Calibrating the Impact of a Photovoltaic Thermal Mechanical Ventilation Heat Recovery System on the Delivery of Net Zero-energy Housing in Scotland

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Abstract

This study was conducted with the aim to assess the potential performance of a photovoltaic thermal mechanical ventilation heat recovery (PV/T MVHR) system. The device is currently considered for the application to the Z-en house project undertaken by Scottish homebuilder, ROBERTRYAN Homes, in collaboration with ZEMCH Network academic partners. The house's whole energy demand was calibrated based on the UK government's standard assessment procedure for energy rating of dwellings, known as SAP, while the PV/T performance was estimated using an 'EESLISM' energy and environmental design simulation tool developed by Kogakuin University. This study concluded that PV generates heat, which makes the fresh air running under the PV roof 10-15˚C warmer than the outside temperature even during the Scottish winter and this warm air extracted from roof integrated PV modules can be used to drastically reduce the domestic space-heating demand. Thus, the building integrated PV/T MVHR system was considered as one of the effective means to facilitate the net zero-energy operation of housing in cool and cold climates.

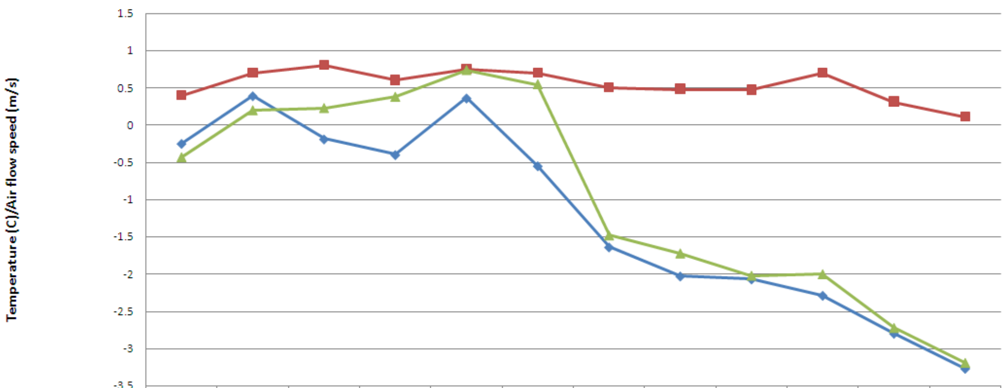
Keywords: net zero-energy mass customized housing, solar photovoltaic thermal system, mechanical ventilation with heat recovery, EESLISM

1. PV/T HR system overview

A photovoltaic thermal (PV/T) system is a hybrid PV application, which produces usable energy in the form of not only electricity, but also heat that can be used to supplement space and/or water-heating. The heat is a by-product of PV modules and traditionally dumped as it contributes to lowering PV power generation. In collaboration with Mr Stefan Larsson, CEO, Finsun Inresol, a PV/T heat recovery (HR) system mock-up was constructed in the company's testing facility located in Alvkarleby, Sweden (Fig.1). In this study, the mock-up's performance was initially observed to grasp the basic knowledge of the PV/T system's capacity and building integration issues, so as to discuss on how it can be applied to actual constructions.

Fig.1 PV/T HR Roof System Mock-up Built by Finsun Inresol in Alvkarleby, Sweden.

The system mock-up consists of polycrystalline silicon PV cells accompanied by a parabolic shaped reflector and a solar-powered fan, where ventilation air is used as a medium to extract heat from PV cells. The observation of the mock-up's performance was carried out by MEARU, Mackintosh School of Architecture, between 9th and 11th of November, 2010. The conversion efficiency of the observed air cooled PV/T HR mock-up was estimated at 17.6%, when the outside temperature reaches 25°C. The possible module price was considered to be US$420 (£267.11) or US$1.4 (£0.89) per 1W. The monitoring results indicate that the air velocity associated with the ventilation fan was recorded between 0.11m/s and 0.75m/s. The temperature of PV/T outlet air was slightly higher than that of the inlet or ambient air (Fig.2). However, due to both the small size (2,368mm x 1,014mm x 235mm) of the mock-up observed and the limited PV capacity (300Wp), the rise of the ventilation air outlet was marginal.



	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30
Outside/inlet temp.	-0.25	0.39	-0.19	-0.4	0.36	-0.55	-1.64	-2.03	-2.07	-2.29	-2.8	-3.27
Air flow (m/s)	0.4	0.7	0.8	0.6	0.75	0.7	0.5	0.48	0.47	0.7	0.31	0.11
Outlet temp.	-0.43	0.2	0.23	0.38	0.74	0.55	-1.48	-1.72	-2.02	-2	-2.72	-3.19

Fig.2 Inlet and Outlet Air Temeparture and Velocity Monitoring Results of Ventilated PV/T HR Mock-up, 11th November 2011.

Between 10:00am and 11:00am, the temperature of the outlet air was recorded lower than that of the inlet. This might be attributed to the system components' remained cold temperature associated with night-time snow accumulation, although the ice was removed an hour before the monitoring. In addition to the inlet and outlet air temperature and velocity monitoring, thermal properties of the module components were also recorded using a thermal imaging camera on the same day (Fig.3).

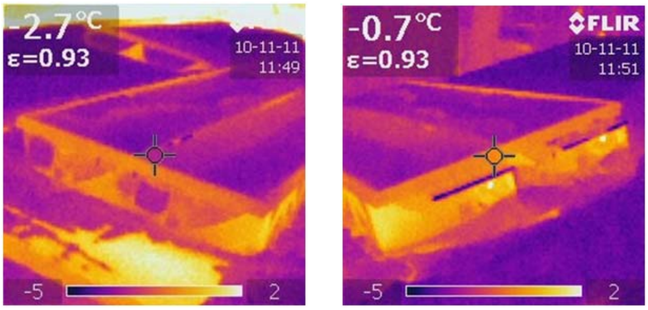


Fig.3 Thermal Image of Ventilated PV/T HR Mock-up: Air Inlet (left) and Outlet (right).

The thermal images clearly indicate the temperature differences not only between inlet and outlet air ducts, but also between the surfaces covered with PV cells and solar reflectors. The extreme surface temperature differences possibly lead to ice dam formation that may damage the PV roof with water leakage (Fig.4).

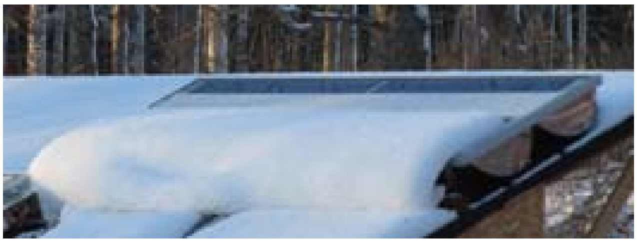


Fig.4 Ice Dam Formation on the PV Integrated Roof Mock-up.

2. Z-en house profile and PV/T MVHR architectural integration

In 2009, the ‘Z-en house’ project was initiated by ROBERTRYAN Homes, which is based in Scotland. In this housing project, PV/T will be installed in a way that the ventilation air heated by PV integrated roof is extracted via a balanced whole-house mechanical ventilation with heat recovery system—i.e. PV/T MVHR (Fig.4).

Fig.4 Building Integrated PV Thermal Mechanical Ventilation Heat Recovery System (BIPV/T MVHR) (Source: MEARU Mackintosh School of Architecture).

The Z-en house project is a single detached home to be built in a new rural residential development in West Kilbride, Scotland. The house contains 4 bedrooms and a study. These private rooms are located on the 1st floor, while 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 PV/T system.

3. PV/T MVHR whole-house energy simulation

The Z-en house will be clad with highly insulated building envelopes. U-values of the walls, floors, and roofs are considered to be 0.15, 0.10, and 0.10kW/m^{2}K, respectively. Under the conditions that an MVHR system is installed in the house without any other green technologies, the dwelling's total energy consumption was estimated roughly at 14,400kWh/yr. Separately, based on the authors' previous studies, the performance of a PV/T system that would be applied to the house was estimated using an 'EESLISM' energy and environmental design simulation tool developed by Kogakuin University [1][2][3]. The simulation of the PV/T HR system led to identifying the potential heat and power generation capacity under Scottish climatic conditions (Table.1).

	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
	Amorphous Silicon PV Electricity Generation [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°	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 28.57m^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°	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

Table 1 Annual Heat and Electricity Generation Capacity of Ventilated PV/T Roof Integrated Design Alternatives Given.

In order to facilitate builders' design decision on PV/T integrated roof configurations, the effect of roof angles (30°, 40° and 50° alternatives) on the building integrated PV heat and power generation performance was also analysed. 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. The BIPV modules tend to generate heat that makes the air running under the PV roof 10-15˚C warmer than the outside temperature under Scottish winter conditions.

4. Conclusions

This study confirmed that the installation of a roof integrated PV MVHR system in housing has a great potential to drastically reduce operational energy consumption. When the Z-en house is equipped with the PV/T MVHR system of 8kWp PV modules, which are accompanied by 14% conversion efficiency, the total energy use of the house can decrease potentially to 1,746kWh/yr, when the roof angle is set to be 40˚ and the heat loss of the PV/T system is completely ignored. However, it is worth noting that 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. Thus, the proper choice of PV modules can be regarded as essential in view of the initial and operational cost and performance. Also, ice dam formation needs to be avoided by proper integration of PV roofs.

Acknowledgements

The authors would like to express their sincere gratitude to Mr Stefan Larsson, CEO, Finsun Inresol, who collaborated on the PV/T system mock-up monitoring. This study was supported by Japan Society for the Promotion of Sciences (JSPS) KAKENHI, Grant-in Aid for Scientific Research (B) 22360239. The authors are National Experts representing their countries in the International Energy Agency (IEA). The first and fourth authors of this paper are currently contributing to the joint Implementing Programmes Solar Heating and Cooling (SHC) Task 40 / Energy Conservation in Buildings and Community Systems (ECBCS) Annex 52: Towards Net Zero Energy Solar Buildings. The work presented in this paper is informed by their participation in the Task40/Annex 52.

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