Roof Integrated Photo Voltaic with Air Collection on Glasgow School of Art Campus Building- a Feasibility Study

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Abstract- Building integrated photovoltaic systems with air collectors (hybrid PV-T) have proved successful however there are few examples of their application in the UK. The opportunity to pull heat from behind the PV system to contribute to a building's heating system is an efficient use of waste energy and its potential to improve the performance of the PV array is well documented.

As part of Glasgow School of Art's estate expansion, the purchase and redevelopment of an existing 1930's college building was used as a testing vehicle for the hybrid PV-T system as an integrated element of the upper floor and roof. The primary objective of the feasibility study was to determine if hybrid PV-T was technically and financially suitable for the refurbished building. The key consideration was whether the heat recovered from the PV panels (to increase the electrical efficiency) can be usefully deployed as a heat source within the building. Dynamic thermal modelling (IES) and RetScreen Software were used to carry out the feasibility study not only to simulate overshadowing and optimize the PV-T locations but also to predict the atrium temperature profile; predict the air load for the proposed new 4 No. roof mounted air handling units and to predict the dynamic electrical efficiency of the PV element.

The feasibility study demonstrates that there is an energy reduction and carbon saving to be achieved with each hybrid PV-T option however the systems are subject to lengthy payback periods and highlights the need for enhanced government subsidy schemes to reward innovation with this technology in the UK.

Keywords- *photovoltatic thermal, building integrated, ventilation, pre-heat air.*

I.INTRODUCTION

The Climate Change (Scotland) Act 2009, sets ambitious targets to reduce emissions of greenhouse gases by at least 42% by 2020, as a step towards an 80% reduction by 2050. However, the 42% target was met in 2014- six years early. The Scottish Government has now set a new interim target of 50% of Scotland's energy bills will be met by renewables by 2030. Whilst the largest percentage of renewable energy is currently provided by onshore wind (accounting for over 73% of installed capacity), solar has been growing significantly with 202MW installed solar PV capacity (1).

Whilst Scotland's climate does not allow for many sunny days, it does get longer daylight hours in the summer. Aberdeen, in the North of Scotland receives 17 hours of daylight in the summer months, a whole hour more than the south of England (2). Several areas in Scotland have similar solar irradiation levels to parts of Germany -one of the leading countries worldwide in terms of installed solar PV capacity. The success of Germany's PV market is partly attributed to their government incentives and Feed-in Tariff (FIT) which rewards the building user with a payment for electricity generation by renewable methods. In 2011 the UK Government introduced similar such incentives including a FIT system which helped to promote the uptake of low-carbon electricity generation technologies- solar PV in particular and the price of PV modules dropped significantly Unfortunately the UK Government quickly retracted the rate of support from 43.3- to 21p/kWh (3).

The success of PV technology in Scotland is therefore evident however examples of combining PV technology with solar thermal collectors to form hybrid solar photovoltaic thermal (PV-T) panels has been less established in the UK. Such a hybrid system combines two well established renewable energy technologies, solar photovoltaics (PV) modules and solar thermal collectors, into one integrated component that removes generated heat from the solar PV thereby improving electrical efficiencies. By combining these two technologies the generation potential per square meter can be substantially increased (4). However, there will always be a system efficiency trade-off between electrical and heat generation due to the effect temperature has on the efficiency of solar electricity generation. Solar electrical efficiencies have been seen to improve by 4-12% when compared to a solar PV only scenario (5).

The West of Scotland, indeed Glasgow itself has proven to provide good conditions for PV performance- (6). Under standard operating conditions, standard PV panels are typically 15% to 18% efficient; 10% of total received solar radiation is reflected back into the atmosphere, and the remaining circa 75% of received solar radiation is converted to heat (increasing PV panel surface temperatures and surrounding air temperatures). This excess heat contributes to reduced panel operating efficiencies as every $1^{o}C$ increase in panel temperature above $25^{o}C$ results in the panel efficiency dropping by around 0.5%. As PV panels can reach $55\text{-}75^{o}C$ the overall operating efficiency can therefore drop by as much as 10–25% of the original panel efficiency (7). PV-T hybrid systems operate by removing heat from the back of PV modules, which can help reduce the temperature by as much as $10 – 20^{o}C$. The reduction in panel temperature can contribute to an increase of 5-10% in panel efficiency (8). By combining the technologies of electrical generation and heat extraction, the overall installation can be as much as 3 times as efficient as PV modules and solar-thermal installations alone.

The system chosen for this study is the PV-T hybrid system by “SolarWall” incorporates standard PV modules mounted on top of “SolarWall” panels into a combined modular rooftop installation called “SolarDuct PV-T”. Perforated panels attached to the PV modules allow air to be drawn off the back of the PV modules, helping to reduce module temperatures and keeping the module operating efficiency as high as possible, while the extracted air is ducted to a nearby air handling unit (AHU). This warm air is then used to pre-heat the AHU’s incoming air supply, thus offsetting and reducing the buildings heating plant load (and additionally reducing the buildings CO_2 emissions). There are number of different approaches to the technology including whether the panel is glazed or insulated, the heat transfer medium used (i.e. liquid or air) and how it is integrated into a building (i.e. on-roof, building integrated etc.). Product choice is limited in comparison to other solar technologies and there are currently only five British companies are currently developing new products for the UK domestic hybrid PV-T market. The UK has a very small PV-T market with an estimated 10 - 100 systems being installed each year and a total of ~500 PV-T systems installed to date (8), the majority of these being small scale domestic systems as opposed to the larger scale system proposed in this feasibility study.This paper examines the feasibility of introducing a roof integrated PV-t system with air collection on to an existing educational building during a roof refurbishment project.

II.CONTEXT

Glasgow School of Art (GSA) purchased an existing college building in a prominent position within the Garnethill area of Glasgow City Centre. The existing 1930’s building is a 5 storey brick structure with single glazing and 2 atrium lightwells in the centre of a deep floor plan. In its current state the building was deemed to be very thermally inefficient therefore any retrofit options required to make significant reductions to the buildings existing carbon footprint. The ambitious refurbishment scheme included an overhaul of 5 floors and a replacement of the current rooftop with a new extension creating more light, wall space and allow for a mezzanine floor to be added. This roof extension thereby provided opportunity for a solar integrated roof fabric with roof pitches which could incorporate gradients to maximize solar gain. As evident in Fig. 2 the new roof structure is a prominent addition to the aesthetic to the building and the addition of the PV-T system into the copper roof required careful integration. It also allowed for glazing over the sizeable interior light wells to form two atria thereby improving thermal performance.

Fig. 1 Stow College Building as existing

Fig. 2 Stow College Building as proposed. *Architect-BDP visualization*

The opportunity to integrate a PV-T system within this new roof (Fig 3) was proposed to take advantage of the large south facing solar opportunity which was largely unshaded from any surrounding buildings or vegetation. This would make a substantial contribution to reducing the energy demand within the building thereby lowering the carbon footprint of the GSA campus.

The wider feasibility study reviewed 2 options of hybrid PVT systems- air sourced PV-T and liquid based PV-T systems, as they provide both thermal and electrical energy from solar radiation, however it was the air based system which was chosen to integrate into the existing air heating system within the building as part of the wider services infrastructure retrofit.

This paper provides an overview of the technical feasibility of introducing the PV-T (air sourced) technology into the redevelopment of the roof works and delivers an assessment of solar photovoltaic potential and the associated solar thermal plant to capture useful energy to offset operational demands within the building.

Fig.3 Visualization of roof profiles and glazed atria

III METHODOLOGY

Initially a review of the proposed design drawings was undertaken in collaboration with the project design team to establish the area of suitable installation space within the roofscape. Detailed discussions with the architect and the mechanical and electrical engineers to ensure there was sufficient space for the panel system and associated ductwork and services infrastructure. Space also had to allowed for the 4 No. air handling units will be located in the roof top plant room immediately adjacent to the PV-T on the Eastern perimeter. 2 alternative sizes of PV systems were selected- $360m^2$ and $770m^2$.

Dynamic Simulation Modelling (DSM) was undertaken using IES Version 2016 software, which is an approved National Calculation Method (NCM) simulation software. The Suncast module has been used to simulate overshadowing and optimize the PV-T locations; calculate the atrium temperature profile throughout the year and predict the air load for the proposed new 4 No. roof mounted air handling units.

To accurately model the dynamic nature of the buildings thermal response, hourly recorded weather data is used. A CIBSE Test Reference Year (TRY) for Glasgow has been used for this analysis as per the National Calculation Method requirements and it includes records of radiation, temperature, humidity, sunshine duration and additionally wind speed and direction.

In order to predict the thermal energy generated by the PV-T air collector RETScreen Software (developed by Natural Resources Canada) has been used. RETScreen's Solar Air Heating simulation has been developed using empirical data obtained from dynamic testing performed by Natural Resources Canada on the proposed PV-T air collection system 'Solar Wall'. The software uses local weather data (Glasgow) and user input data to provide a prediction of thermal energy generated over a period of one year. The increased efficiency of the PV-T panels given that air was being drawn from the rear was taken into consideration in the calculations.

To allow an assessment of how the heat generated by the PV-T air collection system could be effectively deployed in the refurbished building, IES has been used to predict the light well temperature profile throughout the year and the air load proposed for the 4 No. new roof mounted air handling units. In response to the dynamic simulations and RETScreen calculations, the annual electrical energy generated was calculated for each of the 2 array sizes. This together with the thermal contribution to the air handling system is outlined as a payback period.

The following units have been used in the calculation:

Energy tariffs of 0.035£/kWh for natural gas and 0.100£/kWh for grid electricity have been used in the in the feasibility study calculations.

Carbon dioxide emission factors of 0.216 $kgCO_2/kWh$ for natural gas and 0.5190.216 $kgCO_2/kWh$ for grid electricity (as per current UK National Calculation Methodology) have been used in the feasibility study calculations.

TABLE 1

CURRENT FIT TARIFFS FOR PV-T

Installation Size	Lower Tariff Rate p/kWh	Higher Tariff Rate p/kWh
<10kW	0.47	4.04
10-50kW	0.47	4.25
50-250kW	0.47	1.94

The higher tariff rate applies if an Energy Performance Certificate (EPC) of D (or better) is achieved before the commissioning of the PV-T. The lower tariff applies if a minimum EPC of D is not achieved before commissioning. Given the poorly performing existing thermal envelope the lower rate has been assumed for the purposes of the feasibility study.

A. Simulation results

Roof Layout and Solar Shading Study
Firstly consideration had to be given to the varying geometry and roof pitches in the design proposal. Suncast, a module within IES, was utilised to simulate overshadowing and optimise the PV-T locations. This software takes into account the sun’s path and solar irradiance to optimize the PV-T positions.

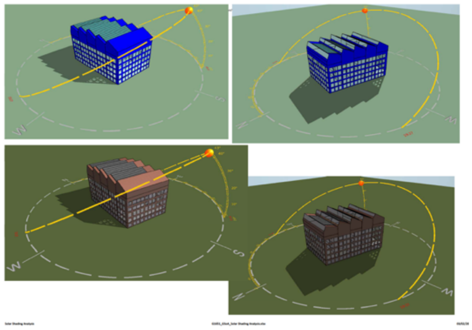

Fig. 4 PV-T location on roof for overshadowing study

The PV-T is located on each of the South facing roof slopes with the exception of the most Southern due to limited access to this slope for maintenance. A 2 metre access margin has been allowed between the units and the building perimeter edge.

Each row of panels is $39m^2$ and allowing for a 10% frame area gives an active area of $35m^2$ per row at the inclination angles indicated in Fig.5.

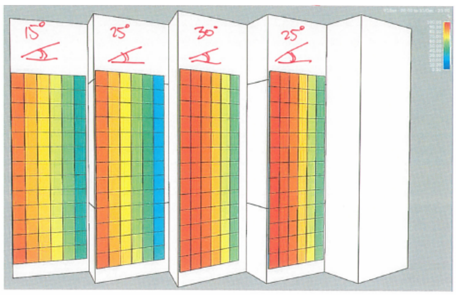

Fig. 5 PV-T location on roof for overshadowing study

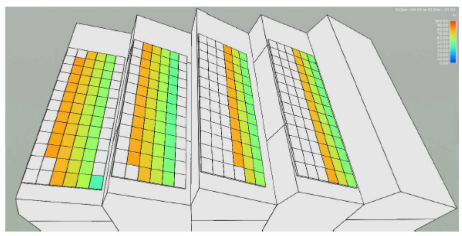

Fig. 6 PV-T panels with medium shading

The IES VE Suncast module identified the threshold for good performance which can be summarized as Shading factor of 0.85 or greater = minimal shaded panels; Shading factor of 0.68 or greater = medium shaded panels; Shading factor of 0.56 or less = highly shaded panels. On this basis the two rows of ‘highly shaded panels’ have been excluded leaving an active PV-T area of $770m^2$.

The results of the optimized PV location and associated overshadowing study are shown in Table 2.

TABLE 2

EFFECTIVENESS OF PV MODULES

PV Effectiveness	Shading factor	Annual Exposure (%)	Effective Solar Area (m^2)	Peak Output (kWp)
Minimal shading	1.0	>80%	280	27.2
Medium shading	0.8	40-80%	490	38.7
High Shading	0.65	20-40%	70	4.5

The array will be mounted on the external sloping roof as indicated in Fig. 7 and the air from the plenum will be extracted at the Eastern edge of the roof and ducted directly into the plantroom housing the air handling plant whilst the warm air will be connected into the supply air stream via a dampened connection. The PV inverters will be located in the same plantroom and the supply connected to the proposed local distribution board. A smaller array of $360m^2$ is also considered as part of the feasibility study as a reduced cost proposal.

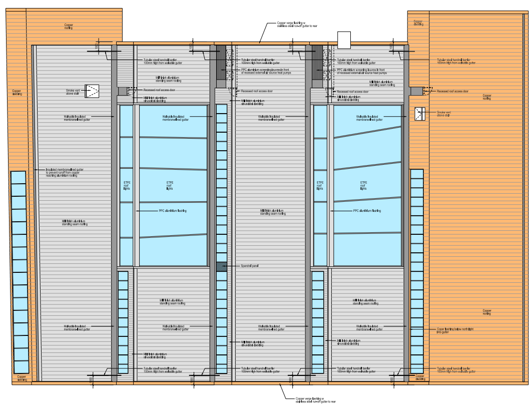

Fig. 7 Roof layout indicating available space for PV-T

B. PV Cell Temperature

As previously discussed, cell operating temperature is a key factor in the amount of electricity produced by photovoltaic panels. The efficiency of the photovoltaic panel decreases as its temperature increases. The dynamic photovoltaic cell temperature has been predicted based on the hourly annual external ambient temperature (Ta) and solar radiation (G) from the CIBSE Glasgow TRY05 weather file.This has been used to calculate the hourly cell temperature based on the following formula:

$$T_{cell} = T_a + (0.0175(G-150)) + (1.14(T_a-25)) + (T_i-T_a)$$

Where Ti is the collector inlet temperature for the heat removal function of the PV-T. This has been taken as an average temperature of 27.5°C.

The estimated annual cell temperature profile is shown in the graph below:

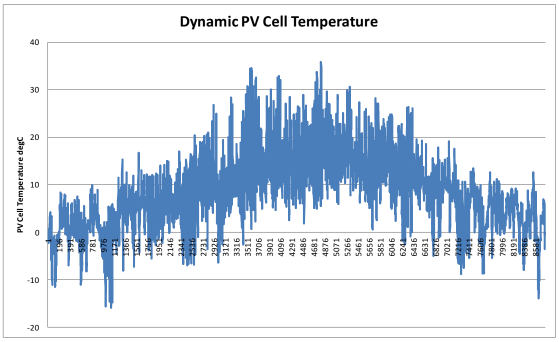

Figure 8. Estimated annual PV-T cell operating temperature

C. Air heating demand

To allow an assessment of how the heat generated by the PV-T air collection system will be effectively deployed in the refurbished building, IES VE simulation was used to predict the lightwell temperature profile throughout the year and the air load proposed for the 4 No. new roof mounted air handling units. The 4 No. air handling units will be located in the roof top plant room immediately adjacent to the PV-T on the Eastern perimeter. 2 No air handling units will serve the internal lightwells. The lightwells are conditioned through displacement ventilation which is ducted to low level and then extracted at high level within the lightwell. The proposed air handling units include a thermal wheel for heat recovery which has an efficiency of 70%. The graph below shows the predicted temperature achieved throughout the year at the upper levels of the lightwells. This warm air recovered within the air handling unit, via the thermal wheel reducing the air heating demand. The reduced air heating demand is subsequently met by an air source heat pump with a sCOP of 3.5.

The lightwell's are each supplied with a volume of $1.5m^3/s$ at a supply temperature of 18°C. On this basis over the year, for each air handling unit, the heating demand is estimated at 12,145 kWh. On the same basis we have estimated the annual heating demand for the 5th and 6th floor AHU's at 14,574 kWh (Fig. 9).

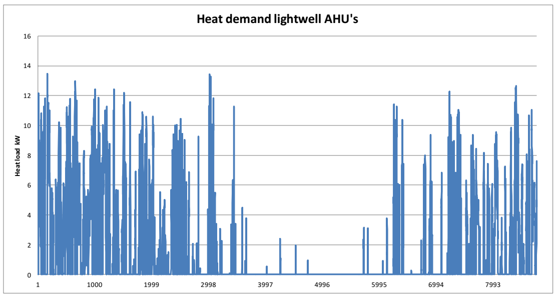

Fig. 9 Estimated Annual heating Demand for the Lightwell AHU's

The new fifth and sixth floors are self contained and each AHU supplies a volume of $1.8m^3/s$ at a supply temperature of 18°C. Again the AHU includes a thermal wheel for heat recovery and an integral air source heat pump. Overall the air heating demand (total 53,438kWh) is greatly reduced through the inclusion of high efficiency heat recovery units.

C. Performance Summary

These predicted energy savings associated with the PV-T Air Collector as indicated in Table 11 are based on a target delivered air temperature of 18°C and a design air volume of $23,760m^3/hr$ based on the 4 No. proposed air handling units.

TABLE 3

PV-T Air Collector Annual Savings

Option	PV-T Array Size m^2	Air Collector Array Size m^2	Energy Delivered kWh	Predicted Heating Demand kWh
1	770	385	92,700	53,438 (+73%)
2	360	180	55,000	53,438 (+3%)

In the larger full array size of $770m^2$ there is an excess of warm air delivered in comparison to the predicted demand. Option 1 has therefore been included to convert this energy for domestic water preheat using an air to water heat exchanger (45% efficiency) and Option 2 to reduce the scale of the array to match the air handling unit demand. Option 2 has lead to an overall $360m^2$ array, both with 50% direct PV coverage and the remaining area the exposed plenum collector assumed black.

Parameter	**PV-T Air Collector (1)**	**PV-T Air Collector (2)**
Array Size	$770m^2$	360 m^2
Capital Cost	£342,074	£152,424
Energy Generation	14,134 kWh (th)/ 45,665 kWh (elec)	24,463 kWh (elec)
Payback	N/A (59 years)	N/A (47 years)
Carbon Saving	29,272 $kgCO_2$	16,353 $kgCO_2$

The system performance is as summarised below:

TABLE 4

PV-T PERFORMANCE SUMMARY

IV DISCUSSION

Theoretical modelling has shown that even with an optimal design, PV-T systems are not able to deliver both maximum electric and thermal efficiency simultaneously (12). Research has found that PV-T systems that are optimised for electrical generation (as is more typically the case in the UK), can potentially meet 51% of total electricity consumption and 36% hot water demand of a typical UK domestic property from a 15m2 collector area, 2% more electricity generation than from an identically sized PV only system (13). Whilst research in the domestic sector can equally be applied to a larger scale educational building the stallation and infrastructure costs are significantly higher which can make the project prohibitively expensive more expensive than other solar technologies.

The capital cost and associated payback periods for the air collector system are surprisingly high despite the costs of PV's having dropped significantly in recent years in the UK. As the building doesn't not benefit from energy efficient upgrade measures such as double glazing and insulation the FIT rate is at the lower level based on an EPC rating of below band D. This does raise concerns whether the thermal envelope should first be addressed to effectively tackle the energy efficiency of the building. Understandably the UK Government incentives reward building owners who have already undertaken basic thermal retrofit options before installing expensive renewable technologies. However, the Renewable Heat Incentive programme (RHI) which provides an incentive to generate heat energy only recognizes water based heat generation rather than a hybrid air collectors system. This particular building lends itself to collecting warm air to pre-heat the atrium spaces which as the analysis shows does contribute to the heating load and there seems to be significant justification for changes to the funding criteria to reward more innovative uses of heat from renewable sources.

The seasonal disparity between peak heat generation and peak heat demand does mean that PV-T will only provide useful pre-heat air at certain times of the year (predominantly Spring and Autumn). In the summer months the atrium spaces may indeed over heat if a bypass system was not in place. A more complex system design with integrated thermal storage capacity would allow greater efficieny and allow waste heat to be stored and used in periods of greater demand. PV-T technology only makes technical and commercial sense where there is a suitable use for the low-temperature heat that the system can provide As the Building is an Art School, the nature and use of the spaces is worth consideration to match the pre-heat air demand with the function of the teaching spaces and workshops. Given the diversity of creative processes undertaken incuding prinkmaking, textiles and ceramics this preheat air could be diverted for use in print drying rooms and kilns to facilitate the drying process.

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V CONCLUSIONS

The installed base, and the number of installations per year, for PV-T in the UK are very low compared with other low-carbon heating or microgeneration technologies. There is clearly potential for the economic case for PV-T to improve if installation volumes increase significantly, both from cost reductions via economies of scale (reduced manufacturing and installation costs) and from design improvements. Solar PV sale volumes are expected to continue to increase worldwide, and improvements in both performance and cost per kWp of solar PV will continue to increase the attractiveness of PV-T compared with a no-renewables baseline. Continued solar PV cost reduction, however, will increase the relative cost of PV-T compared with solar PV only.

Cost reductions from economies of scale in manufacturing, assembly of the thermal components, and improvements in installer awareness and experience, are also likely as sales volumes increase. In the short term these reductions are likely to come from sales increases in the non-domestic sector in the UK, or from non-UK market growth.

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