COMPARATIVE ANALYSIS OF LOW AND HIGH EFFICIENT PV ROOF AIR HEATING CAPACITY FOR ZERO ENERGY HOME BUILDERS' DESIGN DECISION MAKING

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Abstract

The 'Z-en house' is a zero-energy housing project being carried out by ROBERTRYAN Homes based in North Ayrshire, Scotland. In this project, the application of a PV Thermal (PV/T) solar roof has been reviewed and the PV heated ventilation air is intended to be circulated throughout the house with the support of a mechanical ventilation with heat recovery (MVHR) system—i.e. PV/T MVHR. Accordingly, using this Z-en house project, a feasibility study on hypothetical PV/T MVHR systems was conducted with the aim to facilitate the builder's design decisions, where the heat from PV modules should be used optimally to supplement space heating, while the expected power generation can well be maintained without being reduced drastically by the cumulative PV heat. The heat generating capacity of low efficient PV cells (e.g. amorphous) and the high efficient counterparts (e.g. mono- or poly-crystalline) was analysed using the energy and environment simulation tool *EESLISM*. The air flow assisted by the MVHR system was assumed to be 300m^3/h and drawn under either a 7% efficient PV roof with the module coverage of 57.14m^2 or a 14% efficient PV roof of 28.57m^2. In both scenarios, the roof was also assumed to be tiled at 30˚. As a result, when the roof receives the high incoming solar radiation, say 367W/m^2 at 13.00 on 30th January in Scottish climatic contexts, and the ambient temperature is 5˚C, the temperature of ventilation air under the low efficient PV roof can increase to 20˚C at the ridge, while the temperature under the polycrystalline may reach up to 16˚C when the nominal power output of both systems is set to be 4kW. Not only does this study unveil the differences in the heat and power generation capacity of low and high efficient solar PV roofs, but it catalogues the potential variations (i.e. mass customisation) in response to the change of settings as to the MVHR air flow velocity and the PV power output, roof angle and area, so that builders based in similar cool climates can choose from the collection.

1. Introduction

The zero carbon homes being recognised under the Code for Sustainable Homes in the UK tend to be low-energy houses rather than the net zero energy ones when they come into operation. To realise the delivery of net zero-energy housing in Scotland, the 'Z-en house' project was launched by ROBERTRYAN Homes. The design solutions are currently examined in order to achieve the house's net zero energy operation in view of the UK government's recognised Standard Assessment Procedure known as SAP (BRE, 2011) (Fig.1). ROBERTRYAN homes is an experienced homebuilder dealing with a wide range of residential construction projects and the company is currently planning to build total 4 net zero energy detached homes. In this project, PV/T will be installed in a way that the ventilation air heated by PV integrated roof is extracted by means of a balanced whole-house mechanical ventilation with heat recovery (MVHR) system, which has possibly the high heat exchange efficiency and low specific fun power (Fig.2).

Figure 1: Z-en House South-west Façade (Source: MEARU Mackintosh School of Architecture)

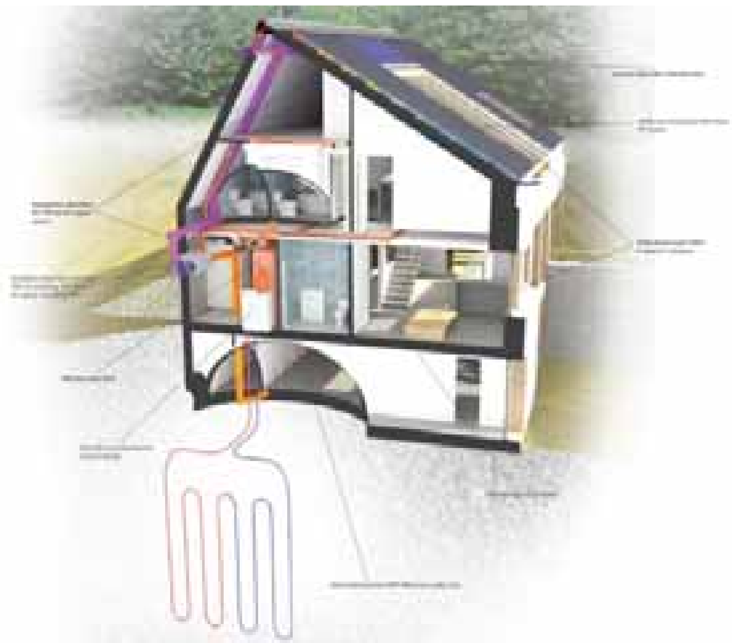


Figure 2: Building Integrated PV Thermal Mechanical Ventilation Heat Recovery System (BIPV/T MVHR)

(Source: MEARU Mackintosh School of Architecture)

The Z-en house is a single detached home to be built in a new rural residential development in West Kilbride, Scotland. The floor area of this house is approx. 346m^2 excluding the basement floor area and the exposed wall area was estimated at 279m^2. The house contains 4 bedrooms and a study are located on the first floor and semi-private spaces, such as a kitchen, dining room, lounge, and sunspace family room, are on the ground floor. A basement is also introduced to this project, designed to serve as a multifunctional space, in which thermal mass components are installed heavily so as to capture heat from the sun and active hybrid renewable energy technologies including the BIPV/T MVHR system, which is relatively new to the homebuilding industry in the UK.

2. PV/T HR Performance Simulation

Based on the initial conceptual design of the Z-en house, the potential performance of a photovoltaic thermal mechanical ventilation heat recovery (PV/T MVHR) system was examined under Scottish climatic conditions. For the comparative analysis of the system's potential seasonal changes as to the heat and power generation properties which may relate to the amount of available solar radiation and the ambient temperature, 30th January and 24th August were selected (Table 1).

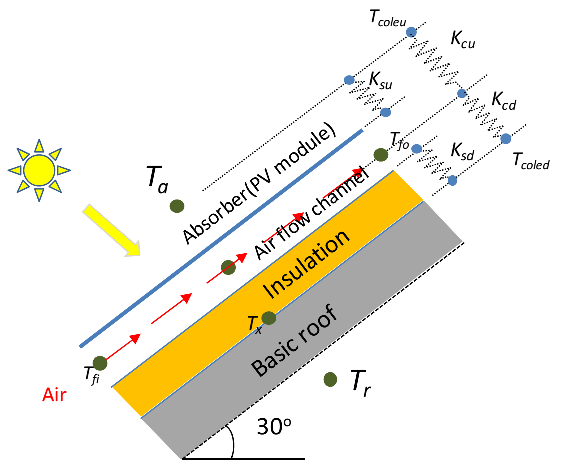
Tab. 1: Solar Radiation and Temperature Profiles, 30th January and 24th August

Time	30th January		24th August	
	Solar Radiation On Roof Surface (W/m^2)	Ambient Temperature (˚C)	Solar Radiation On Roof Surface (W/m^2)	Ambient Temperature (˚C)
1	0	6	0	8
2	0	5.2	0	7.8
3	0	4.4	0	7.3
4	0	4.8	0	6
5	0	5.2	0	5.2
6	0	5.6	12	5.2
7	0	5.4	92	7.1
8	0	5.3	266	10.2
9	6	5.1	470	12.4
10	109	5.1	664	12.7
11	263	5	805	14.3
12	327	5	883	15.2
13	367	5.1	891	16.1
14	286	5.3	814	16.5
15	150	5.4	688	16.6
16	71	5.3	517	15.4
17	9	5.3	331	14.6
18	0	5.2	157	14.1
19	0	5.4	54	13.5
20	0	5.7	7	12.8
21	0	5.9	0	12.1
22	0	6.1	0	11.6
23	0	6.4	0	11.1
24	0	6.6	0	10.7

In particular, 30^{th} January was used as a base date for the detail analysis of the effect of roof configurations on PV/T heat and power generation in the Scottish winter. Due to the need for the use of consistent and detailed statistical weather data, the database of Scottish climate supplied by the 'Energy Plus' building simulation program developed by the US Department of Energy was applied for the PV thermal system simulation.

2.1. BIPV/Thermal Simulation Model

This simulation was based on the authors' previous studies (Udagawa et al., 2009; Hirayanagi et al, 2011). It was conducted using the 'EESLISM' applied for heating, cooling and hot water heating simulation. Since 1990, the simulation tool has been developed constantly and in 2009, it included the performance analysis of solar air heating collector systems combined with PV panels (Udagawa and Satoh, 1999; Udagawa et.al., 2009). Accordingly, the EESLISM simulation of the Z-en house's PV/T HR system encompassed the analysis of heat production capacity and the identification of power generation potential (Fig.3).



T_a	Outside Temperature [°C]
T_r	Indoor Temperature [°C]
K_{su}	Specific Heat Loss Coefficient of the Upper Element of the Ventilated PV Heat Collecting Channel [W/m^2K]
K_{sd}	Specific Heat Loss Coefficient of the Bottom Element of the PV/T Heat Collecting Channel [W/m^2K]
K_{cu}	Thermal Transmittance of the Upper Element of Ventilated PV Heat Collecting Channel [W/m^2K]
K_{cd}	Thermal Transmittance of the Bottom Element of Ventilated PV Heat Collecting Channel [W/m^2K]
T_{coleu}	Outer Surface Temperature of the Heat Collector Panel [°C]
T_{coled}	Inner Surface Temperature of the Heat Collector Panel [°C] (For the roof integrated collector, it equals to the boundary temperature T_x.)
T_{fi}	Inlet Air Temperature [°C]
T_{fo}	Outlet Air Temperature [°C]

Fig. 3: Section of BIPV/T Roof and Description of Denotations Applied to the EESLISM simulation

In the ventilated PV/T system's performance simulation, the fresh air was assumed to pass through the underside of solar roof panels and then connected to an MVHR system. Various air flow volumes were considered and set initially to be 300m^3/h, 432m^3 and 864m^3/h amounting to the air velocity of 0.45m/s, 0.5m/s and 1.0m/s, respectively. It was aimed particularly at identifying the temperature rise tendency of ventilated PV/T air and quantifying the potential heat generation, given that the fresh air runs through a cavity (0.03m in depth and 8m in width) created beneath a PV integrated solar roof.

The outlet air temperature of the PV/T collector was calculated by:

$$T_{fo} = \left(T_{cole} - T_{fi}\right)e^{-\frac{K_C A_{SU}}{CG}}$$

(eq. 1)

K_c is the total thermal transmittance of the heat collector panel (W/m^{2}K) and it was calculated by means of:

$$K_c = K_{cu} + K_{cd}$$

(eq. 2)

$$T_{cole} = k_u T_{coleu} + (1 - k_u)T_{coled}$$

(eq. 3)

$$T_{coleu} = \frac{(a_s - \eta_{PV0})I_{col}}{K_{su}} + Ta$$

(eq. 4)

$$k_u = \frac{K_{cu}}{K_c}$$

(eq. 5)

$$K_{cu} = K_{su} f_{cu}$$

(eq. 6a)

$$K_{cd} = K_{sd} f_{cd}$$

(eq. 6b)

Where,

Asu : Area of the PV/T roof collector (m^2)

as : Solar absorbance of PV (-)

η_{PVo}: Efficiency of PV at standard test conditions (-)

Icol : Solar radiation on PVT array (W/m^2)

C is the specific heat of air (J/kgK). G represents the air flow rate (kg/s) and the symbols of other parameters are explained in Fig.3. Based on them, the collected heat Q [W] is calculated by:

$$Q = CG(T_{fo} - T_{fi}) \tag{eq. 7}$$

$$E = K_{pv}(T_{pv}) I_{col} A_{su} / I_s \tag{eq.8}$$

The power generation of PV array E [W] is calculated based on JIS C8907:2005 as shown in Equation 8. Where, $K_{pv}(T_{pv})$ is a coefficient expressing the effects of PV cell temperature T_{pv} and other parameters to effect on the PV power generation. Is is solar radiation on PV array at the standard test condition (1000W).

For the purpose of this simulation, two types of PV cells were selected: (1) polycrystalline silicon PV whose conversion efficiency was assumed to be 14% and (2) amorphous silicon PV with 7% efficiency. Moreover, two sets of nominal power output, 4kWp and 8kWp, were set in order to analyse the differences in heat and power generating performance between the high and low efficient BIPV modules. The size of each PV/T integrated roof was determined according to the PV type and nominal output given (Table 2). The depth of the PV/T air cavity applied to all variations was fixed to be 0.03m and therefore, the area of the aperture of the inlet fresh air is 0.24m^2. The sectional dimension led to the setting of the volume and velocity of the PV/T air. The simulation was conducted using EESLISM where the room temperature was assumed to be 21˚C for 24 hours of housing operation. Moreover, in order to facilitate builders' design decision for PV/T integrated roof configurations, the effect of roof angles (30˚, 40˚ and 50˚ alternatives) on the BIPV heat and power generation performance was also analysed.

Tab. 2: PV/T System Variations Applied to the EESLISM Simulation

PV TYPE	CONVERSION EFFICIENCY	NOMINAL POWER OUTPUT	PV/T COLLECTOR ROOF AREA
Amorphous Silicone	7%	4kWp	57.14m^2 (8m in width & 7.14m in length)
		8kWp	114.28m^2 (8m in width & 14.28m in length)
Polycrystalline Silicone	14%	4kWp	28.57m^2 (8m in width:& 3.58m in length)
		8kWp	57.14m^2 (8m in width & 7.14m in length)

2.2. BIPV/Thermal Simulation Results

Figures 4-8 identify the simulation results of the 4kWp PV/T HR system performance where the air flow is considered to be 300m^3/h under the aforementioned Scottish climate conditions.

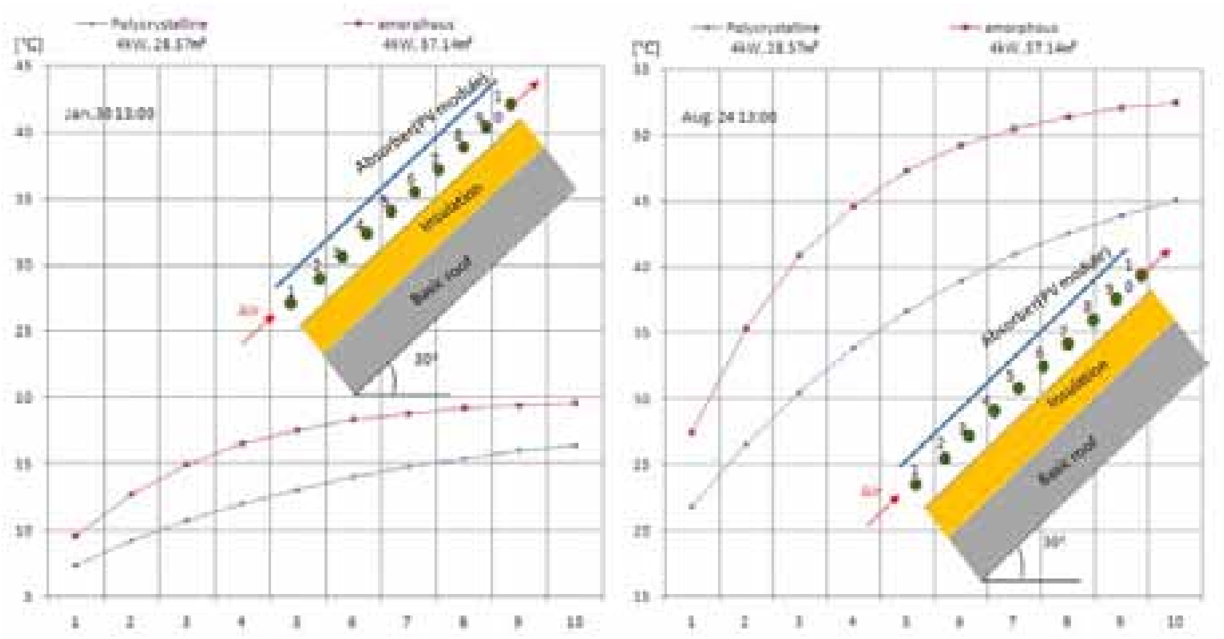


Fig. 4: 4kWp Ventilated PV/T Air Temperature Profile at the Air Flow of 300m^3/h, 30th January (left) and of 300m^3/h, 24th August (right)

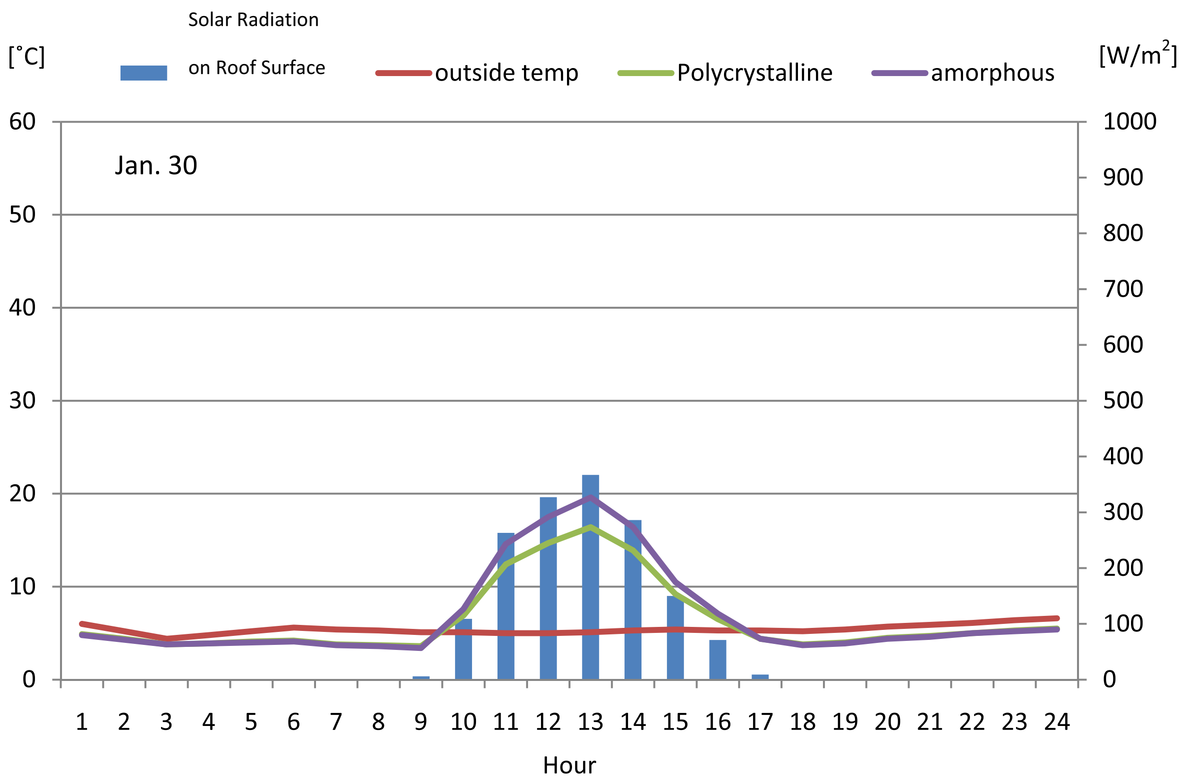


Fig. 5: 4kWp Ventilated PV Heat Generation in Response to Incoming Solar Radiation, 30th January

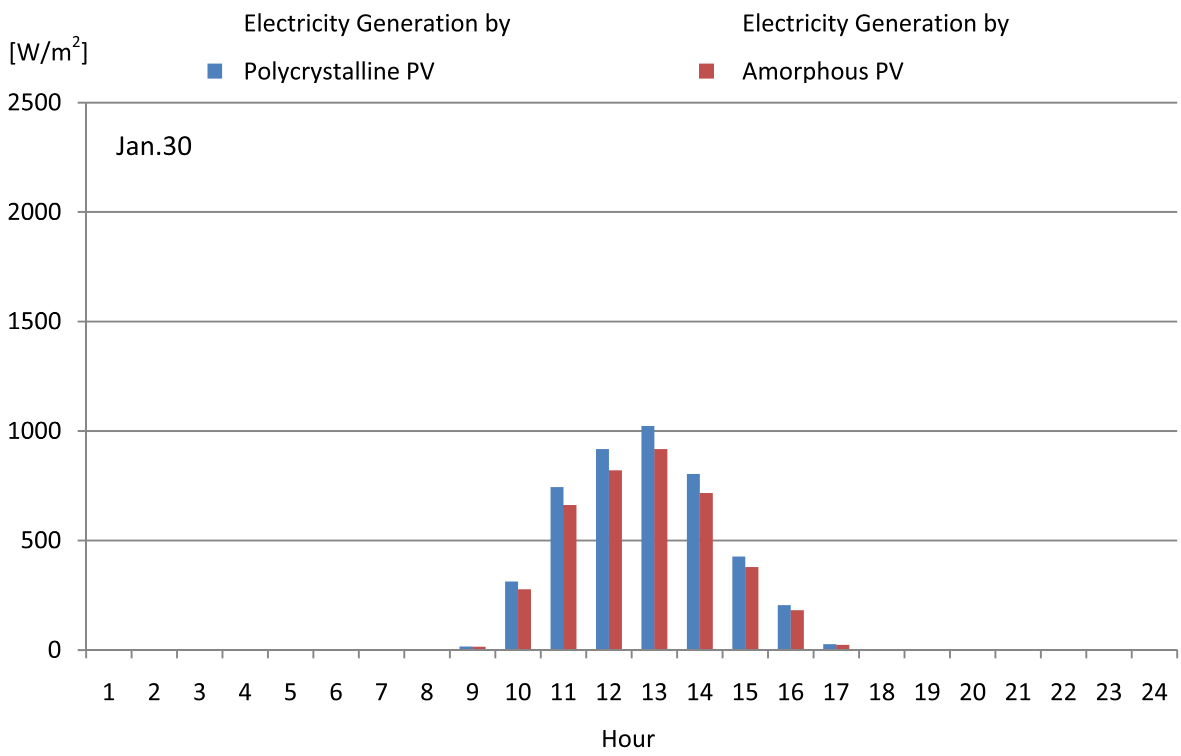


Fig. 6: 4kWp Ventilated PV Electricity Generation in Response to Incoming Solar Radiation, 30th January

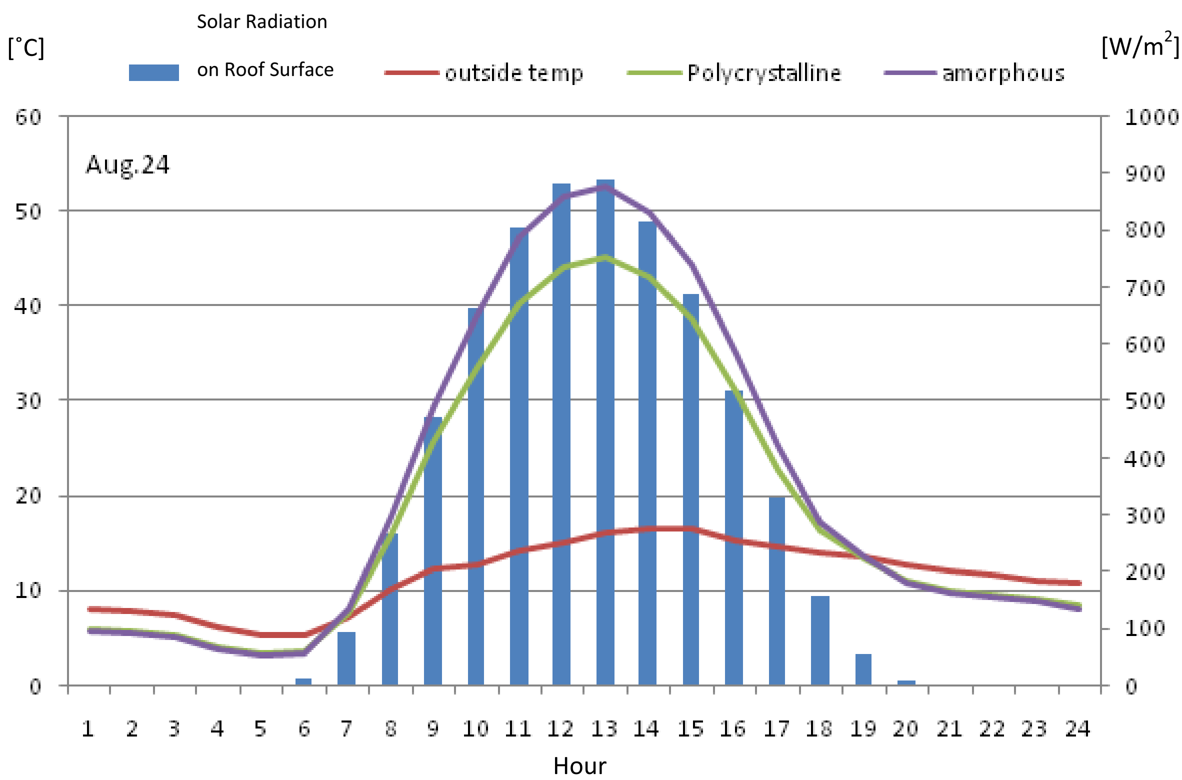


Fig. 7: 4kWp Ventilated PV Heat Generation in Response to Incoming Solar Radiation, 24th August

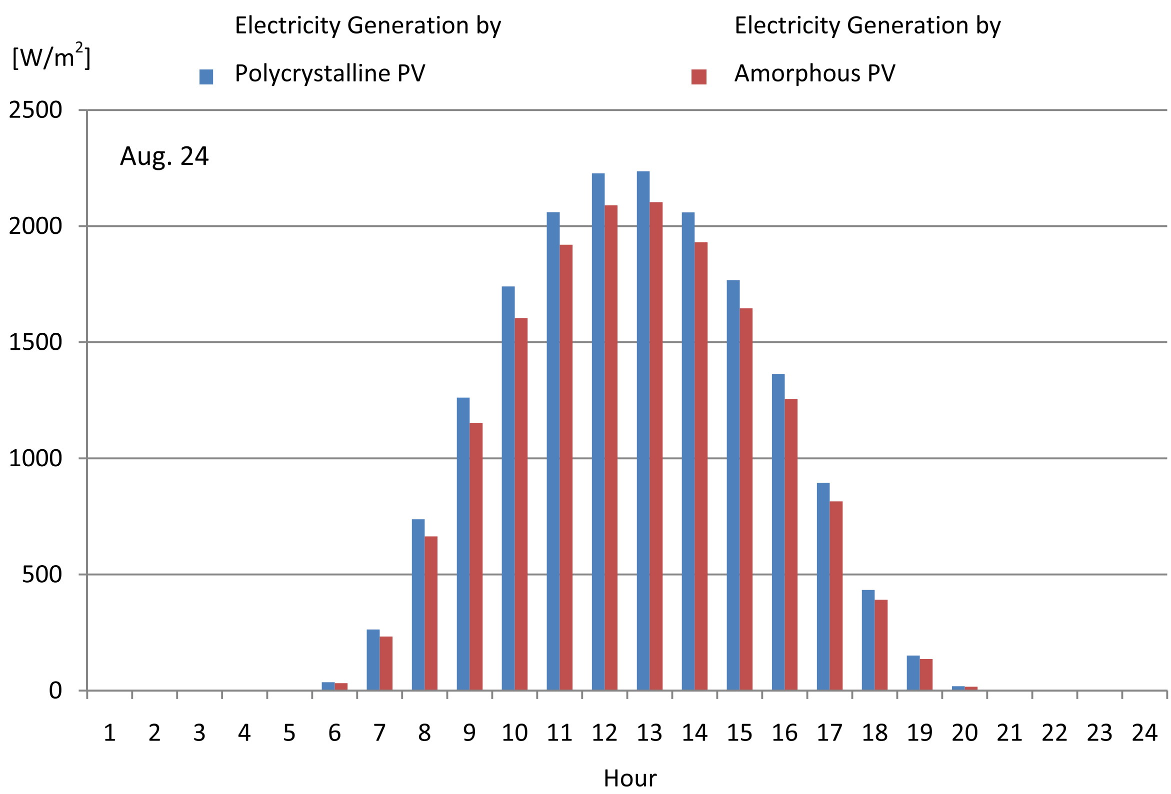


Fig. 8: 4kWp Ventilated PV Electricity Generation in Response to Incoming Solar Radiation, 24th August

Moreover, in order to facilitate the homebuilder's PV/T integrated roof design decision, the effect of different roof angles, air flows and amorphous and polycrystalline PV sizes on the system's heat and power generation performance of each was analysed. Tables 3 & 4 summarise the simulation results of the annual amount of heat and electricity generation achieved by the operation of each of the PV/T system design alternatives given under the Scottish climate condition as described previously.

Tab. 3: Annual Heat Generation Capacity of Ventilated PV/T Integrated Roof Design Alternatives Given

	Amorphous Silicon PV Thermal Energy Production [kWh/year]			
	4kWp 7% Efficiency 57.14m^2: 8m x 7.14m		8kWp 7% Efficiency 114.28m^2: 8m x 14.28m	
Roof Tilt	Air Flow 0.5m/s (432m^3/h)	Air Flow 1m/s (864m^3/h)	Air Flow 0.5m/s (432m^3/h)	Air Flow 1m/s (864m^3/h)
30°	4,689	8,292	4,974	9,671
40°	4,723	8,347	5,010	9,739
50°	4,656	8,228	4,939	9,597
	Polycrystalline Silicon PV Thermal Energy Production [kWh/year]			
	4kWp 14% Efficiency 28.57m^2: 8m x 3.57m		8kWp 14% Efficiency 57.14m^2: 8m x 7.14m	
Roof Tilt	Air Flow 0.5m/s (432m^3/h)	Air Flow 1m/s (864m^3/h)	Air Flow 0.5m/s (432m^3/h)	Air Flow 1m/s (864m^3/h)
30°	3,440	5,327	4,305	7,602
40°	3,466	5,369	4,337	7,660
50°	3,419	5,294	4,279	7,554

Table 4: Annual Electricity Generation Capacity of Ventilated PV/T Integrated Roof Design Alternatives Given

	Amorphous Silicon PV Electricity Generation [kWh/year]			
	4kWp 7% Efficiency 57.14m²: 8m x 7.14m		8kWp 7% Efficiency 114.28m²: 8m x 14.28m	
Roof Tilt	Air Flow 0.5m/s (432m³/h)	Air Flow 1m/s (864m³/h)	Air Flow 0.5m/s (432m³/h)	Air Flow 1m/s (864m³/h)
30˚	2,296	2,297	4,580	4,584
40˚	2,277	2,280	4,546	4,550
50˚	2,221	2,224	4,433	4,438
	Polycrystalline Silicon PV Electricity Generation [kWh/year]			
	4kWp 14% Efficiency 28.57m²: 8m x 3.57m		8kWp 14% Efficiency 57.14m²: 8m x 7.14m	
Roof Tilt	Air Flow 0.5m/s (432m³/h)	Air Flow 1m/s (864m³/h)	Air Flow 0.5m/s (432m³/h)	Air Flow 1m/s (864m³/h)
30˚	2,519	2,526	5,017	5,030
40˚	2,501	2,507	4,979	4,994
50˚	2,439	2,446	4,859	4,873

In addition to PV types, the configuration of a PV/T integrated roof also affects the heat and power generation performance: i.e. PV roof sizes, angles and ventilation rates. For the purpose of this feasibility study that aimed to develop a guideline for PV/T HR applications to Scottish homes, the roof angle was determined to be 30˚, 40˚and 50˚. Amongst these design options, the roof angle of 40˚ provides the best performance in terms of both heat and power generation. Due to the lowest height amongst the options given, the 30˚ roof pitch can be considered to be most efficient in terms of the building material consumption and the associated initial cost. Nonetheless, it also contributes to lessening the amount of PV heat and power generation but the expected outcomes will be better than the PV/T roof with an angle of 50˚. Thus, amongst the given alterative arrangements, the 50˚ angled PV/T roof is the worst option in the heat and power generation performance and the most expensive approach to the construction. When the area of the roof coverage becomes double, both low and high efficient PV panels tend to serve nearly twice as much to generate electricity. On the other hand, albeit the vertical extension of the PV roof from 7.14m to 14.28m (thus, the increase of the roof area from 57.14m^2 to 114.28m^2), the heat production of the amorphous PV roof with an angle of 30˚ can increase by 6% only when the velocity of ventilation air is limited to 0.5m/s and about 17% when 1.0m/s. In the case of the polycrystalline PV under the same condition, the heat production can increase by 25% when the air velocity is set to be 0.5m/s and 43% increase with the air flow of 1.0m/s. The ventilation rate of the PV/T roof can be considered as one of the most cost-effective influential factors that help improve the heat collecting performance while contributing to cooling the temperature of PV cells. For instance, in the low efficient 4kWp PV roof with an angle of 30˚, the annual rate of heat collection can be increased by 77% when the velocity is changed from 0.5m/s to 1.0m/s and this approach is about 13 times more efficient than the mere increase of the PV size from 4kWp to 8kWp. In the case of high efficient 4kWp PV roof, 55% performance improvement can be expected and it is about twice higher than the increase achieved by enlarging the PV size itself.

3. Conclusions

Research on photovoltaic thermal (PV/T) capacity is far from new; however, there was no reliable source of the information or practical technical data on the performance to which Scottish homebuilders (and architects alike) can refer when designing low to zero-energy/carbon-emission homes in Scotland that usually necessitate the use of renewable energy technologies—particularly, PV. In practice, such technologies are still expensive; thus, the device(s) invested is expected to perform at maximum. The hybrid application can be considered as one of the alternative solutions to add the value of investment. Accordingly, this study focused on analysing the heat and electricity generation capacity of PV panels based on an ongoing net zero-energy housing project in Scotland. It confirmed that PV generates heat which makes the air running under the PV panels 10-15˚C warmer than the outside temperature even during the Scottish winter. Low efficient amorphous silicon PV generates more heat than high efficient PV of the same nominal power output due to the necessarily larger area of amorphous PV roof coverage as well as the less sensitivity to temperature rise as opposed to the mono/polycrystalline counterparts. However, the simulation did not extend to the study of the effect of the ventilated PV/T air velocity any more than 1m/s; thus, it may be worth examining the extended scope so as to clarify the relationship between the increased air flow and the PV/T heat collecting capacity under the Scottish climate condition in depth.

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