CIC START ONLINE FEASIBILITY STUDY

ASSESSING THE ENERGY IMPACT OF DIFFERENT STRATEGIES OF INTEGRATING PV/THERMAL HEAT RECOVERY SYSTEMS IN SCOTTISH HOMES

Dr Masa Noguchi

Dr Filbert Musau

MEARU

Mackintosh School of Architecture

The Glasgow School of Art

In Collaboration with:

Prof Mitsuhiro Udagawa, Kogakuin University, Japan

Dr Yoshiki Higuchi, Kogakuin University, Japan

Stefan Larsson, Finsun Inresol, Sweden

Audirus Ringaila, MEARU, UK

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ROBERTRYAN Homes
32A Hamilton Street
Saltcoats
North Ayrshire
KA21 5DS

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EXECUTIVE SUMMARY

The research on photovoltaic thermal (PV/T) solar systems has been on the rise. In 2005, the International Energy Agency (IEA) Solar Heating and Cooling (SHC) programme launched the 1st Task 35 experts meeting to initiate international collaboration on PV/T solar systems. Following the end of the Task 35 research activities, SHC and the Energy Conservation in Buildings and Community Systems (ECBCS) formed a Task 40/Annex 52 joint programme and commenced collaboration on net zero energy solar buildings. Their studies encompass the scrutiny of exemplary net zero energy solar building projects selected from each participating country. Canada's first net zero energy home, called *Écoterra house*, built in 2007 through the federal government's sustainable housing initiative, and the United Kingdom's *Z-en house* are currently amongst them. Both projects have been aimed at demonstrating PV/T systems for space heating in addition to power generation. This feasibility study was initiated in order to lead Scottish Z-en house builder, *ROBERTRYAN Homes*, to thorough understanding of basic features and potential performance of a PV/T HR system under Scottish climatic conditions and further explore how the system can effectively be integrated with the Z-en house to be constructed in 2012/13. The house is being designed to circulate PV heated air throughout the interior via a mechanical ventilation heat recovery system—i.e. implementation of a *PV/T MVHR* system. In this study, the heat generating capacity of low efficient PV cells (amorphous silicon) and the high efficient counterparts (poly-crystalline) was analysed using the energy and environment simulation tool called *EESLISM* which was invented in 1989 by Prof. Mitsuhiro Udagawa, Kogakuin University, Japan. The air flow assisted by the MVHR system was assumed to be 300m^3/h, 432m^3/h or 864m^3/h and the velocity of 0.45m/s, 0.5m/s or 1m/s, respectively. The fresh air is drawn under a 7% or 14% efficient PV roof whose module coverage is set according to the nominal power output of either 4kWp or 8kWp. This study confirmed 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. 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 short, the ventilated PV/T integrated roof helps raise the temperature of the fresh air running under the PV panels and being extracted by an MVHR system, if both the roof and the extractor are connected physically via a duct; thus, it contributes to supplementing the indoor space heating. The architectural integration was considered as important and was visualised in the course of this study. Moreover, the air flow of the PV/T HR system was also considered as one of the key cost-effective design factors that help improve the PV/T heat collecting performance while maintaining electricity generation properties as the PV modules are cooled by the ventilation. In the 7% efficient 4kWp PV/T roof with an angle of 30˚, the EESLISM simulation indicated that the annual rate of PV/T heat collection could be increased by 77% when the ventilation air velocity is changed from 0.5m/s to 1.0m/s. The mere manipulation of the air flow is more economic and about 13 times more efficient than the increase of the PV size from 4kWp to 8kWp. Similar tendency was observed in the 14% efficient PV/T roof. However, the simulation did not extend to analysing the effect of the ventilated PV/T air velocity any more than 1m/s; thus, it may be worth continuing to investigate the extended scope in order to clarify the relationship between PV/T heat collecting capacity and the further increased ventilation rate under the Scottish climate condition in depth.

PART I: EXAMINATION OF SOLAR PHOTOVOLTAIC THERMAL HEAT RECOVERY SYSTEMS

ROBERTRYAN homes is an experienced homebuilder dealing with a wide range of residential construction projects, recognised as a brand for Ayrshire based RDK Construction which was formed in 1992 and Robert Ryan Timber Engineering created in 1999. They develop and sell apartments, executive and family homes; have many projects planned for the future; and have an established customer base. The company is currently planning to build total 4 net zero energy detached homes in North Ayrshire. The initial housing prototype has been called *Z-en house* aiming to demonstrate the outcome of this feasibility study on photovoltaic thermal (PV/T) heat recovery (HR) systems. In the 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 heat recovery (MVHR) system which has possibly the high heat exchange efficiency and low specific fun power. This approach articulates the feature of this residential project.

The following sections will review PV/T HR systems constructed outside Scotland in order to grasp the knowledge of the basic features and performance and examine the potential architectural integration.

1.1 PV/T HR System Market Stimuli

The Scottish Government is aiming to meet its renewable energy targets where 80 per cent of Scottish electricity consumption is expected to come from renewable energy technologies by 2020. One of the market stimuli to promote the installation of renewable energy technologies is the ‘Feed-in Tariffs’ (FITs) scheme. It became available in the United Kingdom (UK) on 1st April 2010. FITs have been introduced by the UK Government to help increase the level of renewable energy produced in the UK with the aim to meet its green target level, i.e. 15% of total energy from renewable source by 2020. The key part of the FIT scheme is the standard tariff. It is used between power companies and consumers when electricity generated locally (e.g. PV roof) is exported to commercial grid. The power generation is paid as per every kilowatt hour (kWh) of electricity produced using renewable energy technologies identified under the scheme. The amount paid per kWh varies depending on the source being used, the size of the system and the building type. Table 1 tabulates the standard tariff applied for the use of solar PV technology.

PV Size	Tariff	Duration
≤4 kW new	36.1 p/kWh	25 years
≤4 kW retrofit	41.3	25
>4-10kW	36.1	25
>10 - 100kW	31.4	25
>100kW - 5MW	29.3	25
Standalone	29.3	25

Table 1: FIT Standard Tariff Applied for PV Systems Installed before April 2012
(Source: http://www.fitariffs.co.uk/eligible/levels/)

Moreover, on 11th March, 2011, the UK Government launched *Renewable Heat Incentive* and this £860 million scheme is expected to increase green capital investment by £4.5 billion up to 2020, stimulating a new market in renewable heat. PV thermal capacity is currently out of the list provided for the applicable technologies; however, the economic benefit from exporting electricity generated by PV to the national grid still makes a good sense for the installation in roofs and walls of buildings as the economic burden associated with the capital cost can be reduced drastically in consideration of the continuous increase of operational electricity cost.

1.2 Observed PV/T HR System Mock-up Profiles

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. This study initially examined three types of PV/T HR systems. 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-ups were built in his testing facility in Alvkarleby, Sweden (60.57N, 17. 45W) (Fig.1). The mock-ups were 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.

Figure 1: PV/T HR Roof Integrated System Mock-ups Built by Finsun Inresol in Alvkarleby, Sweden

The first type was a polycrystalline silicon PV cells accompanied by a parabolic shaped reflector and a fan powered by PV where ventilation air is used as a medium to extract heat from PV (Fig.2); thus, this helps cool the PV cell temperature for enhancement of the conversion efficiency. The second type had the similar structure yet the PV panel was designed to be tilted according to the height of the sun (Fig.3). In this mock-up, water is circulated to cool PV cells rather ventilation air. These systems are all based on stand-alone 300Wp PV modules which incorporate mirror-like reflectors that concentrate incoming solar radiation on the PV cells. The dimension of the PV module is typically 2,368mm in length, 1,014mm in width and 235mm in depth.

Figure 2: Ventilated PV/T HR System Mock-up Equipped with a Fan and Solar Reflector

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. Moreover, to further increase the power output, each row of polycrystalline silicon PV cells is aligned with an optical parabolic reflector; thus, the amount of sunlight on the PV surface can be increased drastically (Fig.3).

In the PV/T modules, ventilation air/water ducts are created by placing as PV cells vertically and horizontally. In the ventilated PV/T HR mock-up (Fig 2), 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.

Figure 3: Water-circulated PV/T HR System Mock-up Equipped with Solar Reflectors

The observation of the mock-ups' performance was carried out by MEARU staff between 9th and 11th 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 (like Scotland today). This also helped identify the negative impact of snow on PV cells if the system is not integrated with building properly—i.e. ice dam formation (Fig.4). 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.

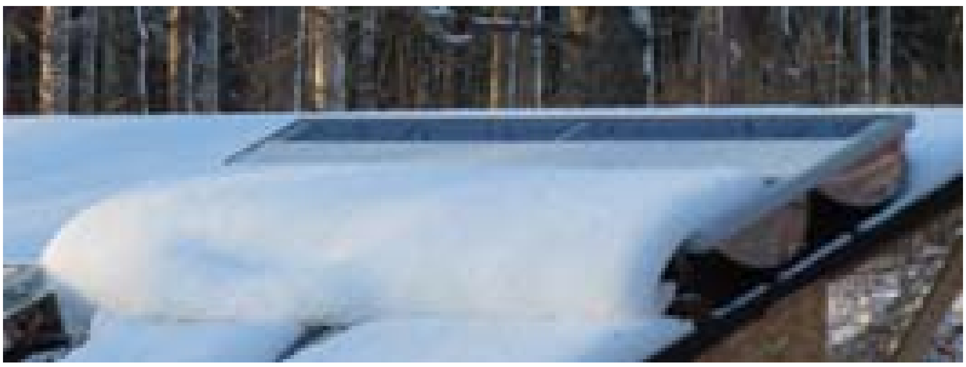


Figure 4: Ice Dam Formation on the PV Roof Mock-up

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 1W.

The last type of a PV/T system observed during the study visit to the test house in Sweden was a PV integrated blind (Fig.5). The PV solar blinds generate both electricity and heat while blocking out or diffusing unwanted direct sunlight. The air around the blind can be heated by PV cells and it in turn contributes to space heating while reducing the risk of vapour condensation over the windows. Also, water is running through the pipes connected to the underside of the PV blind blades for cooling so the PV heated water can be served directly via a tap or entering a domestic hot water tank.

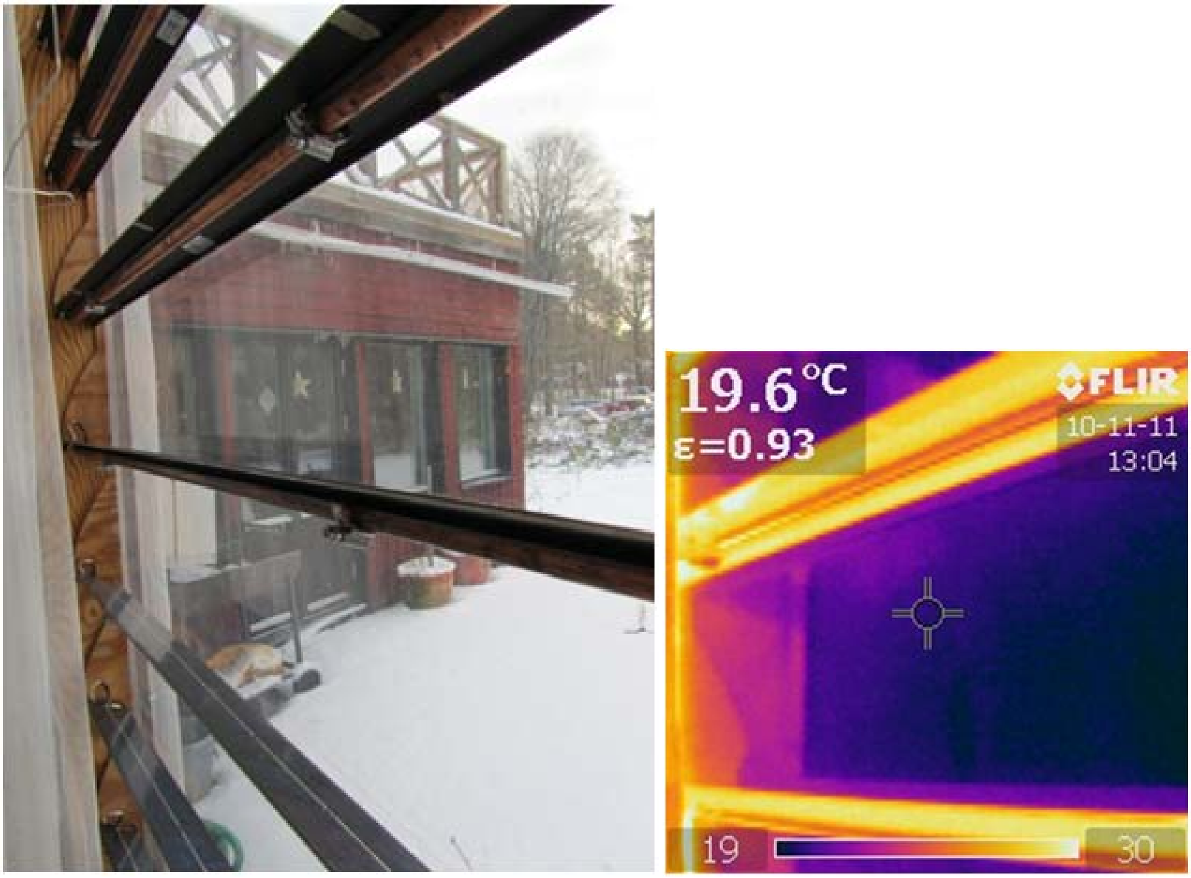


Figure 5: Water-cooling and Air Ventilated Blind Integrated PV/T System (left) and the Thermal Image (right)

1.3 Monitoring Results of Ventilated PV/T HR Mock-up

The reflectors installed in PV/T HR mock-ups help increase the level of solar radiation on PV cells; hence, the conversion efficiency of PV cells can 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 lessens power output (Fig.6). The observed PV/T modules consist of polycrystalline silicon PV cells which are 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.

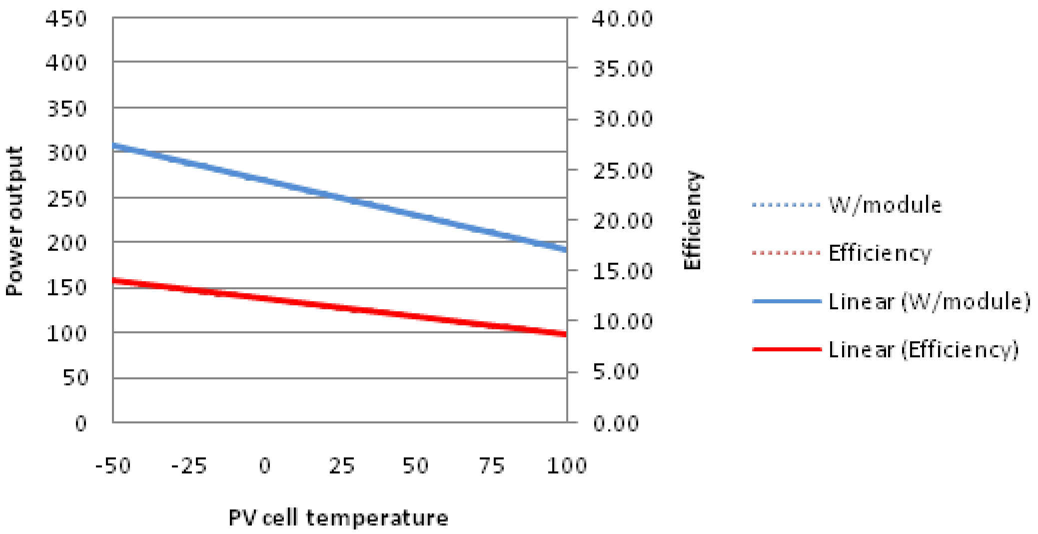
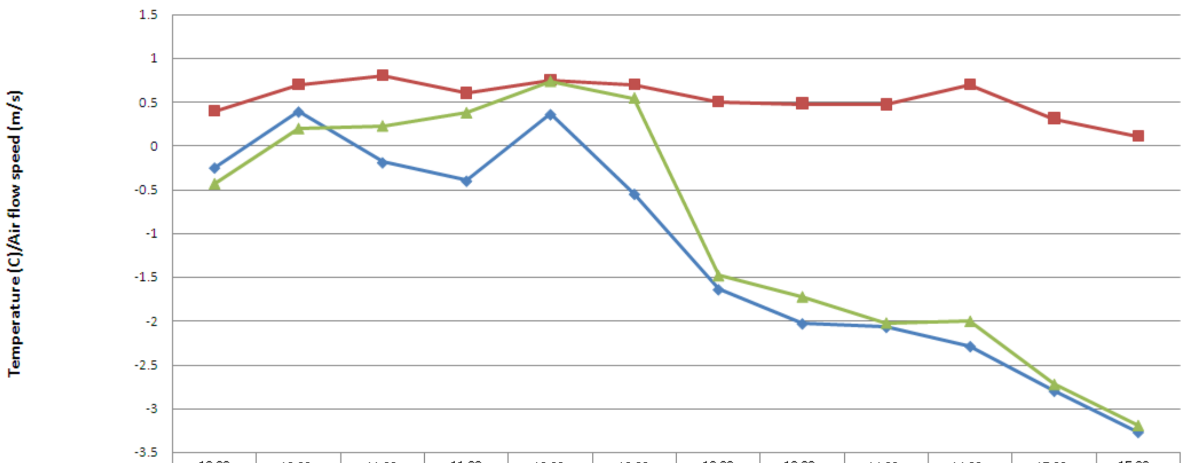


Figure 6: Co-relationship between the crystalline-silicon PV efficiency and the temperature

In view of the moderate cost and the simple configuration, the concept of a ventilated PV/T HR system rather than one with water circulation was considered as attractive and applicable to the Z-en house project. Accordingly, the system was examined in order to identify the PV air heating potential. Figure 7 shows the monitoring results of the PV/T system in question where the inlet and outlet ventilation air temperatures and flow velocity are measured.



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

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 the inlet or ambient temperature (Fig 7). However, due to the small size (2,368mm x 1,014mm x 235mm) of the mock-ups 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. 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.8).

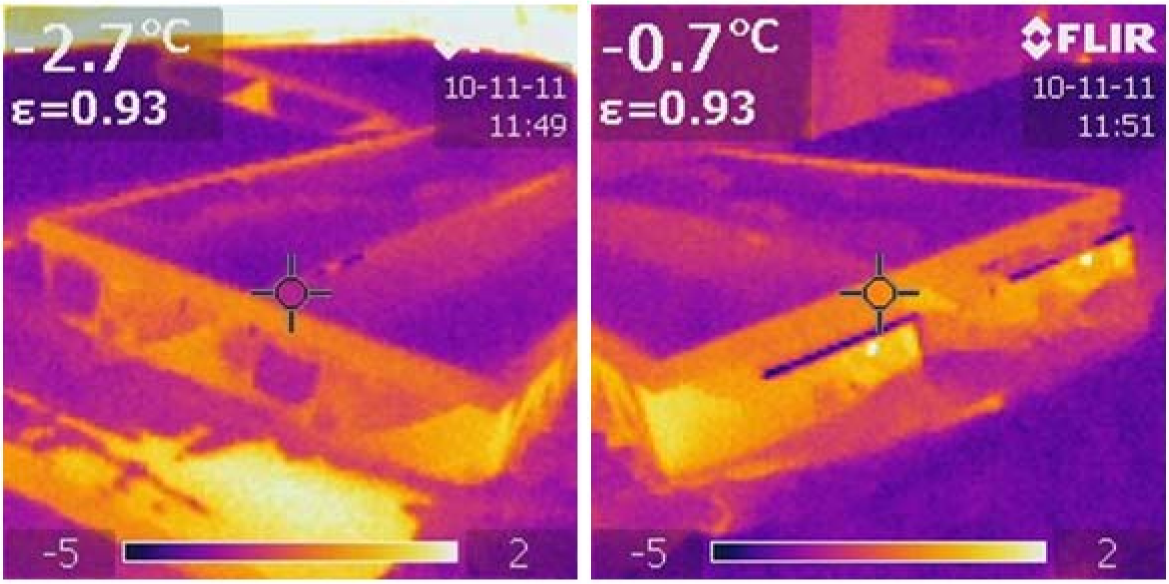


Figure 8: Thermal Image of Ventilated PV/T HR Mock-up: Air Inlet (left) and Outlet (right)

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.

1.4 Lessons Learned

The investigation of PV/T HR mock-ups 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-ups also demonstrated the formation of ice dams on the PV roof which should be averted by proper architectural integration. In view of the experience, the way to integrate a PV/T MVHR system with the Z-en house will be visualised in Part 2.

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. Also, it could not lead to identifying the potential effect of PV/T HR systems under Scottish climatic conditions. Accordingly, those aspects will be investigated further by making use of the state-of-the-art *EESLISM* energy and environment simulation tool which was developed by Prof Mitsuhiro Udagawa, Kogakuin University. The simulation outcomes will be unveiled in the later sections.

PART II: PV/T HR DESIGN GUIDELINE

2.1 Z-en house Project Overview

International Energy Agency (IEA) indicates energy use in buildings worldwide accounts for over 40% of primary energy use and 24% of greenhouse gas emissions. Energy use and emissions 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 requests the industry to achieve their bold green target that all newly built homes need to be carbon neutral by 2016. Despite the policy, the homebuilding industry today is barely ready for accomplishment of the 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 for meeting the society's need, government's expectation and industry's obligation, ROBERTRYAN Homes is currently developing design ideas and solutions towards the actual construction of Scottish first net zero-energy healthy housing prototypes in North Ayrshire in 2011/12 which aims to surpass the energy usage profile of net zero carbon counterparts. The zero carbon homes being recognised under the Code for Sustainable Homes in the UK tend to be low-energy solutions rather than the net zero energy due to the dominant domestic energy source for water and space heating today. The expected housing prototype has been called *Z-en house* with the aim to achieve the net zero energy housing consumption in view of the UK government's recognised Standard Assessment Procedure (SAP) (Figs.9 & 10).

Figure 9: Z-en House South-west Façade Image

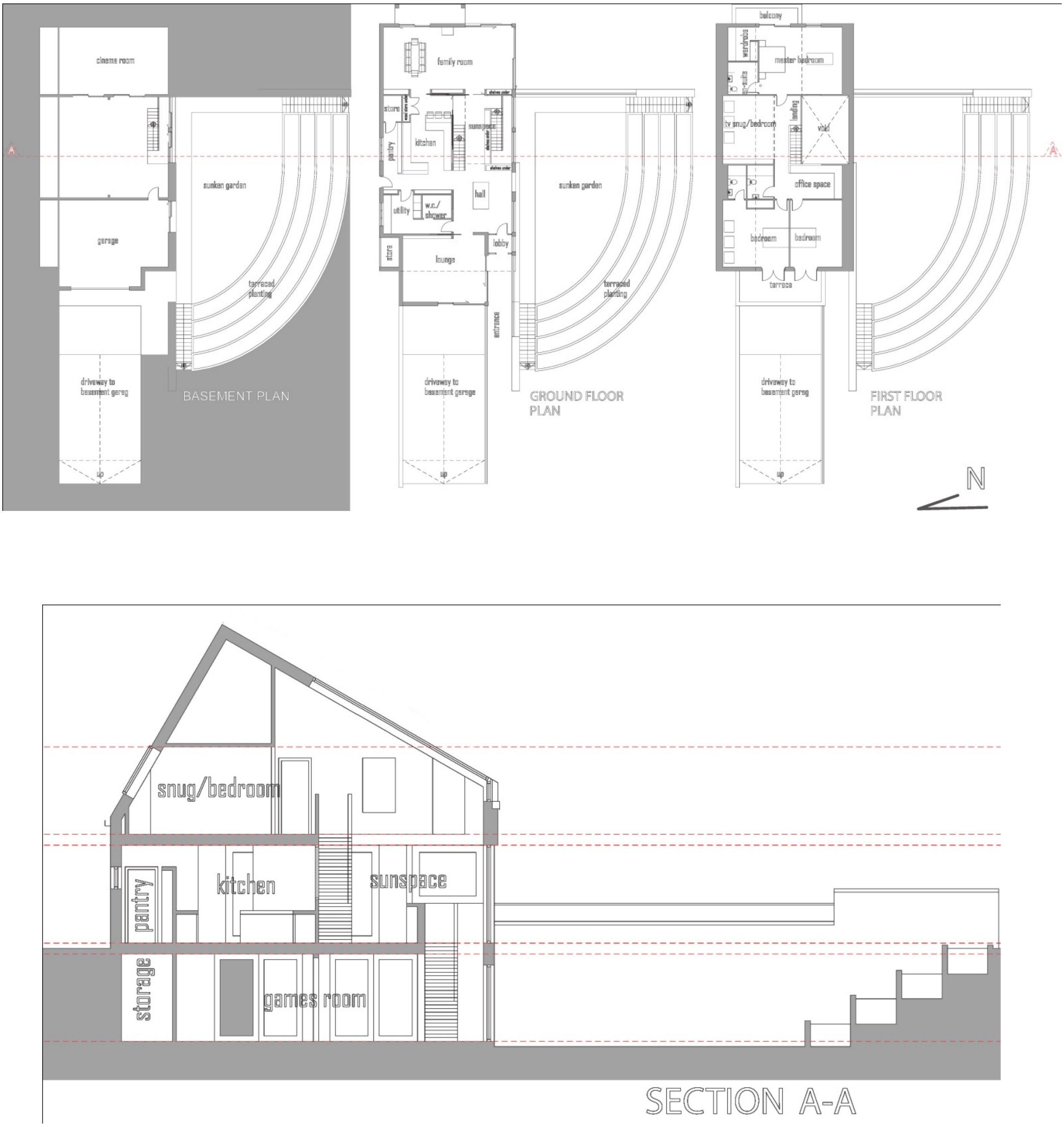
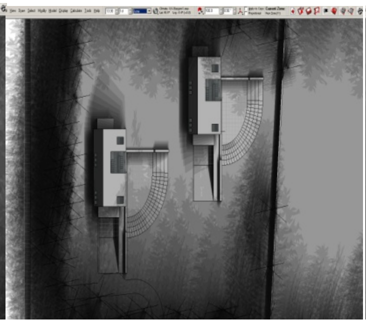


Figure 10: Z-en House Initial Plans and Section

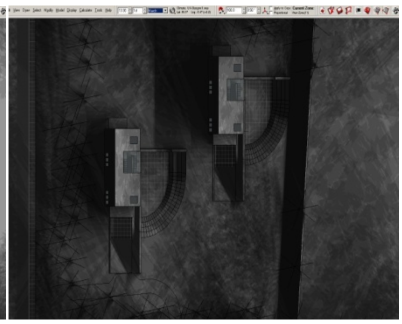
The construction site will carefully be selected based on solar access and sun shading analyses with the aim to optimise the natural light and solar heat gains (Figs.11).

Panoramic view of Z-en house construction site

March



June



October

South-East facade

South-facing sunken garden

Figure 11: Construction Site's Sun Shading Analysis

2.1.1 Z-en House Design Characteristics

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 new to the homebuilding industry in the UK (Fig.12).

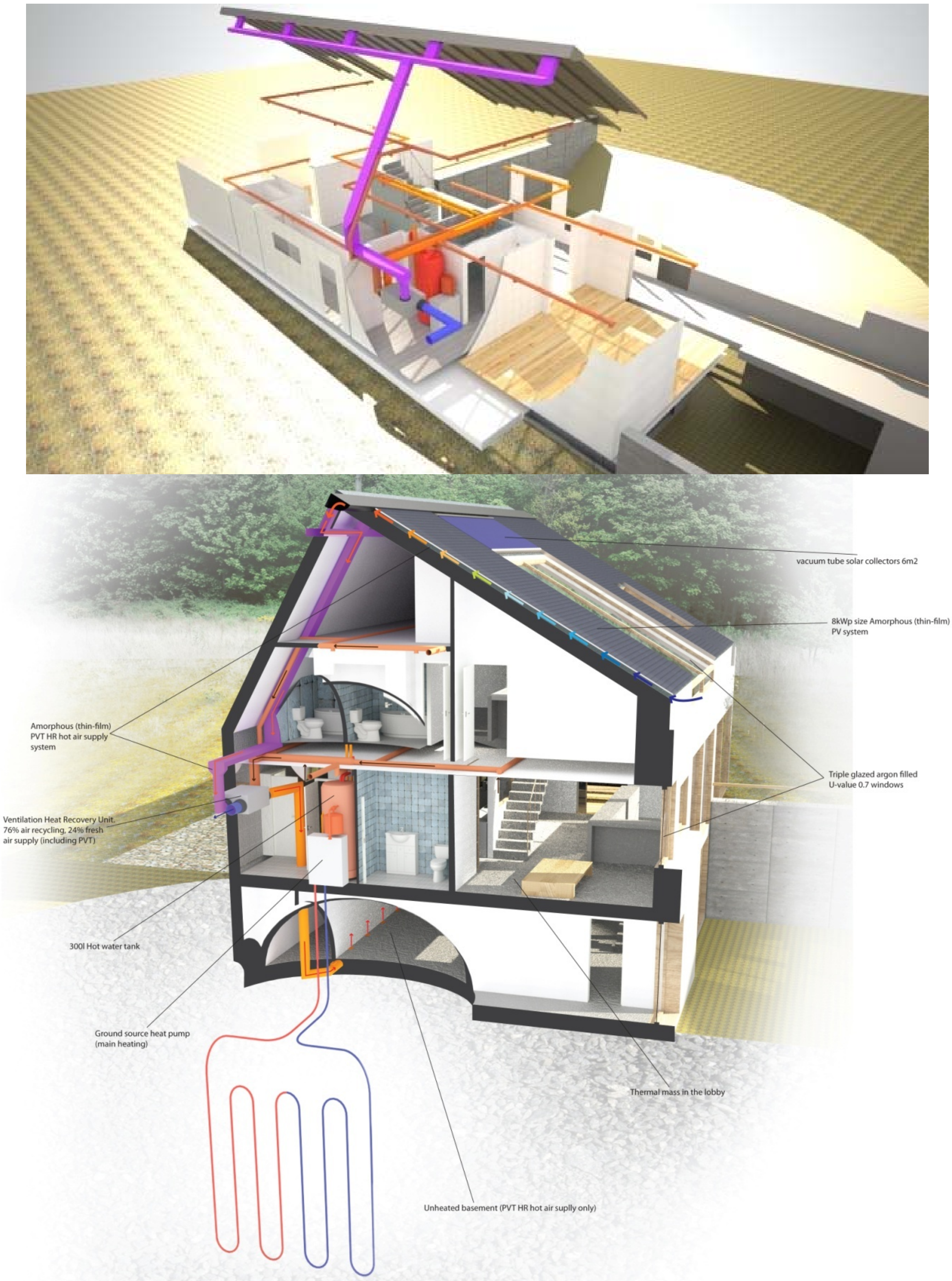


Figure 12: Building Integrated PV Thermal Mechanical Ventilation Heat Recovery System (BIPV/T MVHR)

The Z-en house will be designed to meet both net zero-carbon and -energy target based on SAP 2009 and will 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 (Fig.13).
- 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).

- 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% dedicatedenergy 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.

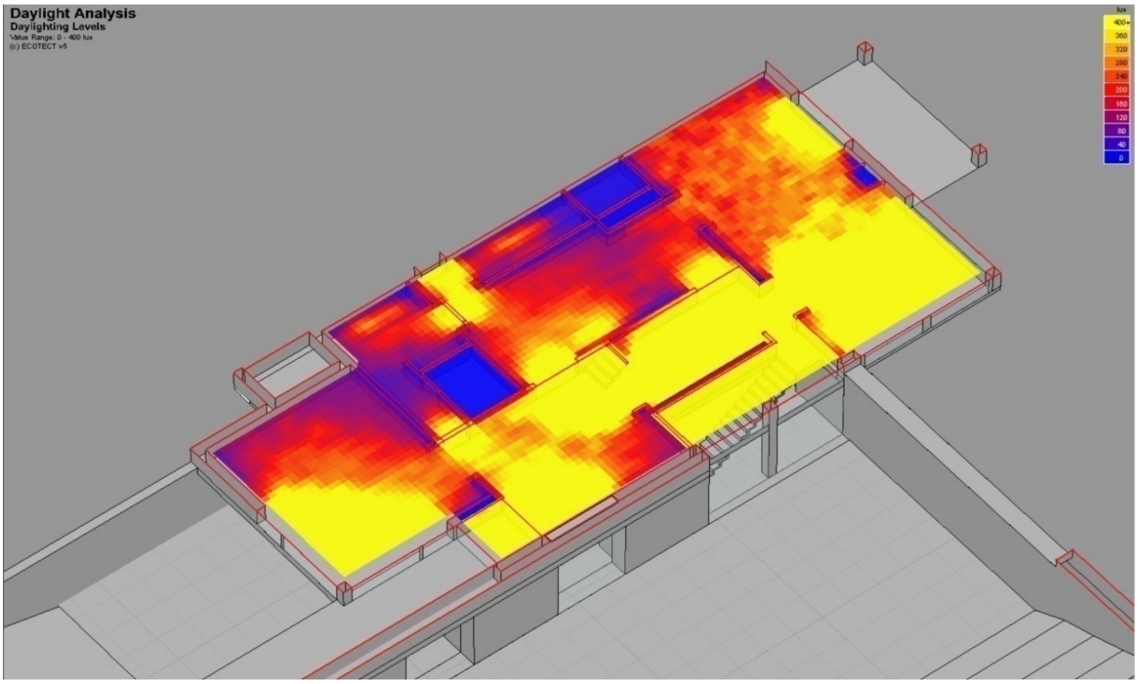
- Introduction of energy label A++ white goods for reduction of stand-by energy use.

- Installation of weather compensator and enhanced load compensator to maximise the performance of heat distribution accompanied by zone control multiple thermostats and programmers for energy saving.

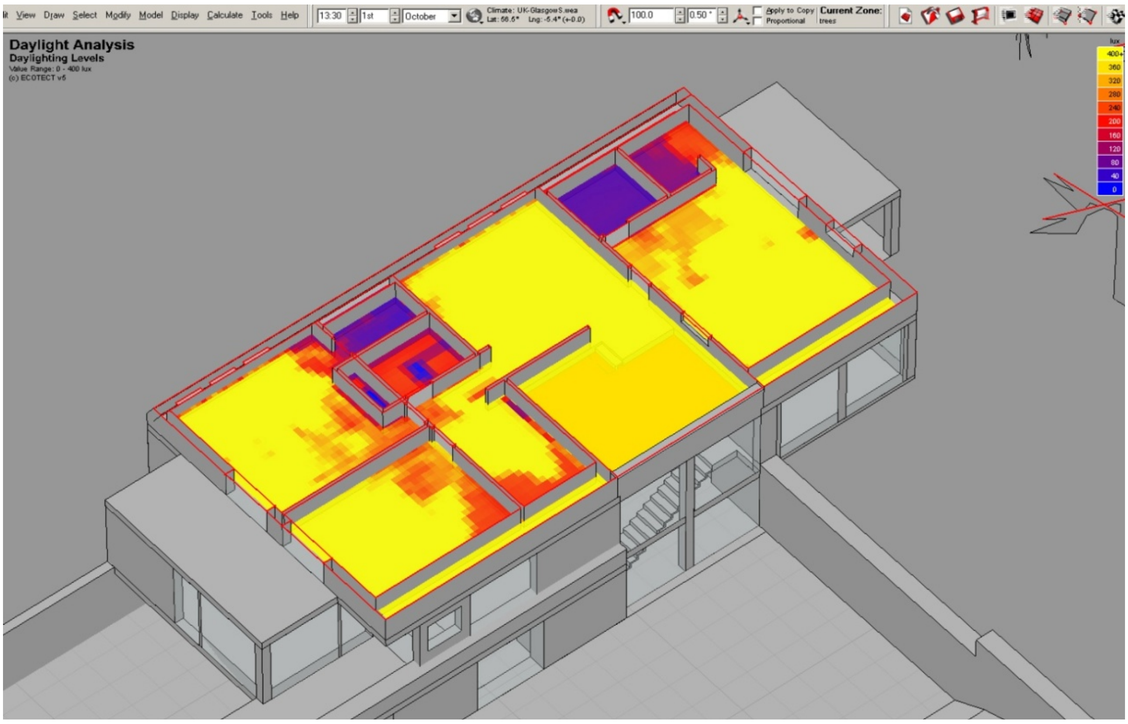
- Installation of interactive energy and water consumption monitors for enhancement of energy-saving user behaviour and for post occupancy evaluation.

- 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 of Scottish first as-built net zero-energy housing—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 expected to be built within next 3 years. Currently, the Z-en house project has been nominated by IEA SHC/ECBCS Task 40/Annex 52 as one of the UK top net zero-energy housing projects and the house will be introduced widely through the IEA Subtask C source book, which will be published in 2013.



Ground floor



1st floor

Figure 13: Daylight Analysis of Zen House Internal Space

2.2 PV/T HR Performance Simulation

Based on the initial conceptual design of the Z-en house, as detailed in the previous section, the potential performance of a photovoltaic thermal mechanical ventilation heat recovery (PV/T MVHR) system was examined under Scottish climatic conditions by making use of the *EESLISM* (i.e. thermal system simulation tool) in collaboration with the programme inventor and developer, Prof. Mitsuhiro Udagawa, Kogakuin University, and Dr. Yoshiki Higuchi, respectively. 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. Figures 14 & 15 indicate the dry-bulb ambient temperature and the horizontal solar radiation levels of the location (Latitude: 56; Longitude: -6) selected from the Energy Plus weather data.

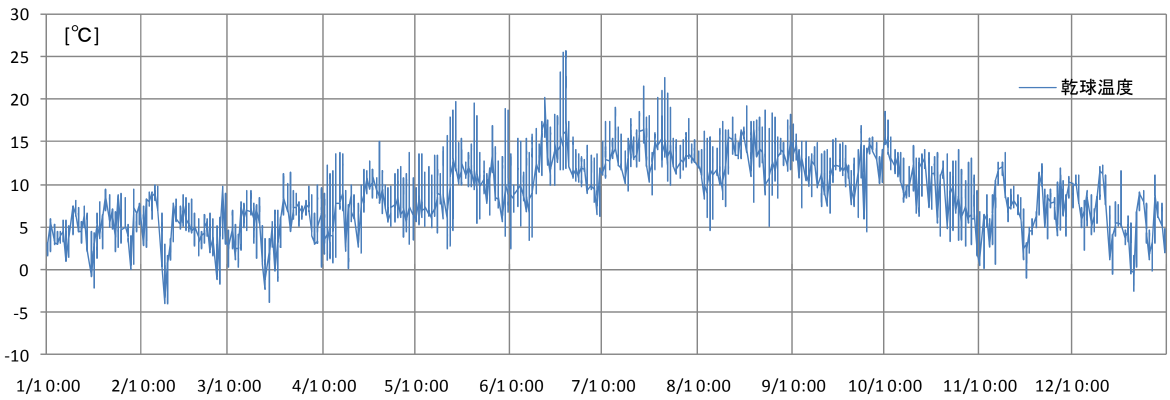


Figure 14: Annual Ambience Temperature Profile

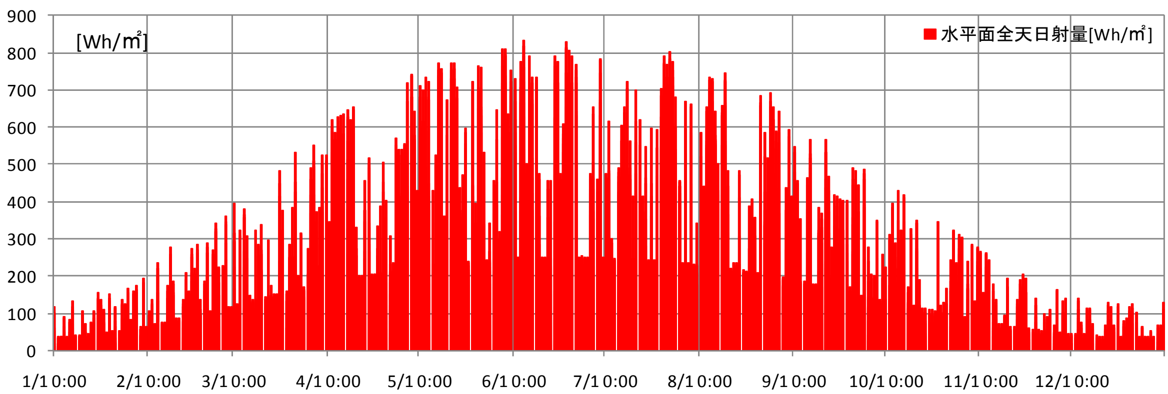


Figure 14: Annual Horizontal Solar Radiation Profile

The EESLISM simulation of the PV/T HR system in question extended to the analysis of heat production capacity and the identification of power generation potential.

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 a MVHR system (Fig.12). 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. For the comparative analysis of the system's potential seasonal changes as to the general 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 2 and Fig.15). In particular, 30th January was used as a base date for the detail analysis of the effect of roof configurations (e.g. angles) on PV/T heat and power generation in the Scottish winter.

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

Table 2: Solar Radiation and Temperature Profiles, 30th January and 24th August

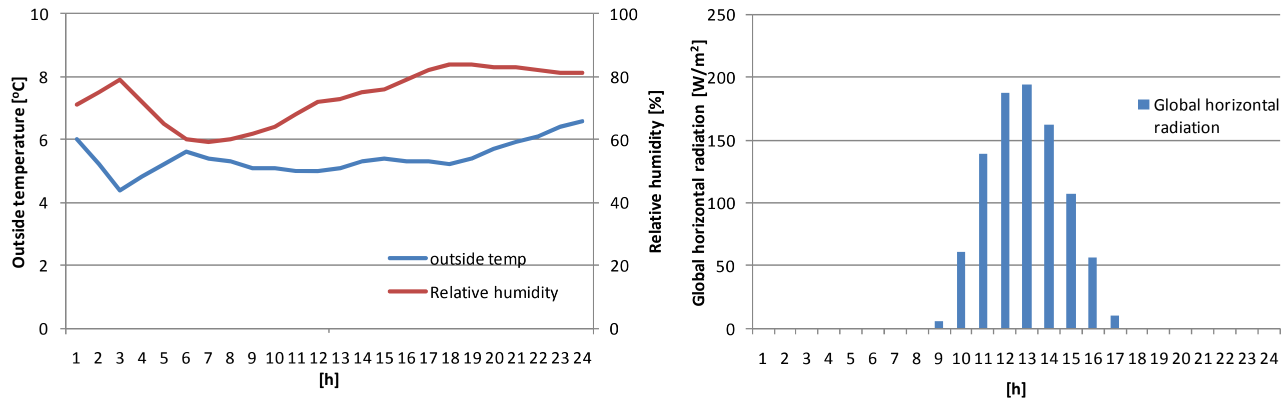
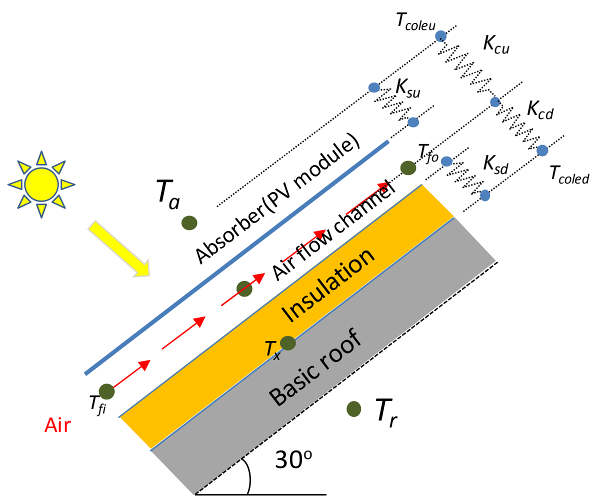


Figure 15: Hourly Profiles of Relative Humidity, Outside Temperature and Horizontal Solar Radiation

2.2.1 BIPV/Thermal Simulation Model

This study 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 (Fig.16).



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/㎡ K]
K_{sd}	Specific Heat Loss Coefficient of the Bottom Element of the PV/T Heat Collecting Channel [W/㎡ K]
K_{cu}	Thermal Transmittance of the Upper Element of Ventilated PV Heat Collecting Channel [W/㎡ K]
K_{cd}	Thermal Transmittance of the Bottom Element of Ventilated PV Heat Collecting Channel [W/㎡ K]
T_{coleu}	Outer Surface Temperature of the Heat Collector Panel [°C]
T_{coled}	Inner Surface Temperature of the Heat Collector Panel [°C]
T_{fi}	Inlet Air Temperature [°C]
T_{fo}	Outlet Air Temperature [°C]

Figure 16: Section of BIPV/T Roof and Description of Denotations Applied to the EESLISM simulation

The temperature rise tendency of the ventilated PV/T air was calculated by:

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

K_c is the total thermal transmittance of the heat collector panel (W/m² K) and it was calculated by means of:

$$K_c = K_{cu} + K_{cd} \ , \quad T_{cole} = k_u T_{coleu} + (1 - k_u)T_{coled}$$

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

$$K_{cu} = K_{su} f_{cu} \ , \quad K_{cd} = K_{sd} f_{cd}$$

A_{su} denotes the area of the PV/T roof collector (m^2) while *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.16. Based on them, the quantity of potential heat generation, *Q*, was calculated by:

$$Q = CG\left(T_{fo} - T_{fi}\right)$$

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 (Tables 3). 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.

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)

Table 3: PV/T System Variations Applied to the EESLISM Simulation

2.2.2 BIPV/Thermal Simulation Results

Figures 17-22 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.

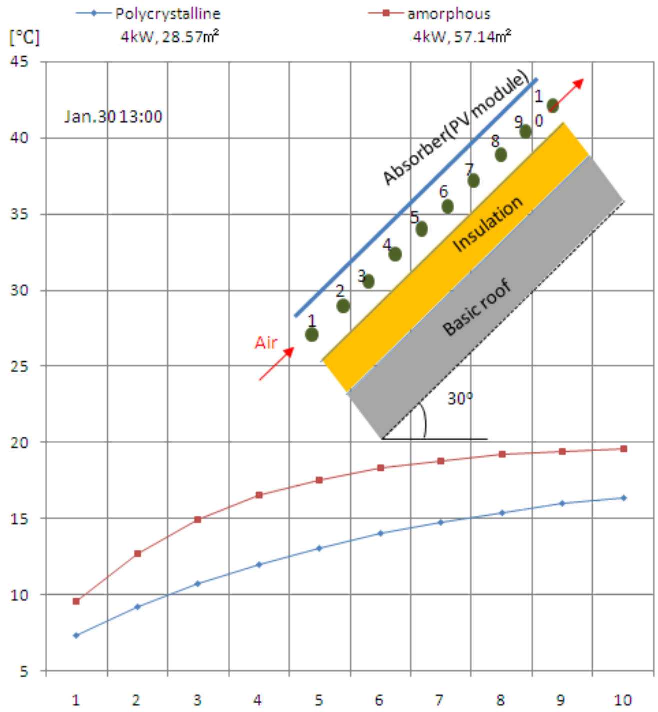


Figure 17: 4kWp Ventilated PV/T Air Temperature Profile at the Air Flow of 300m^3/h, 30th January

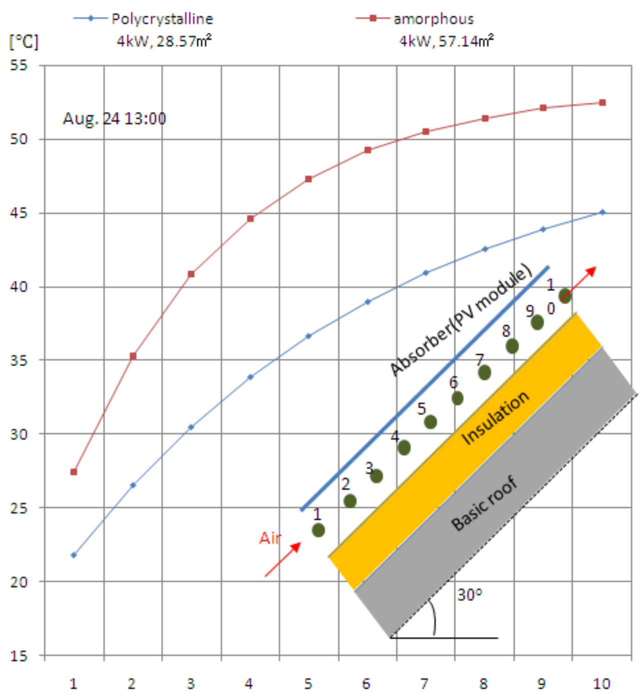


Figure 18: 4kWp Ventilated PV/T Air Temperature Profile at the Air Flow 300m^3/h, 24th August

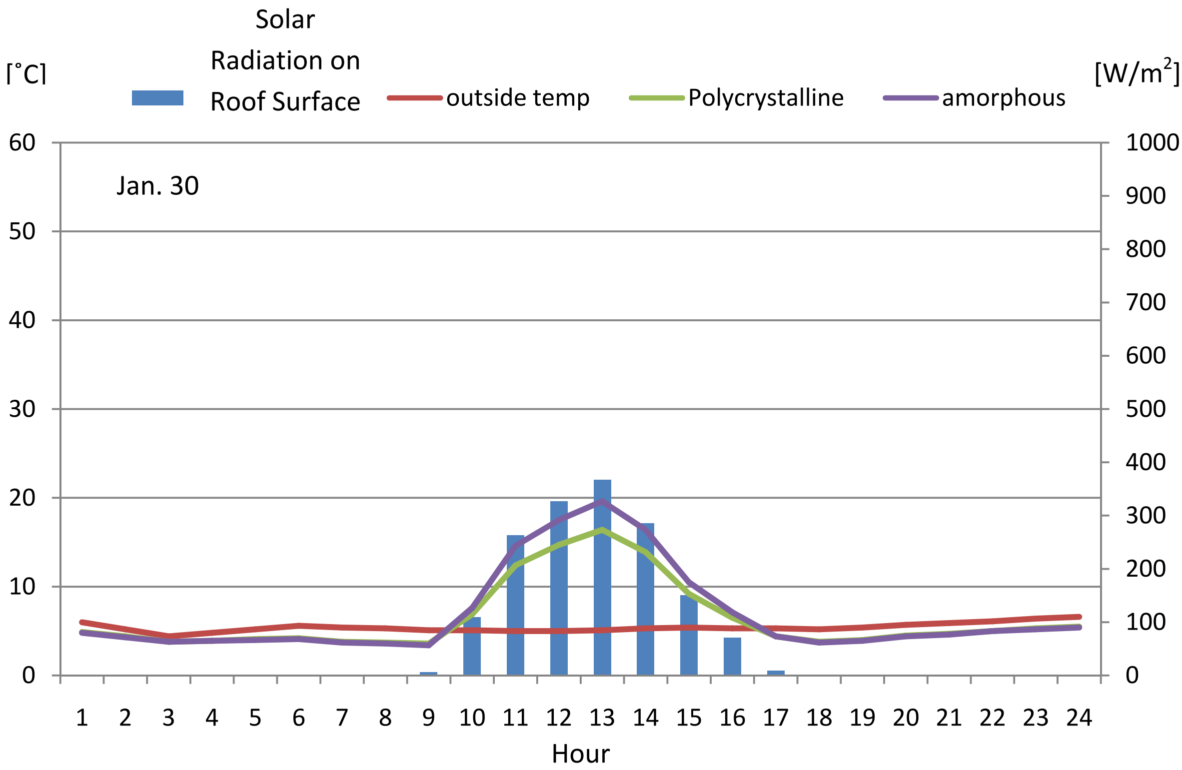


Figure 19: 4kWp Ventilated PV Heat Generation in Response to Incoming Solar Radiation, 30th January

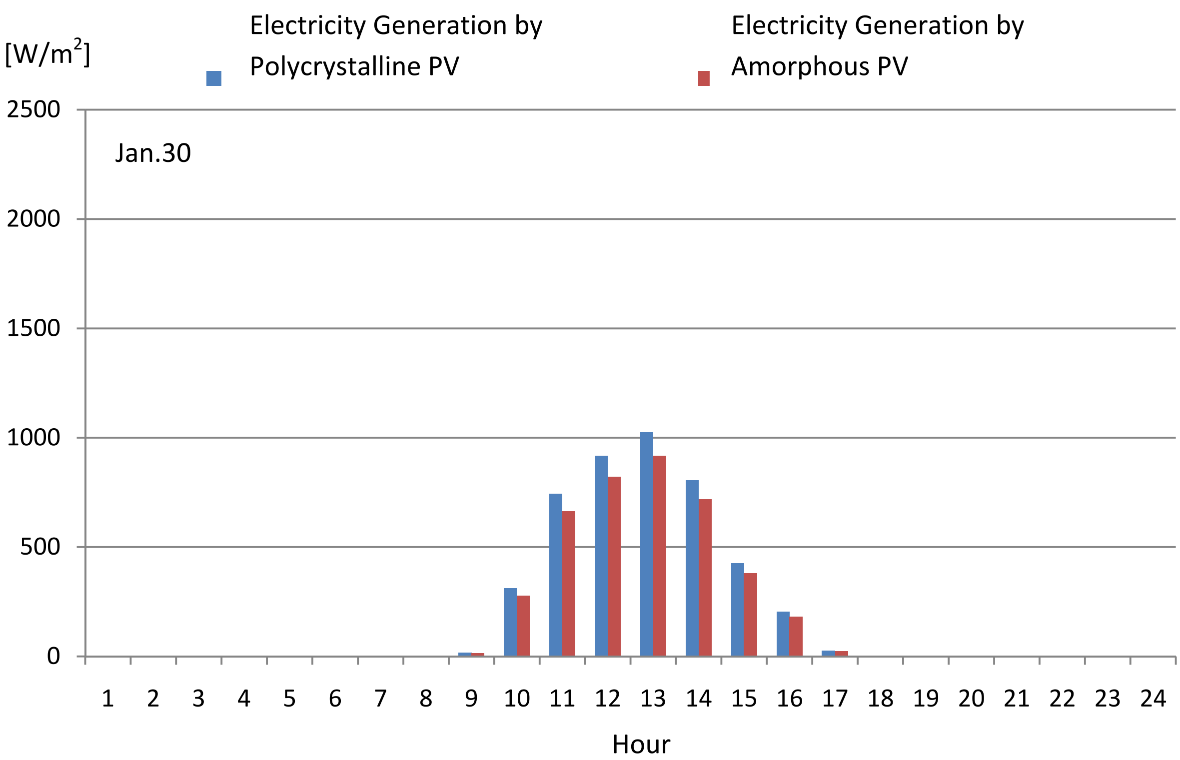


Figure 20: 4kWp ventilated PV Electricity Generation in Response to Incoming Solar Radiation, 30th January

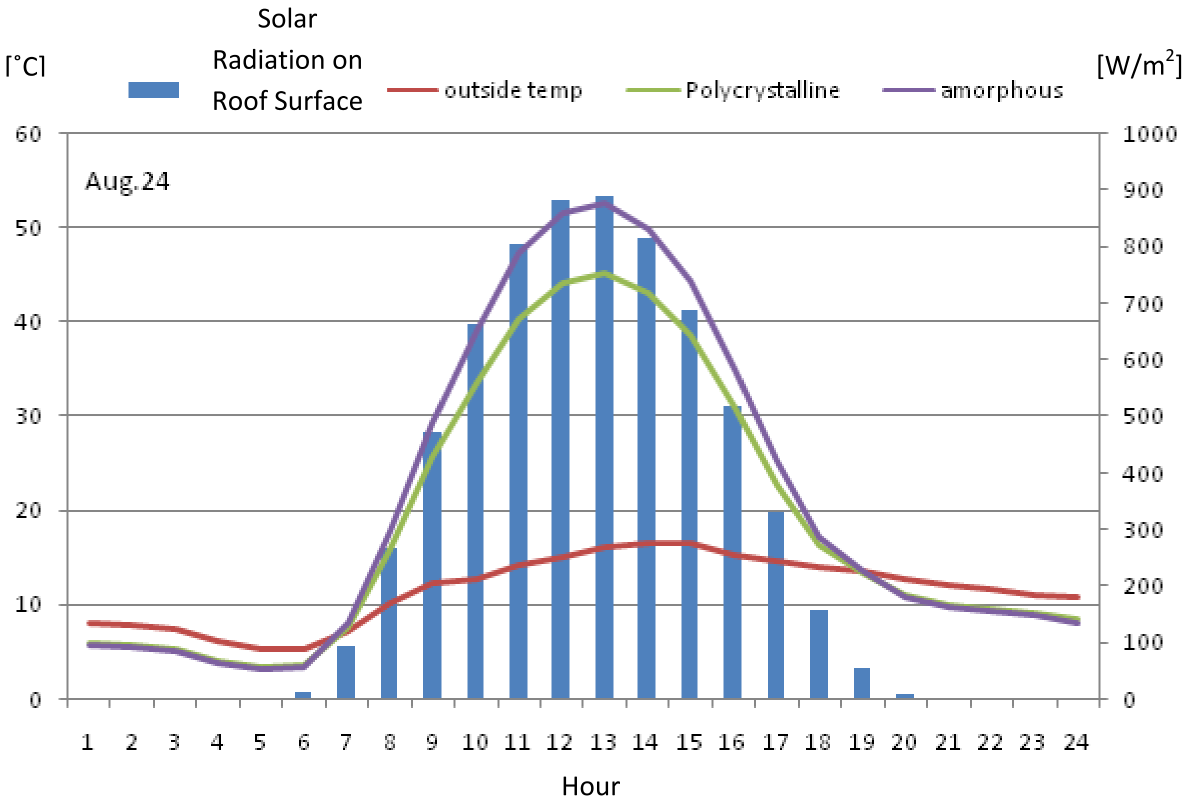


Figure 21: 4kWp Ventilated PV Heat Generation in Response to Incoming Solar Radiation, 24th August

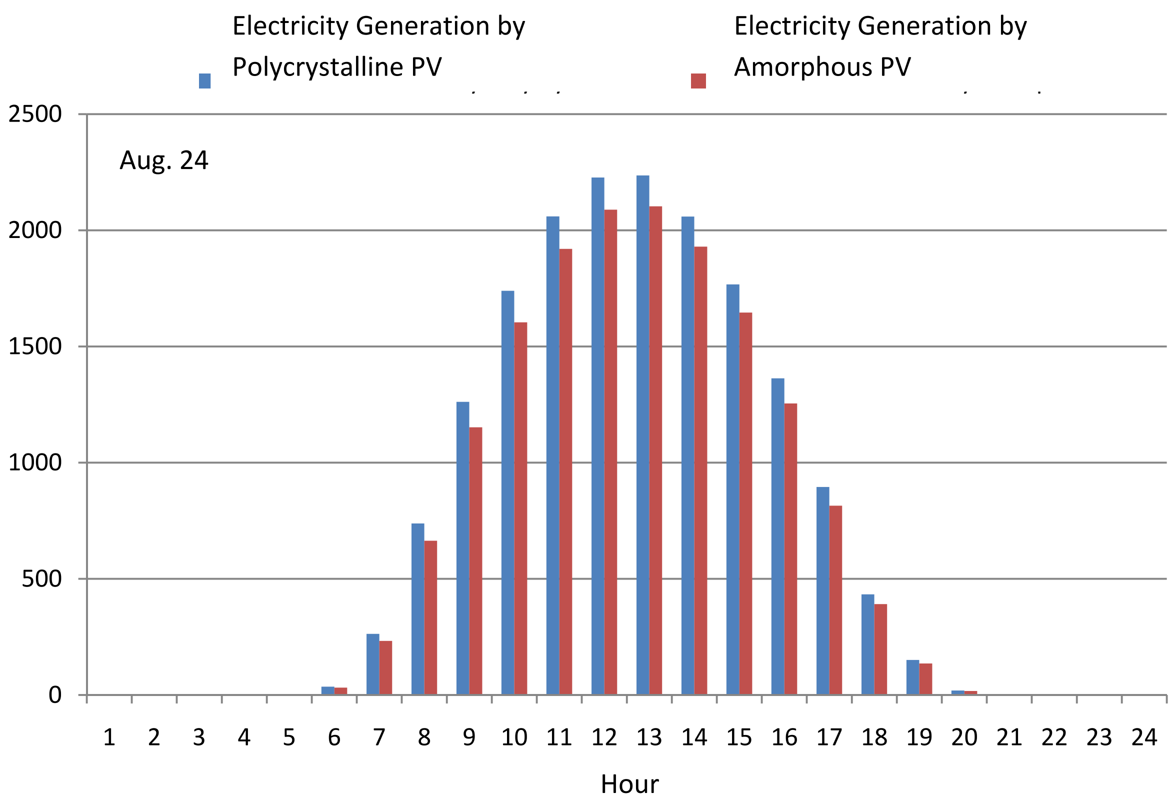


Figure 22: 4kWp Ventilated PV Electricity Generation in Response to Incoming Solar Radiation, 24th August

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 4 & 5 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 described previously.

	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 Heat Generation Capacity of Ventilated PV/T Integrated Roof Design Alternatives Given

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

In addition, Figures 23-24 exhibits the simulation results of the analysis that aimed to identify the effect of different roof angles, air flows and amorphous and polycrystalline PV sizes on the ventilated PV/T integrated roof's heat production when the operating data is set to be 30th January alone.

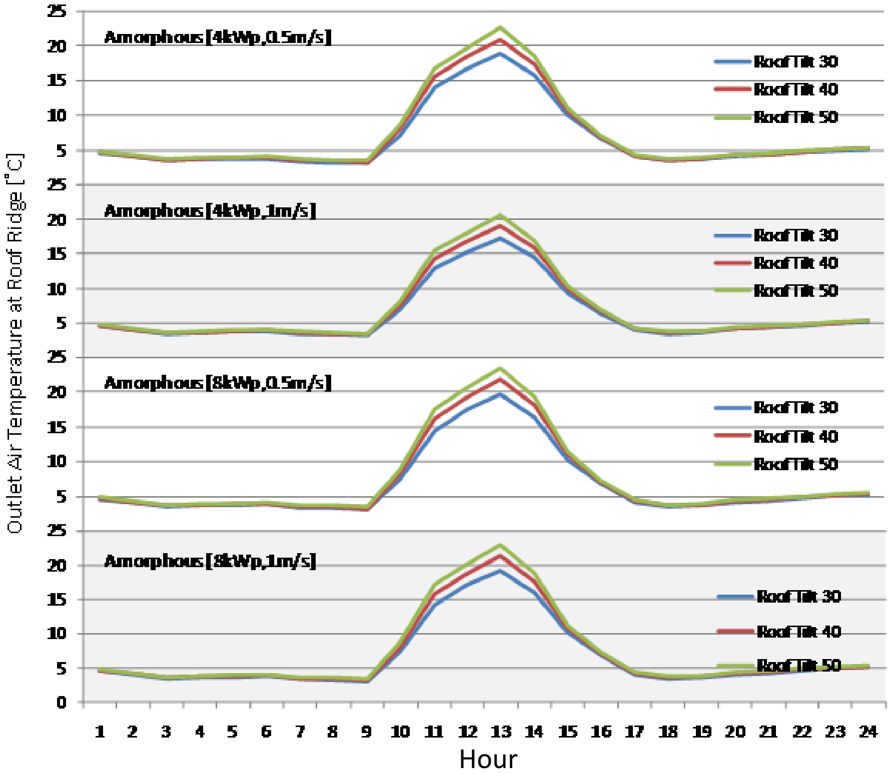


Figure 23: Hourly Profile of 7% Efficient PV Heat Production, 30th January

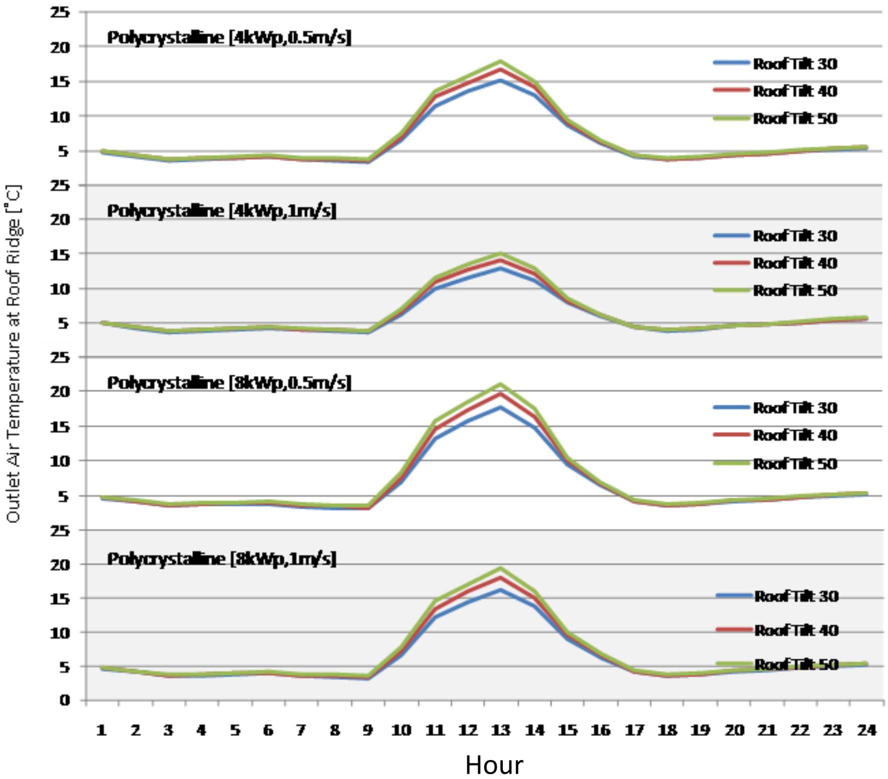


Figure 24: Hourly Profile of 14% Efficient PV Heat Production, 30th January

Under the same condition, the effect on the electricity generation was also simulated (Figs.25 & 26).

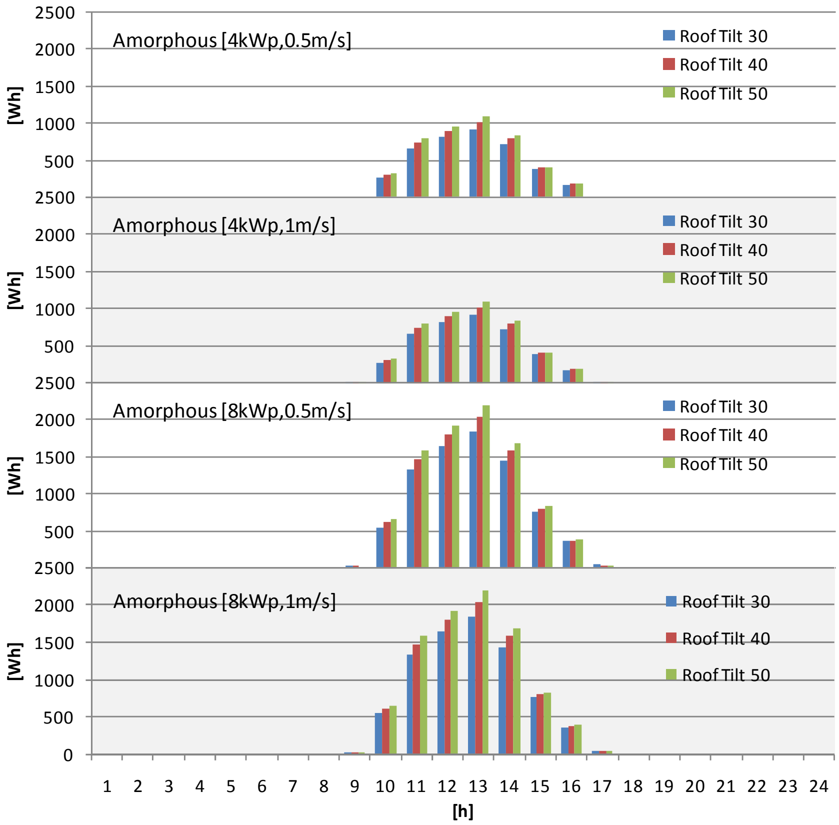


Figure 23: Hourly Profile of 7% Efficient PV Electricity Generation, 30th January

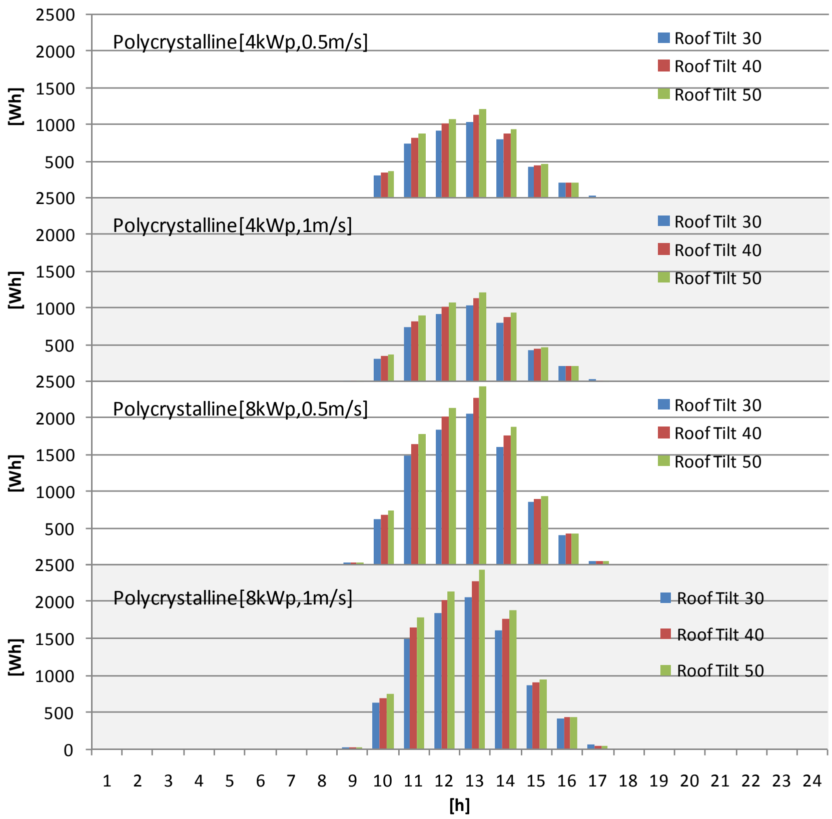


Figure 24: Hourly Profile of 14% Efficient PV Heat Generation, 30th January

PART III: CONCLUSION

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. 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.

This study 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.

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 lessoning 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. 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.