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Article

Choice of Domestic Air-Sourced Solar Photovoltaic Thermal Systems through the Operational Energy Cost Implications in Scotland

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Abstract: In Scotland, homebuilders are requested to take valiant efforts to meet the government's ambition that all newly built homes should be carbon-neutral by 2016/17. In delivering net zero carbon homes, the application of renewable energy technologies, such as solar photovoltaic (PV) power generating systems, is almost inevitable. Cost-effectiveness of emerging green technologies is a major factor that affects stakeholders' housing design decision-making on whether or not the innovations can be applied in practical terms. Based on the United Kingdom (UK) government's Standard Assessment Procedure (SAP) for energy rating of dwellings, this study conducted a comparative value assessment of 19 design alternatives set. The options also included ones that encompassed both electricity and heat generation potentials of PV applications—*i.e.*, air-sourced PV thermal (PV/T) systems. Based on the SAP simulation results, it concluded that operational energy use and cost, as well as carbon dioxide (CO_2) emission levels, can drastically be reduced particularly when a PV/T system is combined with a low-energy and high-performance mechanical ventilation with heat recovery (MVHR) system that can extract fresh air heated by PV. This study led to visualizing the cost-effectiveness of PV/T MVHR systems and identifying the economic value over 10 years at the interest rate of 10%, based on an assumption that the innovations are applied to Scottish homes today.

Keywords: cost-effectiveness measurement; PV/thermal MVHR systems; low to zero energy/carbon housing; renewable energy technologies; design decision-making

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1. Introduction

In general, the energy use required to operate a comfortable house depends on the occupants' family structure and usage patterns related to their behavior [1]. Moreover, climatic variations, housing sizes and types, and thermal properties of building skins also correlate with the amount of energy demand particularly for space and water heating capacity of houses built in Scotland [2]. Besides the human factors, the cost and performance of housing depends generally on design components selected. Thus, design decisions need to be made carefully with due consideration of the current and future values of not only component alternatives in question but also the combined attributes. In the UK, the Standard Assessment Procedure (SAP) for energy rating of dwellings has been applied for issuing Energy Performance Certificates today [3,4].

In Scotland, the installation of heating systems in housing is almost inevitable keeping the occupants' thermal comfort throughout the year. In addition to domestic heaters, active building service devices including mechanical ventilation systems and renewable energy technologies are readily applicable to the delivery of low-energy healthy homes today. A natural gas combination (or combi) boiler is one of the most popular heating systems being installed in homes build in Scotland. It is a compact system applied for domestic water and space heating and radiators are dominant devices that help spread the heat throughout a house. Ventilation in Scottish housing has been secured basically in two ways: natural and mechanical ventilation. The latter has a clear linkage to electricity consumption. Seemingly, the specific fan power (SFP), efficiency and ductwork arrangements have an impact on energy consumption particularly when a balanced mechanical ventilation with heat recovery (MVHR) system is concerned. A solar photovoltaic (PV) power generating system is one of the renewable energy technologies being applied to both new and existing homes in Scotland. PV generates electricity and the panels are often installed in the rooftop. The roofs are usually able to accommodate 4kWp PV systems, yet the amount of electricity generation depends on the cell types and panel sizes, as well as the orientation and sloping angle. With the heat released from the cells, snow tends to melt on the PV rooftop during the daytime. Seemingly, there is a synergy between PV and MVHR operations. For instance, PV generated electricity can contribute to the operation of an MVHR system, which is able to extract PV-heated fresh air running under the solar roofs. This linkage can lead to the establishment of an air-sourced photovoltaic/thermal (PV/T) MVHR system, which may be applied to homes in Scotland and help create a thermally comfortable healthy living environment at low energy costs achieved through the synergy.

There is limited research data that clarifies the effect of the hybrid PV/T HVHR application to houses in Scotland on domestic energy consumption and cost, as well as CO_2 emissions. Accordingly, this study was aimed firstly at demonstrating how the hybrid PV/T MVHR system can physically be applied to housing in Scotland and secondly at examining the cost and performance. In this study, SAP was applied for the energy simulation. In order to facilitate the further cost-effectiveness assessment of design alternatives given, a conceptual house was proposed in consideration of the aforementioned passive design considerations.

2. PV/T MVHR System Demonstration

In order to demonstrate the applicability of a PV/T MVHR system to housing in Scotland, a 3-story semidetached house was designed conceptually (Figures 1 and 2). The proposed house was called 'ZEMCH109' assumed to be built in an existing post-council housing development area in Prestwick, Scotland. A PV/T MVHR system was introduced to the house's south-facing roof, whose slope angle was considered to be 30° (Figure 3). The ground floor entrance is designed in the form of a draft lobby and a machine room, two children bedrooms, and a toilet are located on the same level. The 1st floor contains an open kitchen and dining space, which is linked continuously to a lounge that faces north due to the view of a vast green park. A master bedroom is located on the 2nd floor, which is also equipped with a bathroom facing the park and a storage space. In order to reduce the energy load for space heating, high thermal performance building envelopes were desired; for instance, U-value of the walls was assumed to be 0.15 W/m^2K and ceilings and roofs were designed to achieve U-values of 0.10 W/m^2K. The air permeability was expected to be 3 m^3/m^2 h. A natural gas combi boiler was selected for the main space and water heating. Without MVHR and PV systems in question, the house's operational energy consumption was estimated at 9,092kWh/annum [5]. This amount was used for the comparative analysis of design alternatives, which will be identified later (Figure 3).

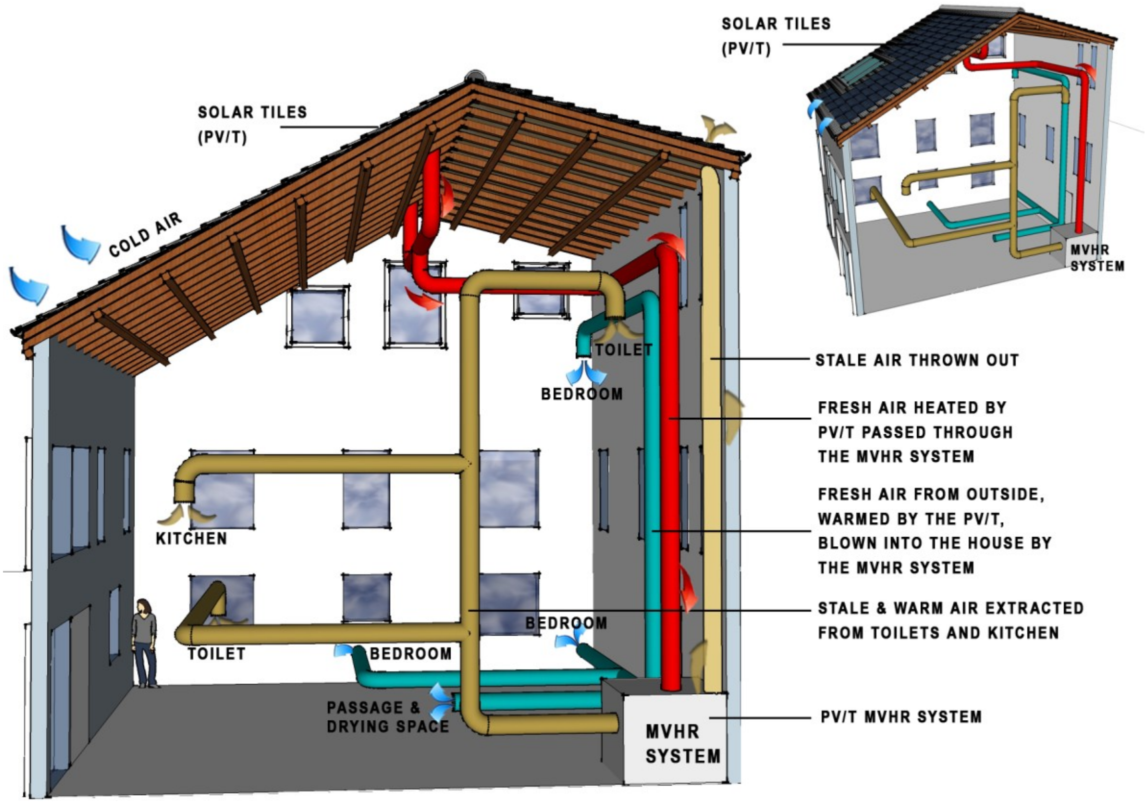
Figure 1. ZEMCH 109 equipped with a south-facing photovoltaic/thermal (PV/T) roof.

Source: NRGStyle.

Figure 2. Ground, 1st and 2nd floor plans of ZEMCH 109.

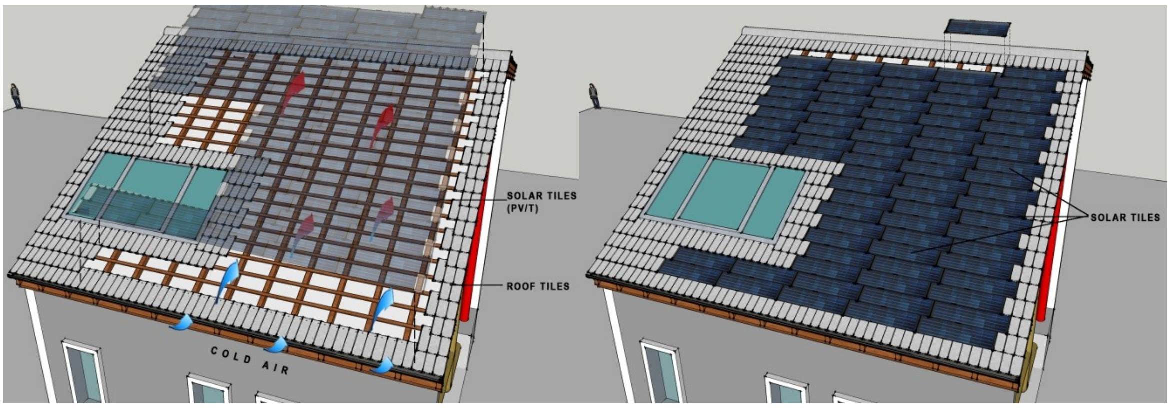
Source: NRGStyle.

Figure 3. PV/T mechanical ventilation with heat recovery (MVHR) system schematic diagram.



In this project, PV tiles were considered as a practical solution not only to enhance the architectural integration but also to secure the heat extraction. Today, such PV tiles are widely available in Scotland being installed in roofs of conventional roofing practice. The size of a PV roof panel is 420 mm in width and 1,220 mm in length. To secure ventilation airflow under the PV roof, wooden battens are laid vertically on the sheathing (Figure 4). Moreover, the ventilation cavity needs to be sealed sufficiently so as to draw fresh air that is running and heated by the PV roof.

Figure 4. PV/T roof building integration.



The conversion efficiency of mono-crystallized silicon PV cells selected was considered to be 14% in view of the author's previous study [5]. When the PV tiles are laid at gauges, the weight possibly becomes nearly 20 kg/m^2. It was concerned that the efficiency of PV systems would be reduced by approx. 0.7% annually [6]. Nonetheless, PV installers in Scotland tend to offer a 10-year warranty for the structural damage and further guarantee the minimal expected power output over the period of 25 years from the date of commissioning.

2.1. Alternative Settings

For the performance assessment, 6 MVHR products were selected in view of their SFP and efficiency variations (Table 1). The products chosen were further studied in order to identify their impacts on operational energy consumption and cost, as well as CO_2 emission levels, when they are applied to the ZEMCH 109 demonstration house, where a 90.3% efficiency mains gas combi boiler is to be installed as the standard water and space heating equipment. The south-facing roof of the house was designed to accommodate 4 kWp PV systems. The PV roof coverage was estimated at 28.57 m^2 accompanied by the underside airflow at 432 m^3/h or the velocity of 0.5m/s. In consideration of the Scottish climatic conditions, the PV thermal energy generation capacity was considered to be 3,440 kWh per annum [5]. The PV heated air needs to be drawn to the rooms sufficiently in order to utilize the byproduct for potential space heating. In this demonstration, MVHR systems were to be installed in ZEMCH 109 with the aim to extract PV heated fresh air and to mix it with indoor pre-heated air constantly.

Table 1. Profile of MVHR products selected.

PRODUCT OPTION	A	B	C	D	E	F
SPECIFIC FAN POWER (W/l/s)	0.4	0.61	0.76	1.2	0.68	0.77
HEAT RECOVERY EFFICIENCY (%)	91	93	94	83	84	88
DUCT TYPE	RIGID	RIGID	RIGID	RIGID	FLEXIBLE	FLEXIBLE

In this study, total 19 options were developed for the cost and performance assessment (Table 2). The Option 1 was considered as the benchmark design alternative, which contains neither an MVHR system nor PV panels. A combi boiler was selected to supply the demonstration house's space and water heating, as described previously. The options given include a PV system for the purpose of power generation alone, while some others contain the device to benefit from the electricity and heat generation capacity.

Using the SAP (version 2009) simulation, the effect of each given design option on the demonstration house's annual operational energy consumption and cost was assessed (Table 3). In the UK, the unit price of mains gas are estimated at 3.10 pence per kWh; the CO_2 emission factor is 0.198 kg CO_2 per kWh; and the primary energy factor is regarded as 1.02 [3]. Similarly, those of electricity are considered to be 11.46 pence per kWh, 0.517 kg CO_2 per kWh, and 2.92, respectively. These figures suggest that the use of electricity in Scotland leads to 2.6 times more CO_2 emissions than mains gas. Thus, the use of a gas combi boiler essentially helps reduce the green emissions as opposed to that of heaters run by electricity, unless the consumption from the grid is replaced with the energy supplied by locally installed renewable energy technologies. On the other hand, the unit price of electricity sold to the grid is considered to be 11.46 pence per kWh, while the CO_2 emission factor and primary energy factor of electricity displaced from the grid is assumed to be 0.529 kg CO_2 per kWh and 2.92, respectively. These figures also articulate the significance of generating electricity via locally installed renewables, such as PV.

Table 2. Design options examined.

OPTION	**MAINS GAS COMBI BOILER**	**MVHR**						**PV ELECTRICITY**	**PV THERMAL**
		A	**B**	**C**	**D**	**E**	**F**		
1	X								
2	X	X							
3	X	X						X	
4	X	X						X	X
5	X		X						
6	X		X					X	
7	X		X					X	X
8	X			X					
9	X			X				X	
10	X			X				X	X
11	X				X				
12	X				X			X	
13	X				X			X	X
14	X					X			
15	X					X		X	
16	X					X		X	X
17	X						X		
18	X						X	X	
19	X						X	X	X

Table 3. Energy cost, usage and production assessment results of 19 alternatives selected.

OPTION	**DELIVERED ENERGY USE (kWh/year)**	**PRIMARY ENERGY USE (kWh/year)**	**PV ELECTRICITY GENERATION (kWh/year)**	**PV/T HEAT GENERATION (kWh/year)**	**ANNUAL UTILITY COST (GBP)**
1	9092	10645	0	0	448
2	6173	8253	0	0	383
3	2968	−1190	3286	0	12
4	513	−3693	3286	3440	−64
5	6362	8861	0	0	408
6	3076	−735	3286	0	31
7	696	−3162	3286	3440	−43
8	6455	9202	0	0	421
9	3169	−394	3286	0	45
10	826	−2783	3286	3440	−28
11	7243	10727	0	0	477
12	3946	1131	3286	0	101
13	1198	−1683	3286	3440	15

Table 3. *Cont.*

OPTION	DELIVERED ENERGY USE (kWh/year)	PRIMARY ENERGY USE (kWh/year)	PV ELECTRICITY GENERATION (kWh/year)	PV/T HEAT GENERATION (kWh/year)	ANNUAL UTILITY COST (GBP)
14	6882	9745	0	0	439
15	3596	149	3286	0	63
16	875	−2626	3286	3440	−22
17	6827	9868	0	0	445
18	3541	272	3286	0	69
19	973	−2347	3286	3440	−11

According to the assessment results, the options that do not contain PV systems can be characterized by their relatively high overall energy consumption, which in turn raise the utility cost (Options 1, 2, 5, 8, 11, 14 & 17). In comparison, the energy use and cost figures are lower in those that benefit from PV power generation (Options 3, 6, 9, 12, 15 & 18). Moreover, the tendency can be accelerated when PV thermal capacity is also treated as a source that advances indoor space heating (Options 4, 7, 10, 13, 16 & 19).

3. Future Worth Implications via Systems' Operating Energy Costs

In order to compare design alternatives given in financial terms, the 'Time Value of Money' concept was reviewed [7]. The concept reflects the fact that today's money is more worth in the future when it is accumulated with an interest rate assigned. The future worth is the value of an asset in the future and determines the worth for a given sum of money at a specific time to which an assumed rate of interest is applied. In this study, the future worth of each design option was estimated using the following formula:

$$\mathbf{FW = AC\ (1 + i)^{n}} \tag{1}$$

Where,

FW = future worth of the option selected
AC = annual energy cost
i = annual interest rate
n = number of the year in question

Moreover, in this study, Option 1 was considered as the benchmark design alternative, as described previously, and the future worth of the benchmark would hereafter be denoted as $AC_{OPT\ 1}$ for further comparative economic assessment. Accordingly, in comparison to Option 1, the cost-effectiveness of all other design alternatives has been assessed using the following formula:

$$\mathbf{CE_{OPT\ x} = (AC_{OPT\ 1} - AC_{OPT\ x}) \cdot (1 + i)^{n}} \tag{2}$$

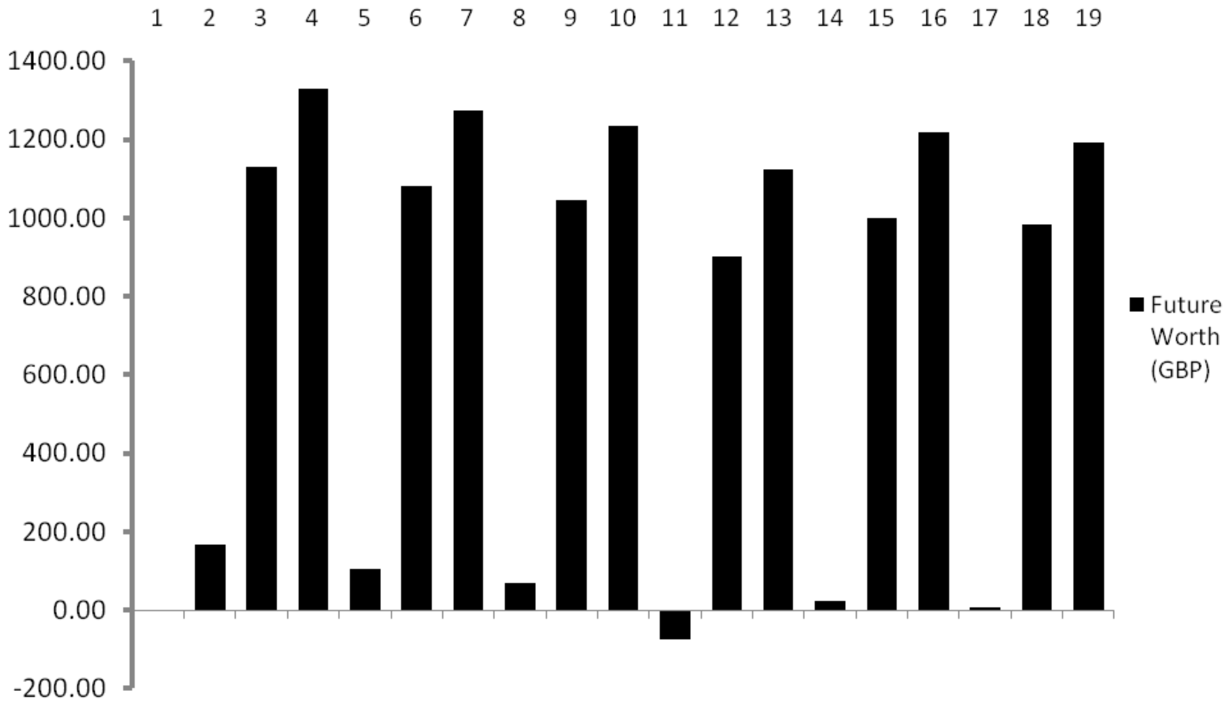
Where,

$CE_{OPT\ x}$ = cost-effectiveness of annual energy cost difference
$AC_{OPT\ 1}$ = annual energy cost of the benchmark option (OPT 1)

$AC_{OPT\,x}$ = annual energy cost of the option selected (OPT X)
i = annual interest rate
n = number of the year in question

The future worth (or value) of the aforementioned options has been calculated based on an assumption that the interest rate of 10% is applicable to a period of 10 years in which the proposed PV/T MVHR system will run possibly without experiencing major operational failures (Figure 5). In this assessment, the positive values imply energy cost savings, *i.e.*, financial benefits to the house owner, at the end of the period set, in comparison to the benchmark design alternative (Option 1) which contains neither MVHR nor PV systems. On the other hand, the negative values indicate the amount of a financial loss at the end of the assessment period set. For instance, Option 11 shows the negative figure of −75.22 GBP at the end of 10 years when it is compared to Option 1. This implies that the selection of the MVHR system, which has the highest SFP requirement (1.2 W/l/s) and lowest efficiency (83%) among the others, brings about worse economic value than the benchmark option with no PV or MVHR systems. On the other hand, Option 4 indicates the highest value among the others, marked with 1328.00 GBP in comparison to Option 1. In addition to Option 4, all others that are equipped with PV/T MVHR systems, *i.e.*, Options 7, 10, 13, 16 and 19, resulted in relatively high returns—*i.e.*, 1273.53, 1234.62, 1123.09, 1219.06, 1190.53 GBP, respectively. The results indicate that the selection of design alternatives that include PV/T MVHR systems leads to drastic savings of operational energy cost. The degree depends on the performance of an MVHR system chosen in consideration of the SFP and efficiency levels, as well as the duct type. Seemingly, rigid ducts tend to reduce the operational energy consumption as opposed to flexible ones in relation to the surface area exposed to the ventilation airflow.

Figure 5. Future worth implications of selected 19 design alternatives compared to the benchmark Option 1.



4. Conclusions

In view of SAP domestic energy simulation parameters, this study started with highlighting some of the key passive design considerations, which are effective in lowering operational energy demand of a house to be built in Scotland. Moreover, this study brought out the synergy between MVHR and PV systems. PV generated electricity can contribute to the operation of an MVHR system, while the ventilator can help extract fresh air heated by PV. To date, PV thermal capacity for space heating had been less of a consideration in housing practices in Scotland. The cost-effective assessment conducted in this study drew the potential positive effect of the hybrid system on the drastic increase of economic values. The applicability of PV/T MVHR systems to Scottish homes was illustrated towards creation of a thermally comfortable healthy living environment at low energy costs. The PV/T roof ventilation cavity should be sealed properly so as to enhance or maintain the extraction level of fresh air heated by PV cells. The velocity of air running under PV panels should be retained higher than 0.5 m/s to collect enough PV heat, which helps advance indoor space heating. Not to mention, insulation of ducts is essential for optimal performance of MVHR systems. Nonetheless, bypass duct arrangement may be required to prevent too much extraction of PV heat that may cause overheating on the hot summer days even in Scotland. This study explored the potential waste heat recuperation of PV/T MVHR systems for the application to Scottish homes in heating seasons. In order to make the hybrid system applicable in both heating and cooling seasons, the design details to avoid the overheating need to be scrutinized and the economic impact during the cooling seasons should be examined further. Moreover, in this study, a fixed interest rate of 10% was applied solely for the economic analysis of each alternative given, regardless of economic fluctuations over products' lifespan. Accordingly, in consideration of local economic outlook, various interest rates can also be set for the further exploration.

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