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Studying the Effect of Shading by Rooftop PV Panels on Dwellings' Thermal Performance

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***Abstract*—**Thermal performance is considered to be a key measure in building sustainability. One of the technologies used in the current building sustainable design is the rooftop solar PV power generators. The application of this type of technology has expanded vastly during the last five years in many countries. This paper studies the effect of roof shading developed by the solar PV panels on dwellings' thermal performance. The analysis in this work is performed by using two types of packages: "AccuRate Sustainability" for rating the energy efficiency of residential building design, and "PVSYST" for the solar PV power system design. The former package is used to calculate the annual heating and cooling load, and the later package is used to evaluate the power production from the roof top PV system. The analysis correlates the electrical energy generated from the PV panels to the change in the heating and cooling load due to roof shading. Different roof orientation, roof inclination, roof insulation, as well as PV panel area are considered in this study. The analysis shows that the drop in energy efficiency due to the shaded area of the roof by PV panels is negligible compared to the energy generated by these panels.

***Keywords*—**Energy efficiency, roof shading, thermal performance, PV panel.

I. Introduction

THE major factors affecting the thermal performance of buildings are basically related to the building architecture design such as: the roof type (e.g., gable or flat), roof orientation, shading from adjacent objects, building materials (e. g., double brick or brick veneer walls), insulation, and glazing. In cold weather zones, shading building façade or roof may reduce the heat gain of the building and increase the heating load during the cold season. On the other side, in hot or warm weather zones, shading the building façade and/or the roof will reduce cooling load and increase building thermal performance. The effect of PV panels shading on heat transfer through flat roof building was simulated and tested by [1]. Part of the roof was covered with PV panels and ceiling temperature measure was conducted to verify and validate the mathematical heat transfer model. The study showed that the reduction in cooling load due to the shaded roof by PV panel is more than the reduction in heating load which enhances the annual net energy balance of the building by 4%. Another work by Kotak et al. [2] studied the effect of rooftop PV panels on cooling load of a flat roof house using computer simulation. The results show that there is significant decrease in cooling load due to the roof area shaded by PV panels. However, the heat transfer model in this study did not consider insulation to the roof or ceiling below the PV panels. A simulation model has been developed to evaluate cooling load and heat gain components through an inclined PV roof structure [3]. It was found that installing of PV rooftop may reduce cooling load by 35% for the roof design considered in that work (gable roof without significant insulation layer). The air gap between PV panels and roof surface as well as roof inclination angle were found to be major factors affecting thermal and energy performance of the building. A thermal model for an inclined PV panel mounted on a ventilated structure was developed by [4]. This model evaluated the total heat loss coefficient of the panel surface and predicted its temperature response time. The study which was validated by experimental test showed that heat loss by radiation between panel surface and sky is very low compared to the convective heat loss and it can be neglected in the thermal model.

Roof orientation and inclination has a significant effect on solar heat gain as well as power generated by the rooftop PV system. A review of optimum tilt and azimuth angles of a rooftop PV panel was conducted considering climate conditions and surrounding obstacles [5]. The study concluded that the optimum tilt angle is closer to location latitude if the clearness index value is constant during the year. It was observed that optimum tilt and azimuth angle of the PV panel was influenced significantly by the surrounding obstacles such as adjacent buildings. Another analytical study was conducted on a larger scale system (50 kW output) and was concluded that maximum PV panel yield occurs when PV panel tilt angle is about 1.5° less than site latitude angle [6]. The impact of roof design on produced solar potential of urban building was studied by [7]. Three types of roof designs were considered in this study: flat, gabled, and lean-to-roof. The results showed that the contribution of solar energy in covering the demand of hot water and electricity of a building is higher in case of the flat roof than the gabled roof design. This is because, in the case of the gabled roof, there will be less irradiation on the side of the roof opposing the sun. The optimal configuration in the roof of the housing unit was implemented to increase the solar potential of the building integrated PV/Thermal system [8]. The effect of the roof configuration shape on energy performance in terms of heating and cooling load was investigated by computer modelling. It was found that the effect of different roof design on heating and cooling loads is less than 5%. However, it was concluded that the integration of PV/ thermal system in the roof design of different orientation enables the spread of peak electricity timing over longer operation hours. This work did not show how to overcome the complexity in the PV roof top installation

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associated with the folded roof design. A breakdown of heat loss and heat gain rate by a house envelope was investigated by [9]. They found that the highest amount of heat loss rate takes place in the ceiling/roof and represents 62% of the total heat loss from building envelope. The heat gain rate by the ceiling/roof was found significant and represents 33.5% of total heat gain rate by the building envelope.

The literature review of the roof top PV system does not show significant analysis of designs that have roof space with insulation. Work in this prospect was found to be substantial to find the effect of shading from PV panels on energy efficiency of the dwellings. This paper studies the effect of shading developed by roof top PV panels on cooling and heating load. The proposed analysis correlates the electric energy generated from the PV panels to the heating and cooling load of a dwelling with roof space design at different roof orientation angles.

II. Thermal Modelling of the Roof

The type of roof considered in this study is gabled roof with PV panel arrangement similar to the design shown in Fig. 1. Thermal modelling for this design can be developed by considering the thermal resistance of different components between the external air and the inner space of the dwelling. There are nine major thermal resistances identified in this roof design, these are:

R1: Thermal resistance of external air adjacent to roof surface.
R2: Thermal resistance of PV panel material.
R3: Thermal resistance of air space between panel and roof surface.
R4: Thermal resistance of roof material (tiles or metal sheet).
R5: Thermal resistance of air gap between roof material and sarking sheet.
R6: Thermal resistance of gabled roof space.
R7: Thermal resistance of insulation above ceiling.
R8: Thermal resistance of ceiling material.
R9: Thermal resistance of inner space air adjacent to ceiling.

Some of these thermal resistances are quite standard and can be selected from tables based on roof type and roof design such as R4, R5, R6, R7, R8, and R9 [10]. Thermal resistance R2 can be calculated by adopting the PV module thermal conductivity given by [3], [4]. The remaining thermal resistances R1 and R3 are affected by surrounding conditions and can be calculated by using conventional heat transfer formulas [11]. To find R1, two components of heat transfer coefficients are considered: heat transfer coefficient by convection of the ambient air, and heat transfer coefficient by radiation with sky temperature,

$$R1 = \frac{1}{h_{c1}+h_{r1}} \qquad (\text{m}^2.^{\circ}\text{C/W}) \qquad (1)$$

where h_{c1} and h_{r1} are the heat transfer coefficients by convection and radiation respectively, and can be found by [11],

$$h_{c1} = \left(\frac{k_a}{L}\right) Nu1 \qquad (\text{W/m}^2.^{\circ}\text{C}) \qquad (2)$$

where *Nu1 is* the Nusselt number,

$$Nu1 = (0.037xRe^{0.8} - 871)xPr^{1/3} \quad \text{(with wind)} \qquad (3)$$

Or,

$$Nu1 = 0.59xRa^{1/4} \quad \text{(with no wind)} \qquad (4)$$

where, *Pr* - Prandtl number, *Re* – Reynolds number, K_a - Thermal conductivity of air (W/m°C), *L* - PV array length (m), *Ra* is Rayleigh number found by [10]

$$Ra = 9.81 \times \beta_t \times (T_{pb} - T_{rs}) \times \left(\frac{L^3}{v^2}\right) \times Pr \qquad (5)$$

where, T_{pb} is temperature of PV panel back surface found by [3],

$$T_{pb} = T_{pv} - \left(\frac{Irr}{1000}\right)^3 \qquad (\text{K}) \qquad (6)$$

where T_{rs} is temperature of roof surface. β_t – *Thermal expansion = 1/Ta [K^{-1}]*. Also,

$$h_{r1} = \varepsilon_{pv}\sigma\left(T_{pv}^2 + T_{sky}^2\right)\left(T_{pv} + T_{sky}\right) (\text{W/m}^2.^{\circ}\text{C}) \qquad (7)$$

where, ε_{pv} - Emissivity of PV panel upper surface, σ - Stefan–Boltzmann constant ($5.670367\text{x}10^{-8}$ W·m^{-2}·K^{-4}), T_{sky} - Sky temperature (K), found by [12],

$$T_{sky} = T_a - 20 \qquad (8)$$

T_{pv} is PV surface temperature is given by [13],

$$T_{pv} = T_a + (0.022)\text{Irr} \qquad (\text{K}) \qquad (9)$$

where *Irr* is the solar irradiation (W/m^2), and T_a is the ambient temperature (K).

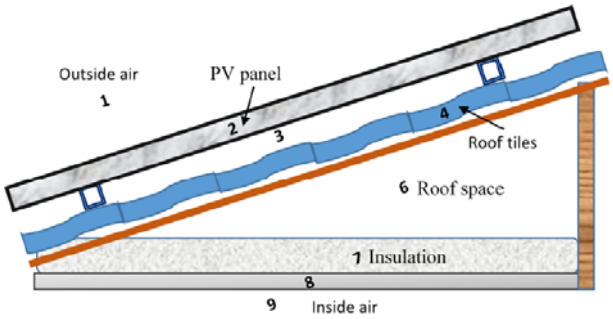


Fig. 1 Gabled roof covered with PV panel

R2 can be evaluated by knowing the PV panel thickness (x), and thermal conductivity (k) where,

$$R2 = \frac{x}{k} \qquad (\text{m}^2.\ ^{\circ}\text{C/W}) \qquad (10)$$

To find *R3,* a similar approach to *R1* is considered using heat transfer coefficient by natural convection in the air gap (h_{c3}) and heat transfer coefficient by radiation between roof surface and PV panel back surface (h_{r3}), where

$$R3 = \frac{1}{h_{c3}+h_{r3}} \quad (\text{m}^2.\,^\circ\text{C/W}) \quad (11)$$

h_{c3} is the heat transfer coefficient by convection for open ended space given by [3],

$$h_{c3} = \left(\frac{k_a}{La}\right) \times 0.644 \times \left(\frac{x_a}{La}\right) Ra \times \sin(\beta)^{0.25} \ (\text{W/m}^2.^{\circ}\text{C}) \quad (12)$$

where La is the length of the air gap (m), x_a is the air gap height (m), h_{r3} is found from heat radiation equation between two parallel surfaces [11] where,

$$h_{r3} = \sigma \times \frac{(T_{pb}^2+T_{rs}^2)\times(T_{pb}+T_{rs})}{\left(\frac{1}{\varepsilon_{pb}}+\frac{1}{\varepsilon_{rs}}-1\right)} \quad (\text{W/m}^2.^{\circ}\text{C}) \quad (13)$$

where ε_{pb}, ε_{rs} are the emissivity of PV panel back surface and emissivity of roof surface, respectively.

The thermal model of the rooftop PV design presented by the thermal resistances R1 to R9 and their associated equations (1)-(13) were used to find out the effect of ambient temperature, optimum insulation size, and solar irradiation on heat transfer through a gabled and a flat roof dwelling. This design was compared with uncovered roof design by eliminating R2, and R3 from the heat transfer model as well as adjusting (7) to address the roof tile temperature T_{rs} rather than PV surface temperature T_{PV}.

III. Thermal Analysis of the Roof System

Engineering equation solver package (EES) [14] was used to investigate the most significant thermal resistance that affect heat transfer through the proposed roof design. The value of these thermal resistances is given in Table I. It is clearly shown that the optimum roof insulation R7 (4 m^2. °C/W) is greater than the total of other roof components thermal resistance which was found in the range of 1.05 – 2.01 m^2. °C/W. Since R7 is the major thermal resistance in the roof design of this study, it was important to investigate its effect on the heating and cooling load of a dwelling. Fig. 2 shows the effect of increasing R7 on heat gain from a PV roof top, and a non PV roof design.

TABLE I
Thermal Resistance of Roof System

Thermal resistance	Winter value (m^2. C/W)	Summer value (m^2. C/W)
R1	0.0614	0.06
R2	0.0075	0.0075
R3	0.221	0.184
R4	0.02	0.02
R5	0.18	0.16
R6	0.34	1.36
R7	4.0	4.0
R8	0.06	0.06
R9	0.16	0.16

The difference in heat loss from the roof between both designs decreases as the value of R7 increases up to a value of R7 equal to 4 m^2. °C/W where the difference in heat loss starts to be negligible. The other finding from Fig. 2 is that the size of insulation (4 m^2. °C/W) represents the optimum limit as after this size the heat loss tends to be almost constant and adding extra insulation becomes unfeasible. This size of insulation is considered to be standard in modern building designs to achieve maximum energy efficiency of dwellings.

Further investigation of the effect of ambient temperature on heat transfer through the roof is conducted at constant irradiation (500 W/m^2), average wind speed 3 m/s, and R7 value equals to 4 m^2. °C/W. The results are shown in Figs. 3 and 4 for winter and summer ambient temperatures. These figures show that the difference in heat loss or heat gain between the PV and non PV roof is quite small and it is in the range of 3 – 4.5%.

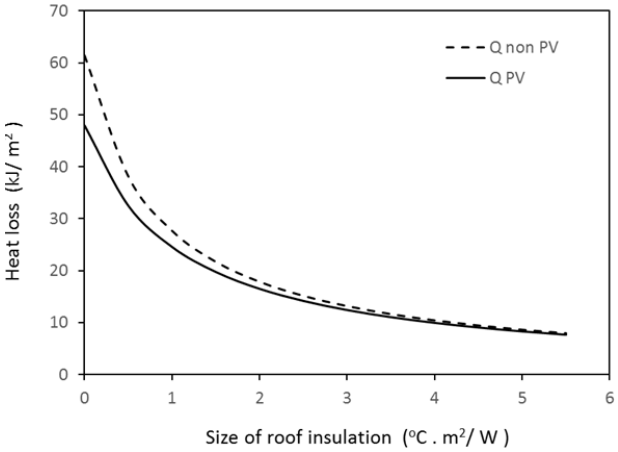


Fig. 2 The effect of insulation size on the heat loss from a PV and non PV gabled roof at irradiation 500 W/m^2, wind speed 3m/s, and ambient temperature 10 °C

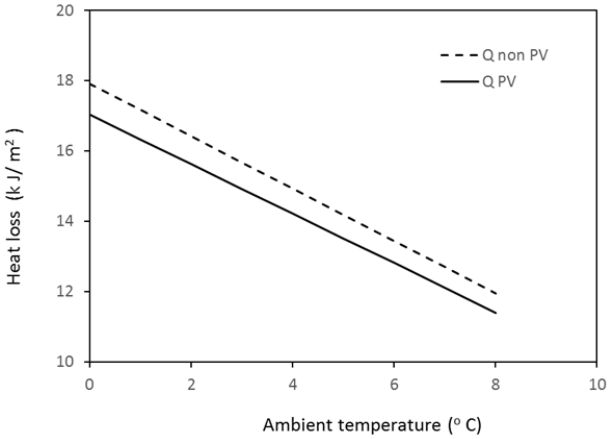


Fig. 3 The effect of low ambient temperatures on the heat loss from the roof - at irradiation 500 W/m^2, wind speed 3 m/s, and roof insulation 4 m^2. °C/W

IV. Transient Analysis of Roof System Heating and Cooling Load

Annual performance analysis was conducted to evaluate the effect of covering the gabled roof by PV panels on total heating and cooling load (Q_{hc}) of a dwelling. The benchmark software "AccuRate sustainability" [15] for house energy

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rating in Australia was used to perform energy modelling of a single story double brick dwelling. The total floor area of the dwelling is 84 m^2 divided into 74 m^2 conditioned area, and 10 m^2 unconditioned area. Glazing to wall ratio of each dwelling side is: 18.5% N, 15.8% E, 11.9% W, and 10% S. Roof inclination of this dwelling is 22° following the Australian standard [16] and consists of the same parts shown in Fig. 1. The northern side of the roof (facing the sun) was assumed to be fully covered by PV panels. The energy rating analysis was conducted on different dwelling orientations and different roof azimuth angles: 0° N, 45°NE, 90° E, 270°W, and 315 NW with PV arrangement similar to Fig. 5. The energy rating simulation was conducted twice for each dwelling orientation, once with roof covered by PV panels and another run without PV panels. To simulate the roof shaded by PV panel, another layer with similar thermal conductivity and air gap was added to the construction option of "AccuRate". The effect of roof insulation on annual heating and cooling load of the prescribed dwelling was conducted for two types of roof: gabled and flat roof design. The aim of this analysis is to investigate the effect of transient weather condition on the heat transfer through a roof covered by PV panels. The effect of roof insulation on annual (Q_{hc}) load was estimated in MJ per square meter of roof floor area and the results are presented in Fig. 6. The trend of the results is quite similar to what was shown by Fig. 2 where optimum insulation size was found to be about 4 m^2. °C/W. At this size of insulation, the type of roof design (gabled or flat) does not change the total heating and cooling load significantly. This finding leads to the conclusion that adding new modules to the external surface of the roof such as PV panels will not have a significant effect on the total (Q_{hc}) load if roof insulation is within the optimum range. It is clear from Fig. 6 that gabled roof has less (Q_{hc}) load than the flat roof for insulation of R values less than R2.5. This is because the thermal resistance of the gabled roof air space becomes dominant at low R values of insulation. It is worthwhile to mention here that the percentage change in Q_{hc} due to roof top PV panel shading may have a positive or negative impact on energy consumption by space air-conditioning. The annual percentage of change in Q_{hc} due to PV panel shading was estimated at different roof orientation and shown in Fig. 7. In some roof orientation such as the West roof (azimuth angle is 270°), the percentage of decrease in Q_{hc} is 3%, i.e., adding PV panel to the roof will improve the dwelling thermal efficiency due to the reduction in heating and cooling loads. It can be concluded from Fig. 7 that the percentage of increase in Q_{hc} in general is very small (between 0.15 to 0.7%) at roof azimuth angles 0, 45, and 315° due to the increase in heating load at these roof orientations. In general, Fig. 7 shows that the percentage of change in Q_{hc} is very small and it is in the range of -3 to 0.74%.

V. PV Energy Contribution to the Heating and Cooling Load

The annual electricity produced by the PV panels covering the northern side of the proposed dwelling was estimated using the simulation package "PVSYST" [17] at Sydney weather conditions and site latitude 33.5° south. The main specification of the PV system used in this study was adopted from [18] which uses an identical mono crystalline silicon PV panels mounted on 22° slope gabled roof. The total roof area of the adopted dwelling is 90 m^2 divided evenly between north and south side. The PV panel's area covering the northern roof is 42 m^2 and its estimated capacity is 4.4 kW.

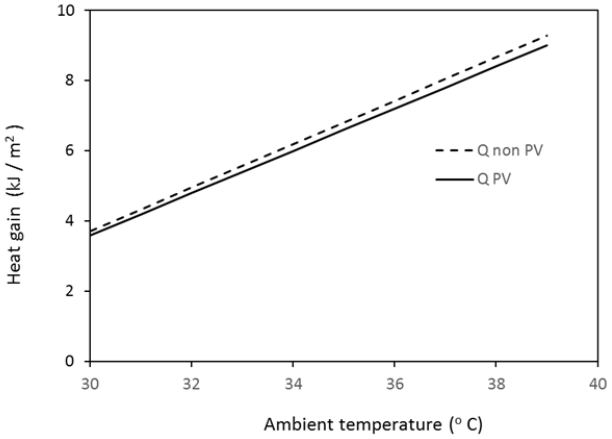


Fig. 4 The effect of high ambient temperature on the heat gain from the roof - at irradiation 500 W/m^2, wind speed 3 m/s, and roof insulation 4 m^2. °C/W

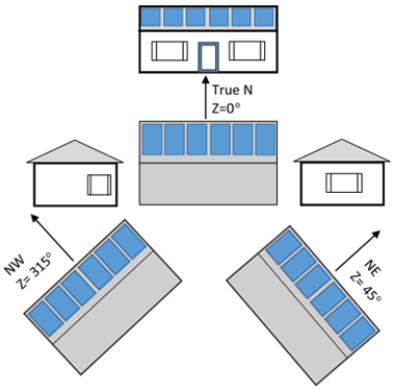


Fig. 5 PV roof top arrangements

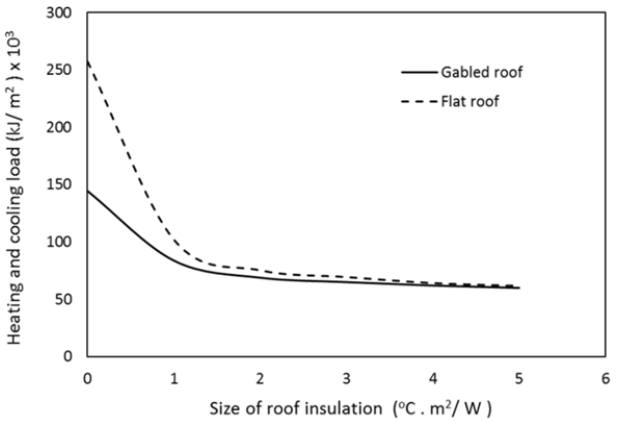


Fig. 6 The effect of roof insulation on annual heating and cooling load for gabled and flat roof design

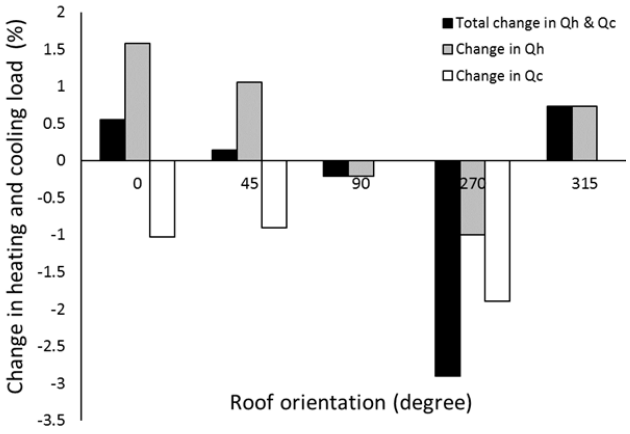


Fig. 7 The percentage of change in annual heating and cooling load due to shading developed by the PV panels on a gabled roof

In order to investigate the overall impact of the roof top PV panel on the dwelling energy efficiency both solar energy generated by the PV system and the change in Q_{hC} due to roof shading by the PV panels must be considered. A formula that describes the ratio of net energy produced by the solar PV system to the heating and cooling load Q_{hC} with no PV rooftop system was developed and given by,

$$PVR = \frac{Q_{PV} - [(Q_{hc})_{PV} - (Q_{hc})_{NPV}]}{(Q_{hc})_{NPV}} \quad (14)$$

where, PVR – The ratio of PV energy to the heating and cooling load with no PV rooftop. Q_{PV} – Energy produced by PV system (MJ/m^2 of roof area), $(Q_{hc})_{PV}$ – Heating and cooling load of the dwelling with PV roof (MJ/m^2 of roof area), $(Q_{hc})_{NPV}$ – Heating and cooling load with non PV roof top (MJ/m^2 of roof area).

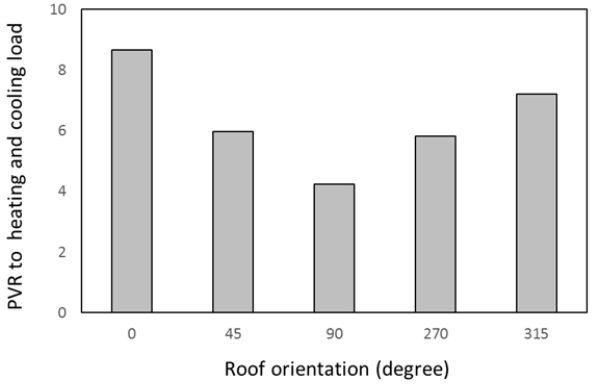


Fig. 8 The ratio of energy produced by the rooftop PV system to the heating and cooling load (roof is facing north and fully covered by PV panels)

The PVR value in (14) depends on two major factors: the energy produced by the PV panels covering the roof, and the size of the dwelling that contributes significantly in the amount of Q_{hC}. The maximum PVR value can be achieved when Q_{PV} is maximum and $(Q_{hc})_{PV}$ is less than $(Q_{hc})_{NPV}$. The PVR was estimated at different roof orientation and the results are shown in Fig. 8. It is quite obvious that the northern orientation yields the highest value of PVR due its highest value of energy production. Fig. 8 shows that the smallest value of PVR is when the roof is facing east, i.e., azimuth angle equals 90°. It can be concluded from Fig. 8 that the effect of change in Q_{hC} due to PV roof top installation is negligible compared to the green energy produced which can cover, with surplus, the heating and cooling load of the dwelling.

VI. Conclusion

In this paper, the effect of installing rooftop PV panels on heating and cooling load of a typical dwelling was investigated. Thermal modelling of gabled roof was developed considering the thermal resistance of different roof components. The thermal model showed that roof/ceiling insulation is the key thermal resistance in the model and the heat gain and loss from the roof becomes almost steady when insulation size approaches 4 m^2. °C/W. At this insulation size, the model showed that adding extra components to the external surface of the roof has a minor effect on heat gain or heat loss. To investigate the effect of shading developed by the roof top PV panels on the dwelling energy efficiency two types of software where used, "ACCURATE sustainability" for dwelling thermal assessment, and "PVSYST" for energy production by the PV system. The results of thermal assessment showed that in some roof orientation, such as the east and west roofs, adding rooftop system will cause a reduction in total thermal load of the dwelling. However, the ratio of this reduction is minor and represents only 3% of the total heating and cooling load. The other factor that improves dwelling energy efficiency is the solar electricity (green energy) produced by the PV system. Both factors were integrated in one equation that estimates the value (PVR) which is the ratio of net energy produced by PV system to the energy required to cover the heating and cooling load of the dwelling. The results show that the impact of adding PV roof top system on a dwelling thermal efficiency is negligible compared to the amount of green energy produced by that system which covers with surplus the heating and cooling load.

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