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Industry Aspirations for Building Integrated Photovoltaic Thermal Heat Recovery Systems

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The International Energy Agency indicates energy use in buildings worldwide accounts for over 40% of primary energy use and 24% of greenhouse gas emissions. Energy use and emissions should include both direct, on-site use of fossil fuels as well as indirect use from electricity, district heating/cooling systems and embodied energy in construction materials. National Housing Federation claims that housing in the United Kingdom (UK) is responsible for 27% of carbon dioxide (CO_2) emissions. In particular, Scottish homes today are conspicuous energy consumers emitting on average 3 ton-CO_2 per house annually which is much higher than the UK average of 2.75 ton-CO_2. The UK's fuel poverty issue is on the rise. In fact, 26.5% of households in Scotland alone live in fuel poverty according to Scottish House Condition Survey 2008. In order to encourage the house-building industry to move towards the mass delivery of eco-friendly houses, the Code for Sustainable Homes was introduced in 2006.

Following the code, the UK government now expect the industry to achieve their bold zero-carbon housing target by 2016. Despite the policy, the homebuilding industry today is barely ready for accomplishment of such sustainable housing agenda. Given the national and international challenges related to climate change and resource shortages, much more is required than incremental increases in houses' energy efficiency.

To take the initiative to meet the societal needs, governmental expectations and industrial obligations, ROBERTRYAN Homes is currently developing design ideas and solutions towards the construction of zero-energy healthy houses. The housing prototype has been called *Z-en house* aiming to achieve the net zero energy housing consumption in view of the UK government's recognised Standard Assessment Procedure (Fig.1).

Figure 1: South-west Façade Image of the Z-en House: ROBERTRYAN Homes
(Source: MEARU, Mackintosh School of Architecture)

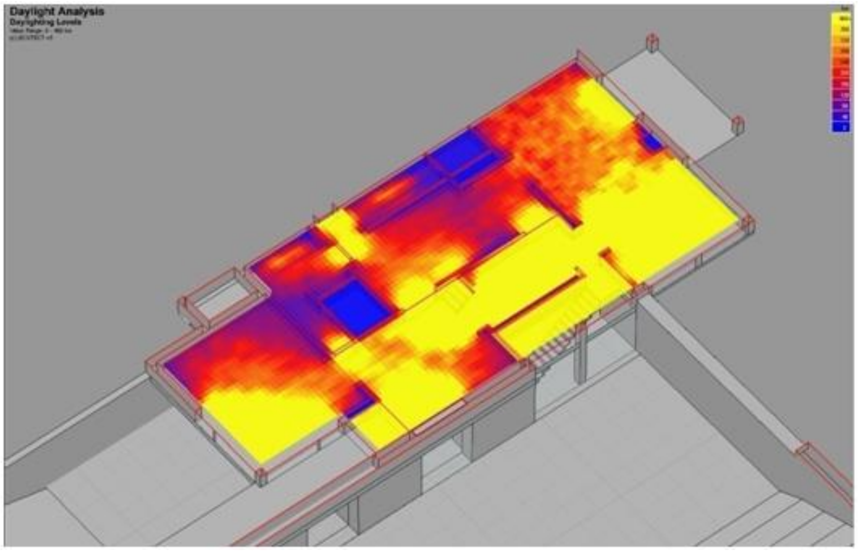


Figure 2: Daylight Analysis of the Zen House Ground Floor (Source: MEARU, Mackintosh School of Architecture)

The construction site has carefully been selected in consideration of the solar access and sun shading potentials. The large south facing windows to be installed in the house also contribute to optimising the use of natural light and solar gains (Fig.2).

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 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 (Fig.3).

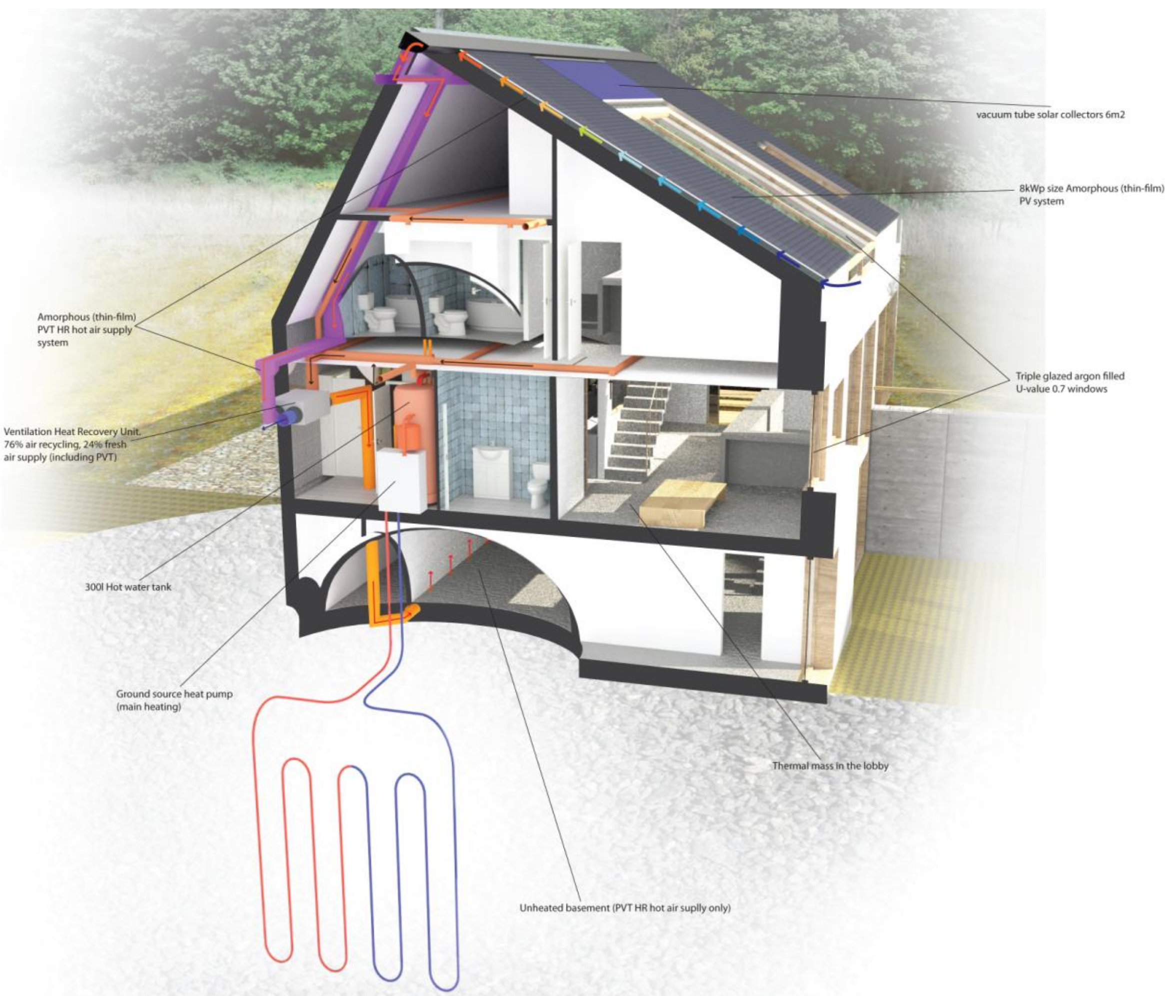


Figure 3: BIPV Thermal Mechanical Ventilation Heat Recovery System's Schematic Diagram (Source: MEARU, Mackintosh School of Architecture)

The Z-en house is aiming to meet the net zero-energy target based on SAP 2009 and encompass passive solar housing design techniques and active hybrid renewable energy technologies. The design features being considered currently can be summarised as follows:

- Elongation of the south-facing façade for optimisation of solar gain and day-lighting opportunities throughout the building.
- Placement of large south-facing windows to achieve 45% glazing to floor ratio (including skylights) for effective balance of desirable heat gains and losses.
- Introduction of a south-side sunken garden that helps enlarge the south façade exposure to the sun and the outdoor recreational green space.
- Placement of an integral south-facing sun space equipped with the generous basement and ground floor thermal mass that is used for heat storage, as well as with the vertical ventilation void that accelerates fresh preheated or cool air circulation to upper floors.
- Placement of a pantry and storage in the north side of the house to provide air buffer for reduction of fabric heat loss from the north walls.
- Minimisation of the north façade opening areas for reduction of heat loss.
- Application of ‘Accredited Construction Scheme’ for reduction or elimination of thermal bridging conjunctions of the building components.
- Application of ‘Insulated Concrete Form’ (IFC) walls and well-insulated roofs and floors to achieve U-values of 0.15W/m^{2}K in walls and 0.1W/m^{2}K in roofs and floors.
- Installation of high thermal performance wood frame triple glazing windows accompanied by argon gas filling and low emissivity coating to maintain U-value of 0.7 W/m^{2}K. Of glazed doors, U-value is 1.2 W/m^{2}K.
- Introduction of multi-purpose basement and attic for post-occupancy renovation through DIY for reduction of initial construction cost.
- Effective placement and sizing of widows located in a north-side pantry, bathroom and bedrooms for reduction of artificial light use and heat loss.
- Effective colour coordination by applying light colour to interior surfaces in the rooms desired for natural light reflection and dark colour to thermal mass walls and floors for heat absorption.
- Use of a ground floor projection on the west side of the house, which to some extent shelters cars parked outside the garage from rainwater drips.
- Introduction of air-tight construction techniques to seal the building envelope junctions to maintain the air permeability less than 3m^3/m^{2}h at 50 Pa, where the air change rate will be kept less than 0.5 through the installation of a humidity controlled balanced mechanical ventilation heat recovery system (MVHR) whose air velocity should be higher than 1m/s.
- Provision of a multi-functional roof for weather protection and power and heat generation by the integration with 8kWp photovoltaic (PV) cells and 6m^2 solar thermal collectors.

- Introduction of a BIPV/T MVHR system with high heat exchange efficiency and a summer bypass that heats 10-30% of incoming fresh air extracted from the outside, where the air heated by PV/Thermal is supplied through MVHR outlets placed in the basement.
- Proper location of humidity controlled MVHR internal extracts particularly in the kitchen, utility room and bathrooms for 70-90% recovery of internally preheated air.
- Installation of a ground source heat pump that is used as the main space heating system where the heat is spread through the screed concrete floor heating system which also serves as thermal floor mass to store the heat.
- Alignment of the vertical placement of a kitchen, utility space and bathrooms for reduction of the total length of service and drainage pipes.
- Use of 100% dedicated energy saving lights.
- Installation of low flush plus dual flush toilets to reduce water usage.
- Installation of rain water butts to use rain water for car washing and gardening.
- Introduction of energy label A++ white goods for reduction of stand-by energy use.
- Installation of a high efficient boiler equipped with weather compensator and enhanced load compensator to maximise the performance of heat distribution accompanied by zone control multiple thermostats and programmers for energy saving.
- Installation of interactive energy and water consumption monitors for enhancement of energy-saving user behaviour and for post occupancy evaluation.
- Limited use of carpets and porous materials to mitigate the accumulation of dusts that contribute to deteriorating indoor air quality.

The Z-en house has the great potential for taking the lead to showcase the state-of-the-art passive solar design techniques and hybrid green building technologies—particularly, the BIPV/T MVHR system that is relatively new to the housing industry at national and international levels. In fact, due to the potential zero-energy housing innovations, the project team has already been invited to introduce the Z-en house design features at several industry and academic events around the globe including the Renewable Energy 2010 Conference's Zero-energy Housing Workshop held in Yokohama, Japan, and the EU-Korea Photovoltaic Applications into Buildings Forum held in Seoul, Republic of Korea. After the construction of the first Z-en house prototype, the post occupancy evaluation to analyse the value mismatch between the domestic energy simulation results and the users' actual energy consumption data gathered by ROBERTRYAN Homes will be carried out with the aim to continuously improve design and production quality of the Z-en house prototype where 3 more houses are hopefully built within next 3 years.

Observed PV/T HR System Mock-up Profile

PV/T is a hybrid PV application which produces usable energy in the form of not only electricity but also heat for heating space and/or water. 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, the Swedish delegate of the 'Zero-energy Mass Custom Mission to Japan' held in June 2010, the PV/T HR system mock-up was built in his testing facility in Alvkarleby, Sweden (60.57N, 17. 45W) (Fig.4). The mock-up was observed at the initial stage of this study with the aim to gain the knowledge of basic features and performance for further discussion on how the system should be integrated with the Z-en house in question.

In general, the higher the temperature of PV cells, the lower the power generation. Thus, the aforementioned systems were designed with the aim to maximise PV power generation by cooling the cells by either air or water.

Figure 4: PV/T HR Roof Integrated System Mock-up Built by Finsun Inresol in Alvkarleby, Sweden

To increase the power output, each row of polycrystalline silicon PV cells installed in the mock-up examined was aligned with an optical parabolic reflector; thus, the amount of sunlight on the PV surface could be enhanced drastically. In the PV/T modules, ventilation air/water ducts are created by placing PV cells vertically and horizontally (Fig.4). In the ventilated PV/T HR mock-up, both ends of the air duct are equipped with NF-P14 FLX Noctua 1.2w direct current (DC) fans which are powered by PV. Thus, the DC fans provide a self adjusting variable air flow rate in proportion to received incoming solar radiation levels—i.e. the higher the insolation the faster the PV ventilation. Each air inlet has a filter that prevents the duct and fans from physical damage associated with air dusts. 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—i.e. summer season. The possible module price was estimated at US$ 420 (£ 267.11) or US$ 1.4 (£ 0.89) per Watt.

The observation of the mock-up's performance was carried out by MEARU staff between 9^{th} and 11^{th} of November, 2011. Equipment to monitor the actual performance of the PV/T HR systems included: a hand held thermal camera, CO_2 and temperature meter, and air flow anemometer. The observation helped identify the performance of PV/T modules in question—particularly, the ventilated PV/T mock-up, which was regarded initially as a relevant application to Z-en house, under snowy winter conditions. This also helped identify the negative impact of snow on PV cells if the system is not integrated with building envelope (i.e. roof) properly. The snow accumulated on the warm surface of a roof (e.g. PV) melts while one on the cold part stays in place forming an ice dam under the cold ambient temperature. This may possibly lead to damaging the PV roof with water leakage.

Monitoring Results of Ventilated PV/T HR Mock-up

The reflectors installed in the PV/T HR mock-up examined could help to increase the level of solar radiation on PV cells; hence, the conversion efficiency of PV cells might be enhanced. However, the concentrated sunlight also contributes significantly to the PV cell temperature rise. It was observed that the high operating temperature of PV cells could lessen power output (Fig.5). The observed PV/T modules consist of polycrystalline silicon PV cells which can be considered as relatively more sensitive to the temperature rise than amorphous PV. Thus, the circulation of air or water under PV cells is a meaningful approach to reducing the temperature rise for sound power generation.

In view of the moderate cost and the simple configuration, the concept of a ventilated PV/T HR system may be considered as attractive and applicable to the Z-en house project. Accordingly, the system was examined further in order to identify the PV air heating potential. The inlet and outlet ventilation air temperatures and flow velocity were measured (Fig.6).

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 inlet or ambient temperature. However, due to the small size (2,368mm x 1,014mm x 235mm) of the mock-up and the limited PV capacity (300Wp), the rise of the ventilation air outlet was marginal. Between 10:00am and 11:00am, the temperature of the outlet air was recorded lower than one of the inlet.

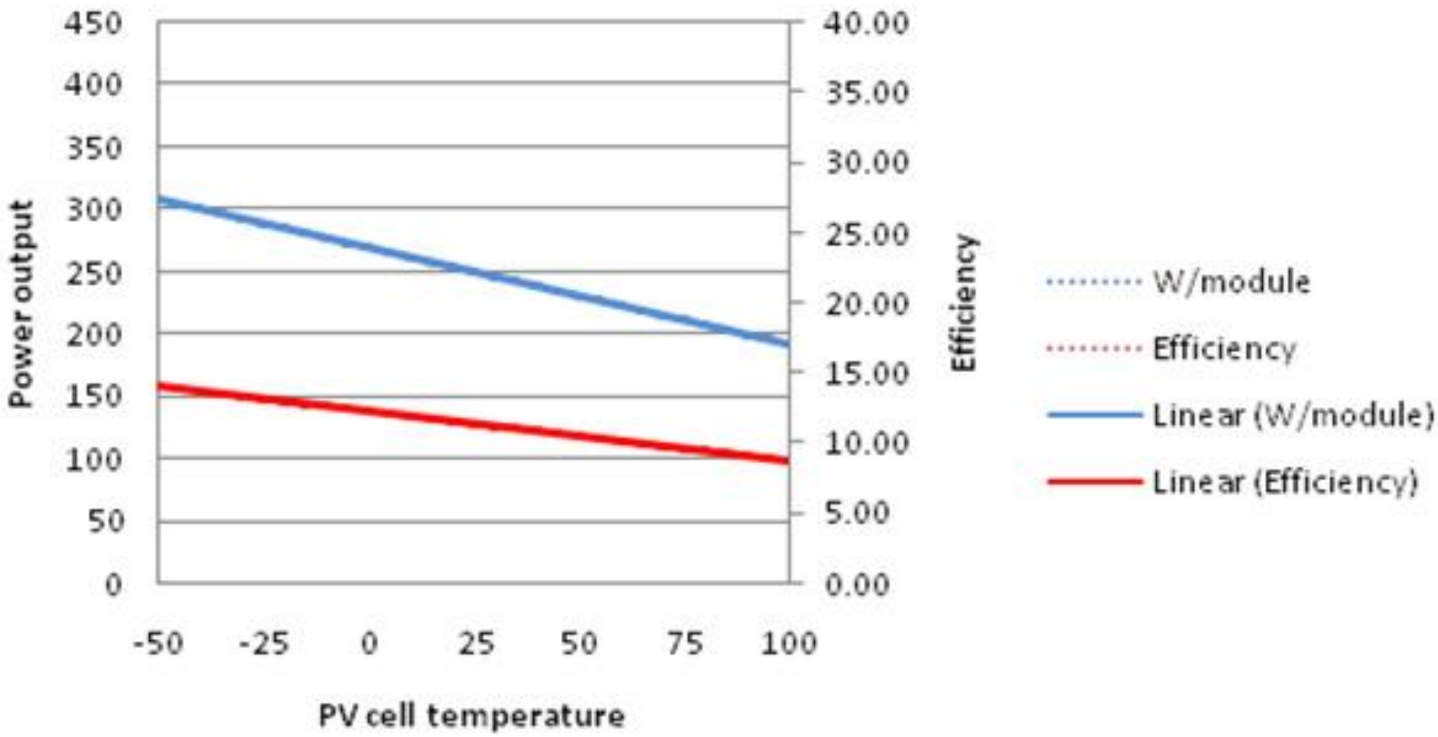
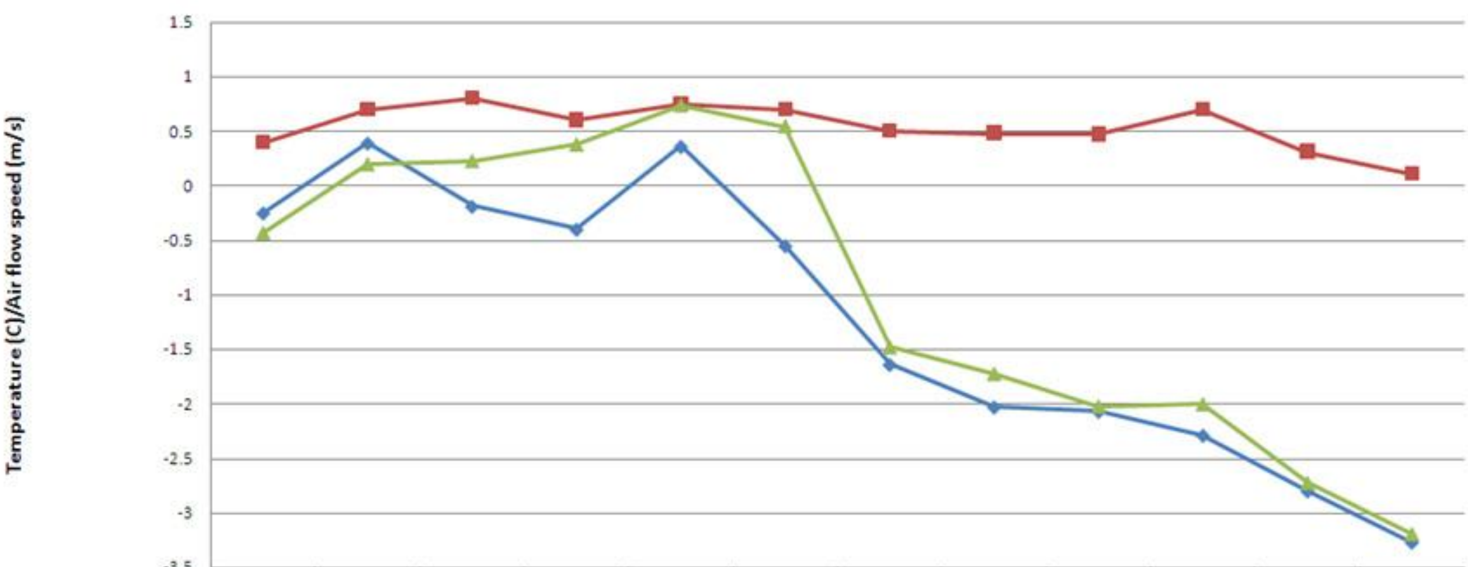


Figure 5: Co-relationship between crystalline-silicon PV efficiency and temperature



	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

Figure 6: Inlet and Outlet Air Temeparture and Velocity Monitoring Results of Ventilated PV/T HR Mock-up, 11th November 2011

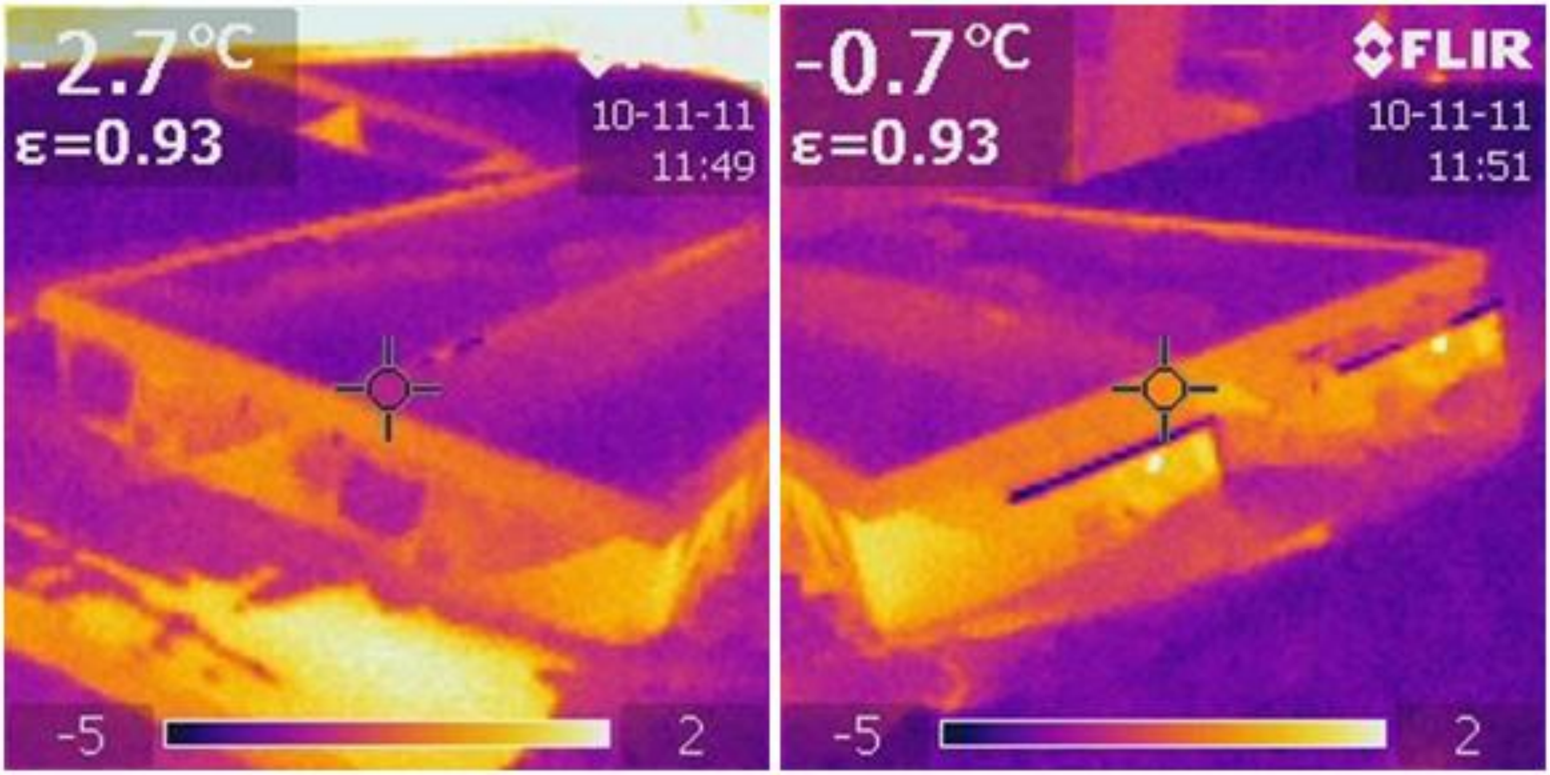


Figure 7: Thermal Image of Ventilated PV/T HR Mock-up: Air Inlet (left) and Outlet (right)

This might be attributed to the module components' cold temperature which stayed for about an hour even after the snow accumulated on the PV surface was removed for the purpose of monitoring. In addition to the inlet and outlet air temperature and velocity measurements, the thermal properties of the module components were also recorded using a thermal imaging camera on the same day (Fig.7).

The thermal image clearly indicates 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 the ice dam formation that may damage the PV roof with water leakage, as described above.

The investigation of the PV/T HR mock-up observed helped corroborate the heat generation that can be applied for heating space and/or water. Particularly, due to the relatively simple configuration that helps reduce installation cost, a ventilated PV/T HR system approach was considered as relevant to the Z-en house development. The mock-up also demonstrated the formation of ice dams on the PV roof which should be averted by proper architectural integration. Moreover, this mock-up study led to suggestions that the PV heat rise correlates with the level of incoming solar radiation, ambient temperature, configuration of PV solar roofs, types of PV cells and the PV/T air velocity. However, the performance may differ when a PV/T HR system is installed in the Z-en house that is expected to be constructed in Scotland.

PV/T HR Performance Simulation

Accordingly, the performance of PV/T HR systems under Scottish climatic conditions were investigated in collaboration with Prof. Mitsuhiro Udagawa and Dr. Yoshiki Higuchi, Kogakuin University, by making use of the state-of-the-art *EESLISM* energy and environment simulation tool which was developed by Prof Udagawa in 1989. The study indicated that PV could generate heat which would make the air running under the PV panels 10-15˚C warmer than the outside temperature even during the Scottish winter (Fig.8). Moreover, 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.

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˚.

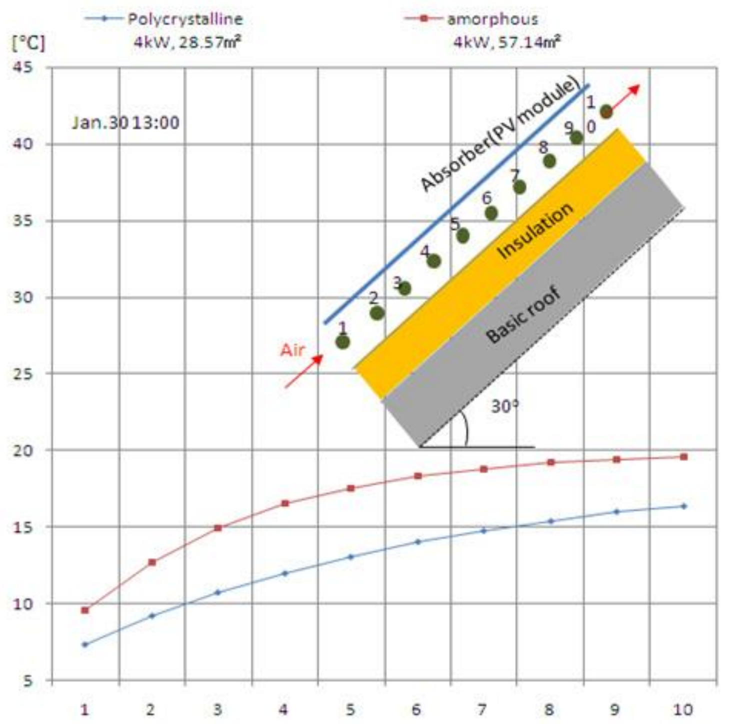


Figure 8: 4kWp Ventilated PV/T Air Temperature Profile at the Air Flow of $300m^3/h$, 30th January

Lessons Learned

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˚. 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 (i.e. the conversion efficiency of 7% and 14%, respectively) 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. 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.

Acknowledgements

The author would like to express his sincere gratitude to CIC Start Online for the financial support that realised this feasibility study and equally to Dr Branka Dimitrijevic, Director, for her constructive guidance on the grant application. Also, I would like to thank deeply Mr Billy Kirkwood, Managing Director, ROBERTRYAN Homes, for the provision of the construction site documents and the company's aspirations accompanied by his patient, effective collaboration. Also, his thanks extend to Prof. Mitsuhiro Udagawa and Dr. Yoshiki Higuchi of Kogakuin University in Japan for their technical support of the PV/T heat and power generation simulation using their own software tool called '**EESLISM' and Mr** Stefan Larsson, CEO, Finsun Inresol, in Sweden to physically demonstrate the PV/T HR system performance using their own facilities. At last, the author would also like to thank Mr Audrius Ringaila who helped monitor the physical performance of PV/T HR mock-up and visualised the Z-en house's design schemes.

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