperatures of 50°C, 60°C and 70°C are shown in Fig. 10. The annual cooling, heating and PV energy available are 9.7 MWh, 15.6 MWh and 1.6 MWh, respectively.

Fig. 10. Annual performance data

5. Cost and Environmental Impact Analysis

Cost analysis of the proposed PVTR system was carried out to measure the feasibility of the system for use in Singapore. With a total PVT area of 8 m², the cost of the PVT modules was about S\$5,100. Meanwhile, the

costs of other components, like, compressor, condenser with heat exchanger coils, expander, fan coil unit, refrigerant, flow meters, valves, piping, sensors, data acquisition, including installation was about S\$8,500, based on the costs of things in Singapore at the time of this paper's preparation. Therefore, the total cost of PVTCH system is about S\$13,600. The annual cooling and hot water produced, electrical energy generated, and electric energy consumed by the compressor is 9.7 MWh, 15.6 MWh, 1.6 MWh and 3.7 MWh, respectively. The electricity tariff in Singapore was about S\$0.22/kWh³⁷. The efficiency of instantaneous water heaters and COP of a normal air-conditioning unit was considered as 85% and 3.5, respectively. The parasitic losses (pumps, flow meter, sensors, etc.) from the system were considered as 10% of the compressor power consumption. The total energies produced and consumed by the system per year will be 22,300 kWh and 4,070 kWh, respectively. Hence, the total energy saved per year will be 18,230 kWh and in terms of cost was about S\$5,104 per year. Operational and maintenance cost of system was considered as 10% of total savings per year. Payback period was calculated using the capital recovery factor which refers to the amount of money required each year to offset an initial investment. A very conservative fuel inflation rate was considered as 4%³⁸. Eq. (21) was used for the analysis³⁹ where P is present value, A is yearly savings, i is interest rate and n is number of years.

$$P = A \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] \quad (21)$$

Based on the calculations, the cost of PVTR system was expected to be recovered after approximately 4 years. This shows that the proposed system was financially feasible. In addition, the amount of greenhouse gas (GHG) emission reduction is also analyzed. With an electricity emission factor in Singapore of 0.69 kg of CO₂ per kWh⁴⁰, the estimated greenhouse gas emission reduction annually was about 12.6 tons of CO₂ equivalents (tCO₂e).

6. Conclusion

An integration of a photovoltaic-thermal module with a refrigeration system to produce both air conditioning and hot water was proposed. The system was tested in the tropical climate condition of Singapore using a dynamic simulated model at various hot water / condenser temperatures. The followings were found:

- The proposed system demonstrated a maximum annual cooling COP value of 9.8, a heating COP value of 11.3 and a combined COP value of 21.1.
- The average energy saving of the compressor was about 53%.
- The average photovoltaic efficiency was 14%, which is higher than PV modules without cooling, or when the cooling effect is insufficient.
- The annual PV energy generation was about 1.6 MWh.
- The annual cooling and heating energies available were 9.7 MWh and 15.6 MWh, respectively.
- Estimated cost payback period of the system in Singapore was 3.2 years.
- Greenhouse gas emission (GHG) reduction annually was about 12.6 tons of CO₂ equivalents (tCO₂e).

The study has shown that the proposed integrated PVTR system is an attractive solution to provide air conditioning and water heating more efficiently in Singapore.

Nomenclature

A	Area, (m ²)
C	Specific heat, (J/kg·K)
$enth$	Specific enthalpy, (J/kg)
E	Energy, J
F'	Flat plate collector efficiency factor, (-)
F_R	Flow rate factor, (dimensionless)
h	Heat transfer coefficient, (W/m ²)
h_T	Heat transfer coefficient back surface of tedlar to fluid, (W/m ² ·K)
h_{p1}	Penalty factor due to the glass cover of PV module, (-)
h_{p2}	Penalty factor due to the absorber below PV module, (-)
$I(t)$	Incident solar intensity, (W/m ²)
K	Thermal conductivity, (W/m·K)
$\dot{m}$	Rate of flow of water mass, (kg/s)
M_w	Mass of water, (kg)
N	Total no. of collectors
N_p	No. of collectors connected in parallel
N_s	No. of collectors connected in series
$\dot{Q}_u$	Rate of useful energy transfer, (W)
T_u	Temperature of water used for showering, (°C)
$U_{t,c,a}$	Overall heat transfer coefficient from solar cell to ambient through glass cover, (W/m ² ·K)
U_b	Overall bottom heat transfer coefficient of collector, (W/m ² ·K)
U_T	Overall heat transfer coefficient from solar cell to back surface of tedlar, (W/m ² ·K)
U_L	An overall heat transfer coefficient, (W/m ² ·K)

V Ambient air velocity, (m/s)

W Work (J)

dx Elementary width

Greek Letters

α Absorptivity

$(\alpha\tau)_{eff}$ Product of effective absorptivity and transmissivity

β_o Temperature coefficient

β_{sc} Packing factor of solar cell

η_i Instantaneous thermal efficiency

η_o Efficiency at standard test conditions ($I(t) = 1000\text{W/m}^2$ and $T_{sc} = 25^\circ\text{C}$)

η_{sc} Temperature dependent photovoltaic efficiency of the solar cells

τ Transmissivity

Subscripts

a Ambient

bs Back surface of tedlar

c Collector

eff Effective

f_i Inlet fluid

f_o Outgoing fluid

g Glass

m Module

sc Solar cell

tk Water tank

w Water

References

1. D. Ürge-Vorsatz, L.F. Cabeza, S. Serrano, C. Barreneche and K. Petrichenko, Heating and cooling energy trends and drivers in buildings, *Renew. Sust. Energ. Rev.* **41** (2015) 85-98.
2. NEA (Singapore's National Environmental Agency) (2017), Stricter Energy Performance Standards for Air-Conditioners from September 2016, <http://www.nea.gov.sg/corporate-functions/newsroom/news-releases/stricter-energy-performance-standards-for-air-conditioners-from-september-2016>.
3. NEA (Singapore's National Environmental Agency), *Singapore's Second National Communication: Under the United Nations Framework Convention on Climate Change* (Singapore, 2010).
4. EMA (Energy Market Authority of Singapore), *Electricity Grid Emissions Factors and Upstream Fugitive Methane Emission Factor* (Singapore, 2017).
5. A. Kumar, P. Baredar and U. Qureshi, Historical and recent development of photovoltaic thermal (PVT) technologies, *Renew. Sust. Energ. Rev.* **42** (2015) 1428-1436.

6. N. Aste, G. Chiesa and F. Verri, Design, development and performance monitoring of a photovoltaic-thermal (PVT) air collector, *Renew. Energ.* **33** (2008) 914-927.
7. J. H. Kim, S. H. Park and J. T. Kim, Experimental performance of a photovoltaic-thermal air collector, *Energ. Procedia* **48** (2014) 888-894.
8. A. S. Joshi and A. Tiwari, Energy and exergy efficiencies of a hybrid photovoltaic– thermal (PV/T) air collector, *Renew. Energ.* **32** (2007) 2223–2241.
9. J. K. Tonui and Y. Tripanagnostopoulos, Improved PV/T solar collectors with heat extraction by forced or natural air circulation, *Renew. Energ.* **32** (2007) 623–637.
10. J. H. Kim, J. G. Ahn and J. T. Kim, Demonstration of the performance of an air-type photovoltaic thermal (pvt) system coupled with a heat-recovery ventilator, *Energies* **9** (2016) 728.
11. S. R. Reddy, M. A. Ebadian and 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.
12. K. A. Moharram, M. S. Abd-Elhady, H. A. Kandil and H. El-Sherif, Enhancing the performance of photovoltaic panels by water cooling, *Ain Shams Eng. J.* **4** (2013) 869-877.
13. S. M. Salih, O. I. Abd and K. W. Abid, Performance enhancement of PV array based on water spraying technique, *Int. J. Sustain. Green Energ.* **4** (2015) 8-13.
14. H. Tabaei and M. Ameri, Improving the effectiveness of a photovoltaic water pumping system by using booster reflector and cooling array surface by a film of water, *Iran. J. Sci. Technol.* **39** (2015) 51-60.
15. S. Dubey and A. A. O. Tay, Testing of two different types of photovoltaic-thermal (PVT) modules with heat flow pattern under tropical climate conditions, *Energy Sustain. Dev.* **17** (2013) 1-12.
16. F. Yazdanifard, E. Ebrahimnia-Bajestan and M. Ameri, Investigating the performance of a water-based photovoltaic/thermal (PV/T) collector in laminar and turbulent flow regime, *Renew. Energ.* **99** (2016) 295–306.
17. M. Y. Othman, S. A. Hamid, M. A. S. Tabook, K. Sopian, M.H. Roslan and Z. Ibarahim, Performance analysis of PV/T Combi with water and air heating system: an experimental study, *Renew. Energ.* **86** (2016) 716–22.
18. M. A. I. El-Shaarawi, A. Al-Qutub, S. A. M. Said and A. Adebisi, Technical and economic investigation of solar photovoltaic (SPV) refrigeration system in eastern province of Saudi Arabia, *Int. J. Air-Cond. Ref.* **21** (2013) 1350022.
19. T. O. Ahmadu, C. O. Folayan and F. O. Anafi, Modeling, Simulation and optimization of a solar absorption air conditioning system for an office block in Zaria, Nigeria, *Int. J. Air-Cond. Ref.* **24** (2016) 1650012.
20. A. Sur and R. K. Das, Review of technology used to improve heat and mass transfer characteristics of adsorption refrigeration system, *Int. J. Air-Cond. Ref.* **24** (2016) 1630003.
21. D. S. Kim, C. A. I. Ferreira, Solar refrigeration options – a state-of-the-art review, *Int. J. Refrig.* **31** (2008) 3-15.
22. M. Zeyghami, D. Y. Goswami and E. Stefanakos, A review of solar thermo-mechanical refrigeration and cooling methods, *Renew. Sust. Energ. Rev.* **51** (2015) 1428-1445.
23. J. C. V. Chinnappa, M. R. Crees, S. S. Murthy and K. Srinivasan, Solar-assisted vapor compression/absorption cascaded air-conditioning systems, *Sol. Energy* **50** (1993) 453-458.
24. S. Göktun and I. D. Er, The optimum performance of a solar-assisted combined absorption–vapor compression system for air conditioning and space heating. *Sol. Energy* **71** (2001) 213-216.
25. R. Daghighi, M. H. Ruslan and K. Sopian, Advances in liquid based photovoltaic/thermal (PV/T) collectors, *Renew. Sust. Energ. Rev.* **15** (2011) 4156-4170.
26. M. Qu, J. Chen, L. Nie, F. Li, Q. Yu and T. Wang, Experimental study on the operating characteristics of a novel photovoltaic/thermal integrated dual-source heat pump water heating system, *Appl. Therm. Eng.* **94** (2016) 819-826.
27. M. N. A. Hawlader, S. K. Chou, K. A. Jahangeer, S. M. A. Rahman and K. W. Eugene Lau, Solar-assisted heat-pump dryer and water heater, *Appl. Energ.* **74** (2003) 185–193.
28. G. Xu, X. Zhang and S. Deng, Experimental study on the operating characteristics of a novel low-concentrating solar photovoltaic/thermal integrated heat pump water heating system, *Appl. Therm. Eng.* **31** (2011) 3689-3695.
29. G. Xu, S. Deng, X. Zhang, L. Yang and Y. Zhang, Simulation of a photovoltaic/thermal heat pump system having a modified collector/evaporator, *Sol. Energy* **83** (2009) 1967-1976.
30. A. Subiantoro and K. T. Ooi, Economic analysis of the application of expanders in medium scale air-conditioners with conventional refrigerants, R1234yf and CO₂, *Int. J. Refrig.* **36** (2013) 1472-1482.
31. S. Dubey and G. N. Tiwari, Thermal modeling of a combined system of photovoltaic thermal (PV/T) solar water heater, *Sol. Energy* **82** (2008) 602–612.
32. S. C. Solanki, S. Dubey and A. Tiwari, Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors, *Appl. Energ.* **86** (2009) 2421-2428.
33. J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes* (John Wiley & Sons, New York, 1991).
34. G. N. Tiwari, *Solar Energy: Fundamentals, Design, Modeling and Applications* (Narosa Publishing House, New Delhi, 2004).

35. National Renewable Energy Laboratory (2017), https://www.nrel.gov/rredc/solar_data.html.
36. E. W. Lemmon, M. L. Huber and M. O. McLinden (2013), NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg.
37. Singapore's Energy Market Authority (2017), <https://www.ema.gov.sg/index.aspx>.
38. Trading Economics (2018), Singapore Inflation Rate 1962-2018, <https://tradingeconomics.com/singapore/inflation-cpi>.
39. O. W. Eshbach, *Eshbach's Handbook of Engineering Fundamentals* (Wiley, New York, 1990), p. 71.
40. DEFRA (2012). Guidelines to DEFRA / DECC's greenhouse gas conversion factors for company reporting. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69568/pb13792-emission-factor-methodology-paper-120706.pdf.