Harjunowibowo, Dewanto and Yate, Ding and Omer, Siddig A. and Riffat, Saffa B. (2017) Reducing greenhouse energy consumption using novelty rooftop: a simulation. In: 16th International Conference on Sustainable Energy Technologies – SET 2017, 17-20 July 2017, Bologna, Italy.

Reducing Greenhouse Energy Consumption using Novelty Rooftop: A Simulation

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Abstract: Recently, more than 80% of total energy of commercial greenhouse in the northern hemisphere is used just for heating. Mostly, the energy loss happens up to 40% caused by the poor U-value of the façades. Therefore, by lowering the U-value would decrease the energy consumption significantly. This simulation is conducted using EnergyPlus software to calculate the heat loss, heating demand and daylighting of a greenhouse with different envelope materials especially novelty rooftop. The orientation of buildings and its effect to electricity generated by semi-transparent PV double glazing are also discussed. In addition, the effect of the novel rooftop to daylighting inside the greenhouse is also investigated.

The simulation shows that use materials with low U-value and novel rooftop could decrease the source energy consumption by 65% which is remarkable compared to commercial greenhouse. Besides, the best orientation for the PV module of the greenhouse in Nottingham, UK is facing west-south-east. While the indoor daylighting factor declined up to 65%. Therefore, using PVs with high efficiency would diminish the electricity losses and could be used for lighting energy alternative and others.

Keywords: U-value, source energy consumption, greenhouse, daylighting, simulation

1. INTRODUCTION

The characteristic of material used in buildings determines the daily energy demand to reach thermal comfort stability. Commonly, commercial greenhouses use polyethylene (PE) as the envelope/walls (Santamouris et al. 1994), since the cost is low, there is transparency, it is light weight, and easy to install. Nevertheless, PE has a high U-value, is too thin, and easily broken, thus its protection to the plantation from environmental temperature changes and pests is very weak. As a consequence of poor U-value of the facades, the heat loss occurred is very high and hence 20-40% energy loss happen (Hee et al. 2015). Consequently, more than 80% of total energy of commercial greenhouses in northern areas is just used for heating (Cuce et al. 2016; Runkle & Both 2012) which makes the operational cost increase as well.

Therefore, to diminish the heat loss percentage of the glazing system and decrease the heating energy demand, a low U-value glazing material is needed (Cuce & Riffat 2015). The most remarkable energy saving is reached by these envelopes combined with a closed greenhouse concept by 80% which is analysed using the TRNSYS tool (Harjunowibowo et al. 2016; Vadiee & Martin 2013). Closed concept means that there is no window or air exchange between inside and outside the greenhouse. Besides using a low U-value glazing material, PV opaque panels may be used as thermal screen combine with novel double glazed semi-transparent PV as the rooftop and closed type of building. It is hypothesised that the electricity generated by PVs could minimise the grid electricity consumption. This paper is focused on the effect of novelty rooftop usage against the heat loss, and energy consumption reduction of a closed greenhouse type.

Therefore, to achieve the energy efficiency goal, authors require effective design tools for analysing and understanding the complex behaviour of building energy use. With the advancement in computing technology, computer simulation and modelling has been widely used for providing an accurate and detailed appraisal of building energy performance. Energyplus V.8.3 software is one of the most reliable building performance simulation tools but at the same time it is difficult to use it as a standalone software, as it requires high expert knowledge (Stadler et al. 2006a). DesignBuilder is then used as a user-friendly interface for modelling and exporting files to EnergyPlus in order to perform simulation processes. In addition, DesignBuilder is compatible with Radiance software that is one of the top daylighting simulation engines (DesignBuilder Software 2015). These analyses will be helpful to design or retrofit greenhouses in a similar or even a different climate.

2. METHODS

The simulation conducted was based on different façades materials i.e. Polyethylene, Polycarbonate, opaque PV, and double glazing semi-transparent PV. The building case is a greenhouse in the Northern hemisphere.

2.1. Building Case

A greenhouse with 46.94 m^2 and volume 142.87 m^3 located in Nottingham, UK (Lat. 53.48°, Longitude -1.0°). Building gross wall area is 98.22 m^2, gross roof area is 77.01 m^2, and occupancies number is 72.99 m^2. The annual weather is less than 18 °C (Weatheronline 2016). The heating system is boiler of grid electricity with 1 radiator as can be seen at Figure 1. The main plan view is shown in Figure 2. The plantation will be cultivated in the main area, while front area is used to store the controller and other equipment. Therefore, the simulation analysis is focused on the main area. The comparing greenhouses envelope use Polyethylene (GHPE), Polycarbonate (GHPC), PC and opaque PV combination (GHPCPV), and GHPCPV combined with novel semi-transparent PV (GHPCSTPV) as the rooftop, as shown in Figure 4. The properties of materials are described in Table 1. The heating set point is 22 °C and the cooling set point is 27 °C.

2.2. Building’s Energy Audit

Data analysis is conducted to estimate the source energy consumption for a greenhouse with GHPE, GHPC, GHPCPV, and GHPCSTPV for each PV wall sides and rooftop, and also the effect of the building’s orientation against the generated PV Power plus the Net energy source. The heat loss analysis is used to obtain the total amount of reduction to indicate the performance of the building.

We use source energy term rather than energy site to describe the energy demand of the building. Source energy refers to the total amount of energy/raw fuel used to produce and transport the energy to the building site (Carlisle et al. 2009). To calculate the greenhouse’s total energy source, the original energy is multiplied by the appropriate site-to-source conversion multiplier based on the utility’s type of energy source. It incorporates all transmission, delivery, and production losses as shown in Figure 3. By taking all energy use into account, the score provides a complete assessment of energy efficiency in a building. While site energy is the amount of heat and electricity consumed by a building as reflected in our utility bills.

Therefore, assessing the relative efficiencies of buildings with varying proportions of primary and secondary energy consumption is needed. It is necessary to convert these two types of energy into equivalent units of raw fuel consumed to generate that one unit of energy consumed on-site. To achieve this equivalency, Environmental Protection Agency (EPA) recommends source energy term (Star 2017).

2.3. Building's modelling

The building analysis is conducted using a simulation equipped with Energyplus and use of the weather data of Nottingham, UK. Energyplus is a software developed by the US Department of Energy to simulate the energy consumed by a building (Alam et al. 2014). EnergyPlus is a recently-developed whole-building energy analysis program that builds on the best capabilities of BLAST and DOE-2 (Crawley 2004). Energyplus is widely used by researchers and is a powerful tool for analysis of a building's energy consumption accurately (Stadler et al. 2006b). Energyplus calculates the heating and cooling using a heat balance module including room envelope surface and the room air heat balance model. Nevertheless, Energyplus is not user-friendly, poor visibility and time consumption for the input data and revising are some of its disadvantages. Hence, we used DesignBuilder version 4.5.0.148 as the GUI to prepare the construction and inputting data.

The third-party interface programme is developed especially to make the energy building simulation easier and faster. DesignBuilder uses the EnergyPlus dynamic simulation engine to generate the performance data. DesignBuilder provides a 3D architectural modelling tool, and simplicity to input many parameters. Moreover, DesignBuilder will produce the graphs of energy consumption, carbon emissions, occupant comfort and daylight (DesignBuilder 2011).

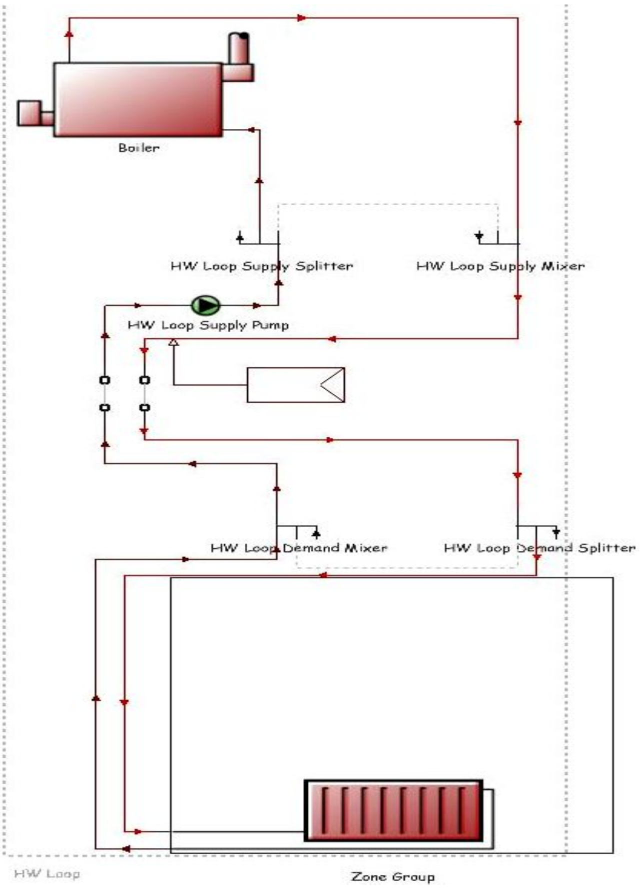

Figure 1: The HVAC design system

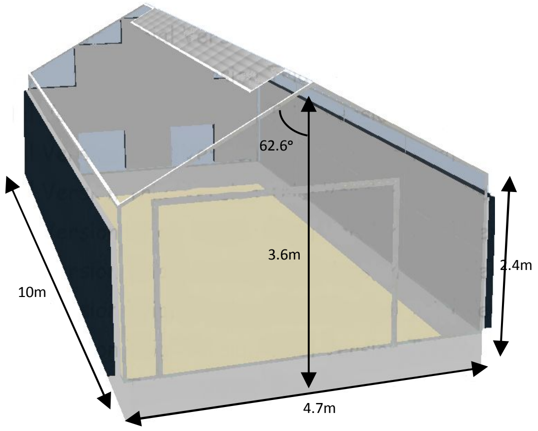

Figure 2: The greenhouse plan view

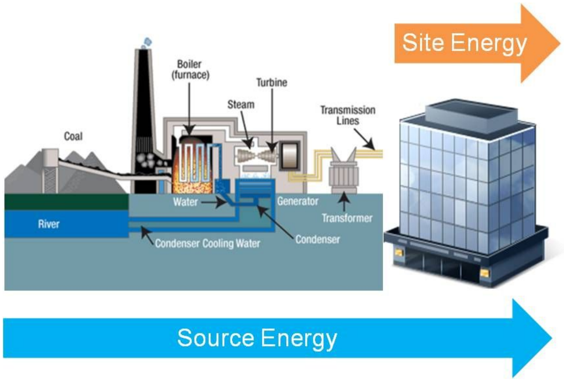

Figure 3: Source and Site Energy Differences (Star 2017)

Authors have to input much information regarding the location; weather, the materials properties such as the properties of the envelope, ground, roof, etc. Besides this, there is an internal usage setup, i.e. lighting, equipment, occupancies, HVAC operational, heat and cold source parameters. Afterwards, the analysis of building's energy simulation can be operated for a whole year.

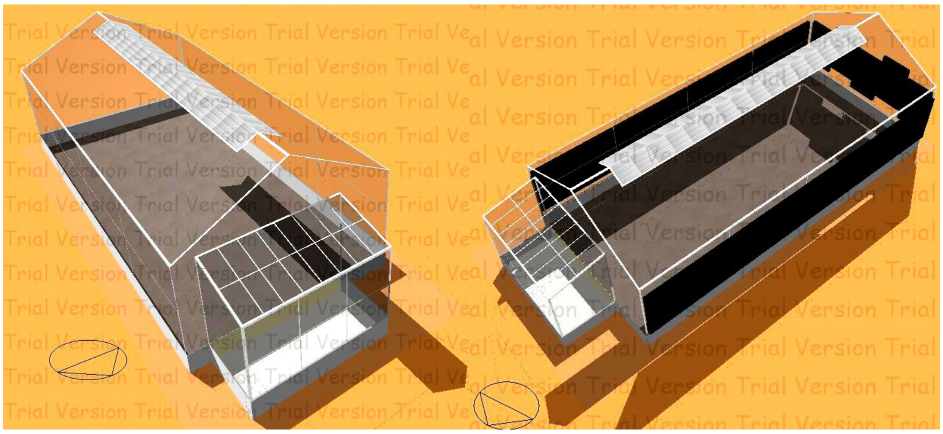

Figure 4: Architectural model of the Greenhouse

Table 1. Properties of envelope materials used in the simulation

Material	Total Solar Transmission (SHGC)	Light Transmission	U-value (W/m^{2}K)	Efficiency (%)	Thickness (mm)
Polyethylene (PE)	0.825	0.87 (Vadiee & Martin 2014a)	5.68 (Vadiee & Martin 2014a)	-	1
Polycarbonate (PC) (Group 2008)	0.82	0.76	2.38	-	20
Opaque PV + air gap	0	0	3.86 (The Scottish Government 2009; Ozgener et al. 2011)	16.79 (Features & Certificates 2009)	70
Semi-Transparent PV double glazed	0.5 (Wong et al. 2008)	0.2 (Limited 2003)	1.4 (Polysolar 2015)	8 (Polysolar 2015)	7 (Limited 2003)

3. RESULTS AND DISCUSSION

3.1. Heating Demand

Since the biggest heat loss comes from the envelope, consequently, focusing on heat loss glazing reduction will significantly reduce the heating energy demand system and give remarkable energy saving on a greenhouse. Moreover, Figure 5 shows that the glazing heat loss percentage of 89-92 % is dominant compared to other parts.

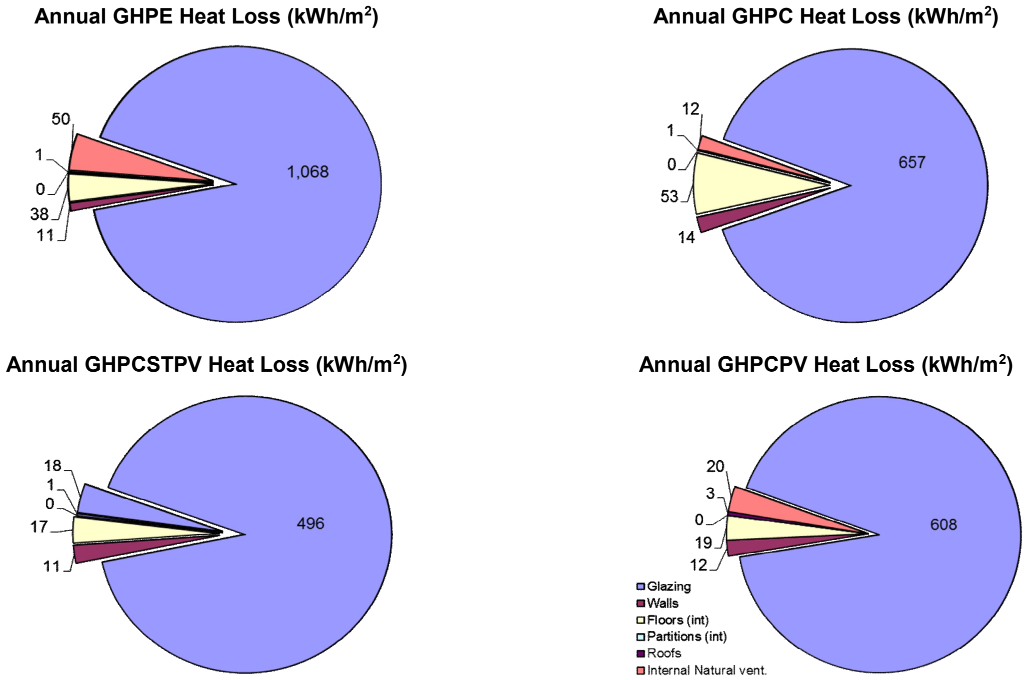

Figure 5: Heat Loss Number Comparison in GHPE, GHPC, GHPCPV, and GHPCSTPV (clockwise)

Furthermore, it shows the glazing heat loss comparison between GHPE, GHPC, GHPCPV, and GHPCSTPV. It can be seen that PC, PCPV, and PCSTPV usage could reduce the glazing heat loss to 38%, 43% and 54%, respectively. These results have good agreement with Bailey that double glazing could reduce the heat loss to 35-60% (Bailey 1981).

In addition, Figure 6 shows that PC usage decreases the heating energy demand up to 60%. On the contrary, PV and the novel rooftop addition to its walls and rooftop only reduce the heating energy demand by 41 to 49%. It is also has a good agreement with Fabrizio, who said that Polycarbonate to retrofit Polyethylene could reduce the heating demand by 30% (Fabrizio 2012). The lower reduction happens since there is a significant heat gain loss when the PV is used. The PV blocks the sunlight irradiation coming to the building through the walls and rooftop. It can be seen in Figure 7 that solar gain exterior windows of GHPCPV and GHPCSTPV vastly decreased the heat gain compared to GHPC.

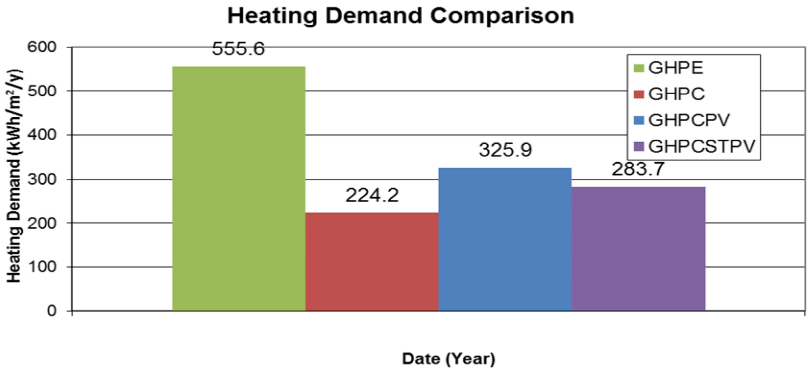

Figure 6: Annual Heating Demand comparison of GHPE, GHPC, GHPCPV, and GHPCSTPV

Figure 7 reveals that the solar gain exterior windows energy of GHPC, GHPCPV, and GHPCSTPV reduction compared to the GHPE are 6%, 32%, and 57%, respectively. Whereas, if there is no obstacle for the sun, radiation is then absorbed by surfaces inside the room, and these surfaces become heat radiators. The heat emitted from these "radiators" is long wave radiation which is not so readily transmitted out of the room through the polycarbonate sheet. The result is that the trapped heat builds up in the room. Consequently, this trapped heat causes the heating energy demand of GHPC to be lower than others.

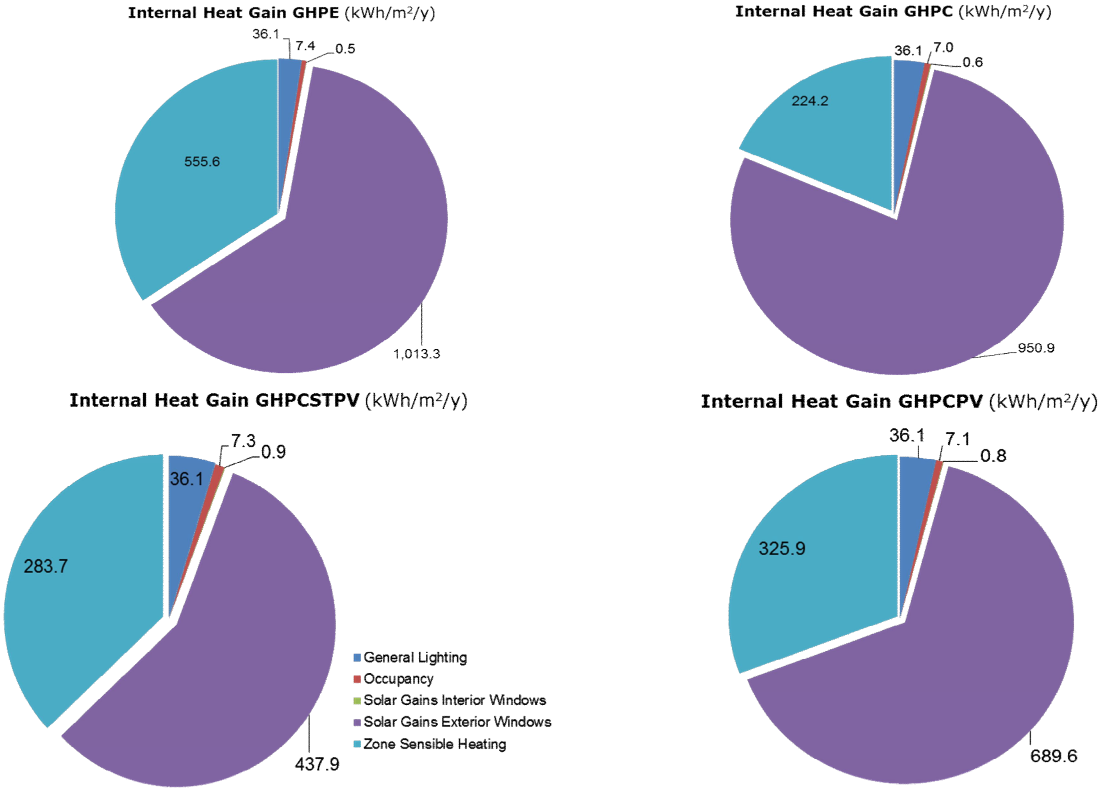

Figure 7: Annual Internal Heat Gain Percentage of GHPE, GHPC, GHPCPV, and GHPCSTPV

Figure 8 shows the source and site energy consumed by each system. Both the graphs show that energy consumption of GHPC is the lowest in terms of passive heating. The total amount of source energy demand reduction of GHPC is 56% which is extremely remarkable. The reduction has been predicted by Tantau et al., and Vadiee and Martin that altering single glazing to double glazing may reduce the total energy demand by 45% (Tantau et al. 2011), and up to 60% (Vadiee & Martin 2014b). Furthermore, overall lowest energy consumption is reached by GHPCSTPV because of electricity benefit of opaque PV and the novel rooftop PV. The source and site energy reduction of GHPCSTPV system are 65% and 68%, respectively. Hence, the energy saving produced by GHPCPV and GHPCSTPV respectively are 14% and 35%.

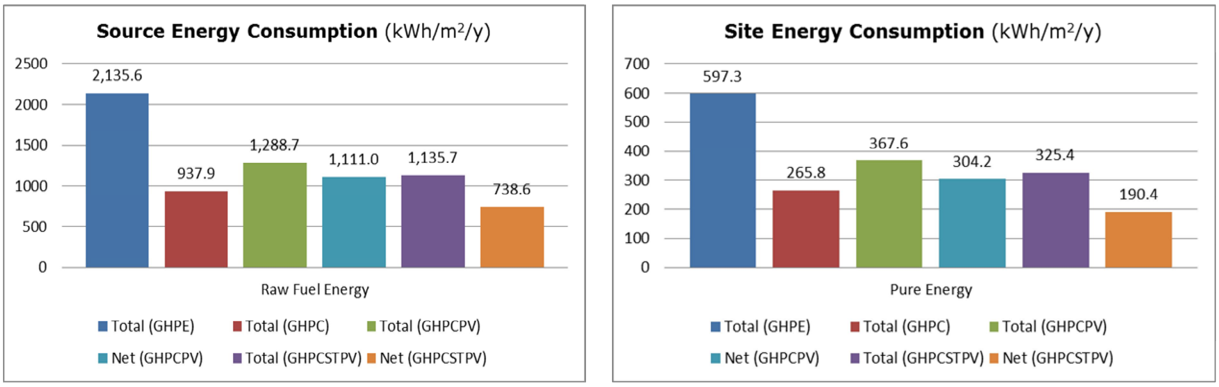

Figure 8: Source and Site Energy of different envelope systems

Additionally, the annual air temperature of GHPE, GHPC, GHPCPV, and GHPCSTPV as shown in Figure 9 are stable between 22-27 °C. These temperatures are suitable for tropical climatic vegetable plants which grow rapidly at daily temperatures between 20–30 °C and 14–18 °C at night (Hassanien et al. 2016).

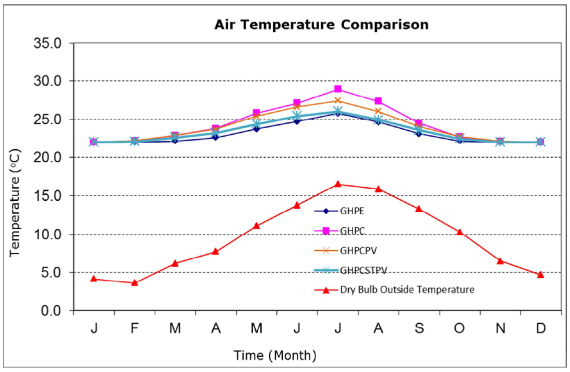

Figure 9: Temperature Comparison of GHPE, GHPC, and GHPCPV

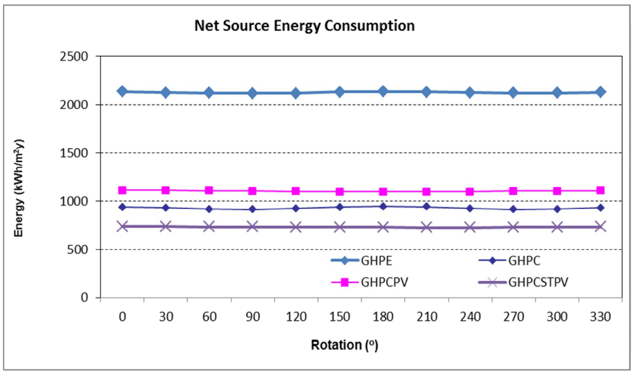

Figure 10: The effect of Greenhouse orientation of PV against the Net Source Energy

Figure 10 shows the effect of building orientation to the net source energy needed for all greenhouses type. The building is rotated for every 30 degrees. The lowest net source energy consumption indicates the best performance for the building. It is shown that for all orientations, the net source energy consumption is linear. Furthermore, it clearly distinguished that GHPCSTPV has the lowest net source energy consumption which means the best performance. GHPCSTPV system shows that the system used might be very flexible because of orientation independency.

However, to have maximum benefit in terms of electricity generated by the PVs, it is recommended for the northern area to build a greenhouse with PV facing to west-south-east. Since the PV will be exposed to the sunlight much more and hence produce maximum power, as can be seen in Figure 11. Besides it having the lowest net source energy consumption annually, it also can be recognised from Figure 11 that Semi-transparent PV (STPV) as the novel rooftop produced electricity two times higher rather than opaque PVs on the walls side.

Additionally, Figure 12 shows the side by side PV power generated for west, south, and east sides. It can be seen that for each orientation the west and east side has different results. However, the total energy produced by both sides are equal, annually. This happens because the position of the west and east alike traversed the path of the sun from morning to evening with a direct normal solar radiation amounting to almost 600 Wh/m^2/y. While on the south/rear side, a large power reaches a minimum at the rotation of 180° where at that time the solar circulation backs the PV as shown in Figure 13. On that orientation, the PV on the rear side is not exposed by the sunlight.

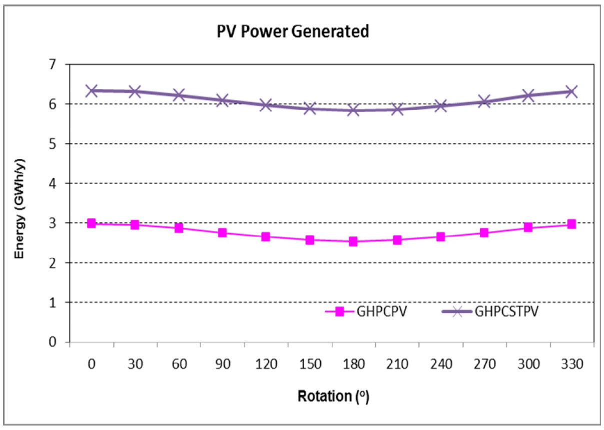

Figure 11: The effect of building orientation against the PV Power and the Net Source Energy per area

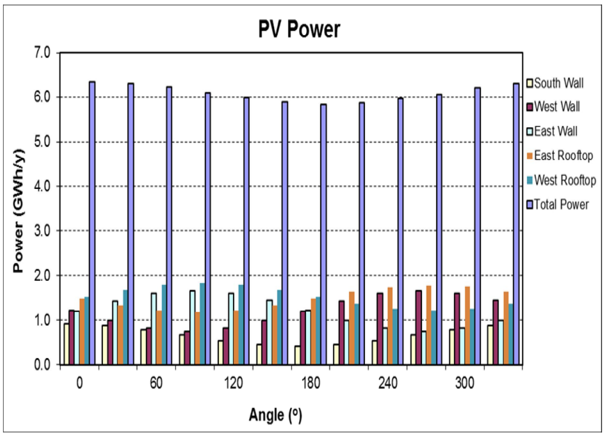

Figure 12: PV power generated by each sides and rotation angle

Table 2 shows the setting power for opaque PV and novel roof top PV. It shows that total peak power of STPV is higher than opaque PV. Although, the efficiency of STPV is less than half of opaque PV which means that maximum power produced by STPV should be less than opaque PV. While the simulation result proved that the power resulted by STPV is double compared to the opaque. Therefore, set position of the modules determined the solar radiation exposure to the modules.

Table 2. PV modules performance

Type	Opaque			STPV	
Position	South Wall	West Wall	East Wall	West Rooftop	East Rooftop
Peak Power (W)	300	600	600	1440	1440
Total		1500		2880	

As can be seen in Figure 13, on orientation of 120°, the parts of PV exposed to the sunlight only on one side and rear. In addition, Photovoltaic vertical position on the wall further reduces exposure to sunlight. On the other hand, on orientation of 0° or the front building facing north side, all PVs' surfaces are exposed by solar irradiation optimally. Particularly for STPV which is always having solar irradiation throughout the day causing maximum electricity generation.

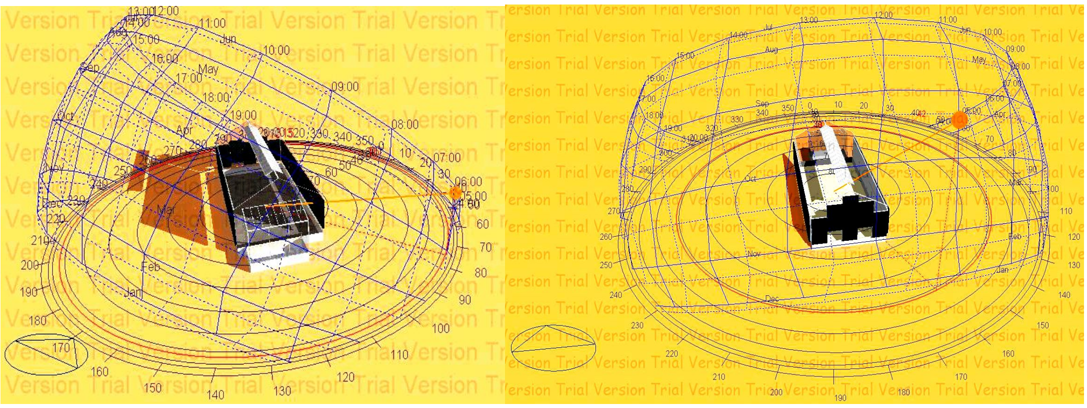

Figure 13: The Greenhouse and PV Orientation for 120° (left of the reader) and 0° (right of the reader).

3.2. Daylighting

Daylight is a free energy and cost effective for sustainable building design (Yu & Su 2015). It provides a more pleasant and attractive indoor environment for human visual response and plants as well, much better than an artificial light source. Moreover, a greenhouse needs sunlight containing PAR for plants photosynthesis wavelength of visible light (Singh et al. 2015; V et al. 1989; Ilieva et al. 2010; Benli & Durmuş 2009; Yano et al. 2014; Benli 2011). PAR wavelength spectrum is around 400-700nm. Therefore, cladding material is an important factor which is related with the PAR that enters a greenhouse's interior space.

Because of the importance of daylighting as the primary light source thereby daylighting analysis has to be taken into account in building a greenhouse. As an agricultural illuminance is used very commonly, then the daylighting calculation will use lux as the unit rather than fc (foot candela). EnergyPlus is a well-known simulation tool for lighting, heating and cooling energy consumption in the building, which builds on the strength of two widely used programs: BLAST and DOE-2. When calculating the lighting energy consumption, the hourly schedules for lighting related settings could be generated in lighting simulation program such as Daysim and read as input file into EnergyPlus. The accuracy of the software has been tested and validated by another simulation program (Witte et al. 2001) and field measurement (Yun et al. 2012). Thus EnergyPlus is used to analyse the daylighting of the greenhouse in this paper.

The concept of Daylight Factor (DF) was developed in the United Kingdom in the early 20th century. Daylight Factor is a ratio that represents the amount of illumination available indoors relative to the illumination present outdoors at the same time under overcast skies. Daylight Factor is typically calculated by dividing the horizontal work plane illumination indoors by the horizontal illumination on the roof of the building being tested and then multiplying by 100. For example, if there were 20,000 lux available outdoors and 400 lux available at any given point indoors, then the DF for that point would be calculated as follows DF = 400/20,000 *100 or DF=2.

Table 3. Daylighting simulation result

	Avg DF (%)	Uniformity ratio DF (Min/Avg)	Min Illuminance (lux)	Max Illuminance (lux)	Lighting electricity (kWh)
GHPE	78.10	0.91	7136.3	9105.8	1955.30
GHPC	66.12	0.92	6097.4	7328.7	1955.30
GHPCPV	49.03	0.54	2673.9	5887.8	1955.30
GHPCSTPV	13.56	0.46	624.2	2165.5	1957.44

Table 3 above shows that the average DF for GHPE is the highest compared to the others with uniformity reaches 0.9 and minimum illuminance higher than maximum illuminance for GHPC, GHPCPV, and GHPCSTPV. It means that electricity demand for supplemental lighting is low to reach 10.800 lux for sunlight or 14.800 lux for fluorescent which equal with 200 μmol m^{-2} s^{-1} (Apogee Instruments 2016). While for GHPCSTPV should need more electricity to supply the artificial lighting inside the greenhouse, nonetheless it is not significant. But as the cultivation needs approximately 200 μmol m^{-2} s^{-1} of PAR for the normal growth then the energy to produce photon from the light lamp should be taken into consideration.

It can be seen that Polycarbonate-Opaque-Semi-Transparent PV sandwich sheets (GHPCSTPV) respectively reduce the DF of Greenhouse PE envelope by 65%. Therefore, it must be taken into consideration in terms of lighting power when using opaque PV as the walls and Semi-Transparent PV as the rooftop. Despite, 2 kWh/y of the lighting electricity using LEDs can be negligible.

4. CONCLUSION

This simulation is conducted to calculate the heat loss and heating demand of a greenhouse with different envelope materials. The orientation effect of buildings and PV to energy demand on the material type PC with and without PV as well. The heat loss reduction of Polycarbonate wall glazing reaches 38% to 54% by using PV opaque as cover addition on its wall and novel rooftop compared to Polyethylene façades. Moreover, the heating energy demand decrease by 60% using PC but only 49% when added with the novel rooftop, respectively. It happens because the solar gain external windows factor declined significantly. Even so, the PV additions are capable to generate electricity thereby saving energy by 35% than reference building, annually. Therefore, the greenhouse with novel rooftop as the purposed system could reduce the source energy consumption by 65% per year which is remarkable. In addition, in order to get optimum performance, the best orientation of the PV modules is facing west-south-east in the area of Nottingham, UK. Even though, there is no difference net source consumption reduction for GHPCSTPV system. Lastly, the daylighting of GHPC and GHPCSTPV reduce the Daylighting Factor of GHPE up to 12% and 65%, respectively which has to be tackled. Therefore, use PV with high efficiency would cover up the lighting need and others.

Acknowledgements

The authors would like to greatly acknowledge to Innovate UK for their financial support of this project. We also thank to DIKTI Scholarship and Doctorate Grant no: 623/UN27.21/PP/2017 for the funding support.

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