# Design of A New Greenhouse Configuration Utilizing Semi-Transparent Photovoltaic (PV)

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***Abstract*: A review of different configuration and orientation of greenhouse (GH) were conducted, the use of different types of cover and solar energy transmissivity into the GH were also presented. This study presents, a new configuration of (GH) implementing the use of semi-transparent photovoltaic (STPV) as cover to improve the performance of GH, for agricultural purposes and power generation. In this work, the solar energy intercepted by the GH cover and the extended hangout is calculated. The total energy available for conversion into electric energy was also calculated. The STPV allows photosynthetic active radiation (PAR) to pass into the GH cavity while the higher wavelength is collected and converted into electric energy. The solar energy intercepted by the STPV roof cover is 69335.78 kWh yr$^{-1}$, the total energy transmitted into the GH cavity is 68842.4544 kW yr$^{-1}$. The air, plants and outside temperature varies between 27- 44% inside the GH. The electrical energy produced by the STPV roofed cover was calculated to be 21.98 kWh yr$^{-1}$. The total electric energy produced from the roof covered with 100% STPV is sufficient to control the GH microclimate for conducive plants growth throughout the year.**

***Keywords*: GreenHouse, Semi-Transparent PV, Solar Radiation, Transmittance, Configuration, Plants.**

## I. INTRODUCTION

Greenhouse (GH) technology is an efficient option for growing plants, the aim is to provide suitable microclimate for maximum plant production in a controlled environment [1]. The structure is covered with transparent material to allow sun light penetration into the GH, short wave solar radiation is allowed into the GH but opaque to long wave solar radiation to ensure greenhouse effect inside the GH. Air temperature in the GH is a key to the success of plants production, heat exchange between the heated air in the cavity and ambient air of the surrounding environment is controlled by heat exchanger to ensure a convenient environment for plants growth [2], [3].

The control of GH environment often requires electricity. Therefore, for sustainable crop production a means to minimize energy consumption is necessary, the use of semi-transparent PV will reduce the cost of maintaining the climate in the GH because it can serve as cover as well generate electricity [4]. The sunlight incident on the structure is divided between the Solar cells for electricity generation and the transmitted for plants photosynthesis. The short-wave radiation penetrates the cavity for plants use while the long wave radiation is intercepted by the STPV module to generate electric energy [5].

The intensity of solar energy reaching the earth surface, sometimes is excessive in relation to what is required by the plants, leading to an increase in the air temperature in the greenhouse cavity to a level not tolerable by the plants and workers. Countries bordering the Mediterranean for example Grace, Israel, Spain etc, GH farming were suspended due to the excessive solar radiation or the cover were removed during intense sunlight, exposing the crops to an open field farming and are replace when the intensity of the sunlight is reduced. However, the purpose of GH is defied if the roof is removed because the GH effect will be cancelled, during that period [6], [7]. These method of removing the roof and replacing, leads to the increase in the cost of construction and maintenance.

The cultivation of crops in GH farming, is face with the challenges of controlling the microclimate of the GH cavity, the energy used are mostly the fossil fuel energy, which causes or increases carbon footprint. This work is aimed at evaluating the energy demand and supply to the GH (energy balance), to design a new GH configuration to be sighted in Maiduguri Northeast Nigeria latitude l1°50'42"N and generate electric energy from the STPV roof, that can power the GH control appliance.

## II. LITERATURE REVIEW

Some technologies and key parts of a GH are presented here;

*Greenhouse (GH) Configurations*

The freestanding structures are built as a separate structure with sidewalls, end walls and roof. The house is built apart from other buildings, it is fully expose to sun, and it can be made small or large as required by the grower. It is constructed to provide more sun light; the surface of the house is exposed to light in such a way that, it will require a mechanism for cooling and heating as appropriate. The lean to-structures are usually constructed against existing building, utilizing one or more sides of the structure, can be lean-to the main apartment or garage. The GH structure attached to the apartment have small surface area as compare to the free-standing house, usually for small crop production, is about 7-12 feet in width but is as long as the length of the structure it lean on. The lean-on GH has the advantages of close to electricity, heat and water, it has a disadvantage of space, sunlight, ventilation and temperature control [1], [8], [9], [10], [11].

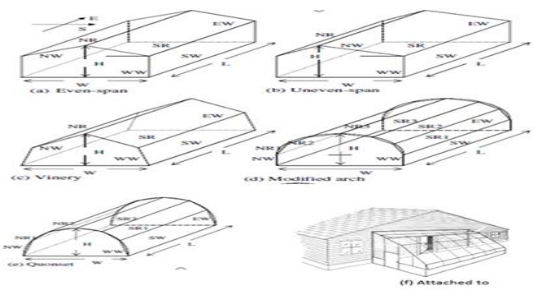

Figure 1: Some common configurations of GH systems.

(a), (b), (c), (d), and (e), [8], (f) [1].

*Greenhouse (GH) Covering Materials*

Authors in [12], [13] reviewed the use of GH cover that incorporate near infra-red (NIR) reflectors, the research focused on the transmittance of the covering materials. It was reported that, NIR reflection during the day and far infra-red reflection at night is more suitable for maintaining good microclimate for plants growth. The effects of GH covering materials were studied on the microclimate of Tomato farm during summer period. The structure is covered with insect-proof net, same temperature was maintained with the outside temperature. While, photo-selective cover could not respond to temperature change during summer [14]. While [15], [16] revealed that the best approach to cooling GH in tropical and subtropical region is the use of ventilation and the use of material with NIR covering properties. The effects of different covering materials on sunlight penetration in GH for cultivation of aborigine were investigated, penetration of solar radiation through single and double layers of polyethylene films on production of the crop. It was revealed that, the double layered cover yielded highest among other covers while solar energy penetration was higher in single layer [16], [17], [18].

*Photovoltaic (PV) Roof*

Photovoltaic (PV) is considered an innovation in GH application, it has the advantages of providing electric energy to power the devices that control GH microclimate, serve as roof, coupled with reducing the intensity of sunlight penetration into the GH cavity [19], [20]. Exergy analysis of photolytic thermal (PVT) was conducted for Indian microclimate by [21] it was reported that an exergy energy efficiency of almost 4% was achieved by the integrated PVT GH. Electrical energy savings of about 716Kwh/year and thermal energy savings of about 12.8Kwh/year for 24-45ºC temperature range in the greenhouse. The use of solar concentrated thermal PV collectors (CPV/T) improves the low exergetic efficiency of PV/T system in GH application. Thermal and electrical energy of CPV/T can reach 65% and 11.3% respectively in GH applications [22]. The performance of PV combining both electrical and thermal energy production were evaluated by [23], the electrical energy produced by the prototype used in Dutch's weather conditions was approximately 20kWh/m$^2$/year and the thermal energy produced per year at temperature of 19.5ºC in summer and 17.5ºC winter was 161kWh/m$^2$.

*Semi-Transparent Photovoltaic (STPV) Roof*

Authors in [6] studied the climatic condition of even span greenhouse covered with photovoltaic cell, with roof slope 22º, length 50m, width 12m, height of eave 3.5m. The transmissivity of the STPV cover is 0.69. The energy demand and supply were evaluated, it was observed that, during summer months from May to August there is excess energy supply ranging from 8MJ m$^{-2}$ d$^{-1}$ and 11MJ m$^{-2}$ d$^{-1}$.

Also, [8], [24] studied some of the most commonly GH configuration and orientation in used, mathematical model was used to calculate the solar radiation transmitted into the GH for each of the shapes. It was reported that, even span, east-west orientation is the most suitable for all year GH application at all latitudes, except at latitudes 10º N.

*Summary of Some Common Configuration of GH Structures*

Table 1.0 present the summary of some common shapes of GH in use, their roof cover and performance in terms of reception of solar radiation and locatio

Table 1: Summary of some common GH Configuration

| S/N | Configurations | Roof cover | Performance | Remarks |
|---|---|---|---|---|
| 1. | Even span | TPV, STPV, glass, fiber glass, polyethylene, plastic | It receives more solar radiation due to the complete exposure of the structure to sunlight; it performs better in east-west orientation. It is flexible for expansion to accommodate more crops, can be located at all the latitude. | STPV is more expensive, but has the advantage of converting sunlight to electricity. The cost of heating even span shaped roof is high. |
| 2. | Uneven span | TPV, STPV, glass, fiber glass, polyethylene, plastic. | It receives maximum solar radiation on one side of the roof, is performs better in east-west orientation. Not flexible, mostly constructed on a hilly terrain, can be sited at all the latitude. | Not suitable for expansion in future. |
| 3. | Quonset/modified arc | Polyethylene, fiber glass, plastic. | The Quonset shape GH receives minimum solar radiation in all the months; it can be sited at all the latitude. | Is the least expensive, it requires flexible covering material. Not suitable for glass roof and power generation. |
| 4. | Attached to | Glass, fiber glass, polyethylene, plastic | It is usually attached to an existing structure, it requires specific direction. It receives limited solar radiation, less ventilation. | It has limited space, close to electricity. |

## III. METHODOLOGY

*Solar Radiation*

The sun is a circular object of extremely hot gaseous matter with a diameter of $1.39 \times 10^6$ km and approximately $150 \times 10^6$ km from the earth surface. The sun radiates energy into the space inform of electromagnetic wave, it has a temperature of 5777K on the surface while in several millions Kelvin (K) at the interior of the sphere. The solar irradiance from the sun received on the earth in the range of 290 to 3000nm wavelengths. Ultraviolet 290-380nm, visible 380-760nm and near infrared 760-3000nm [25].

Therefore, in this research, the best configuration by [8], [24] was modified as shown in figure 2.0. The new configuration is the east-west oriented GH Implementing the even span configuration with an extension beyond the eaves in both the eastern and western part of the span. The whole GH roof and the extended surface area is covered with STPV. The dimension of the new configuration is the same with the dimension used by [24] except the roof which has a total surface area 31.82 $m^2$. However, the energy intercepted and transmitted into the GH through the STPV will be evaluated for all year round in Nigeria at latitude 11.9°, 354m above sea level. The evaluation is done mathematically as in [6].

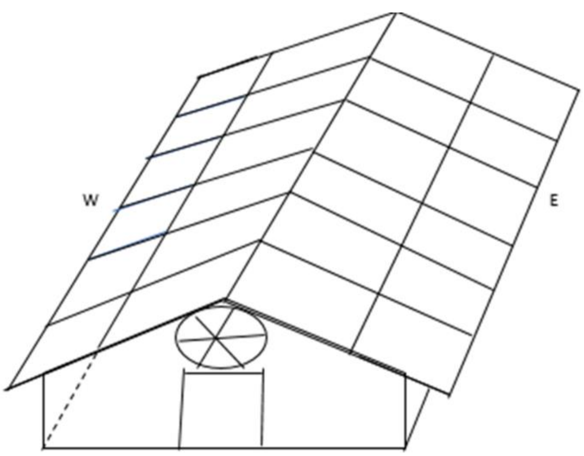


Figure 2: Extended Even Span Configuration

The solar radiation incident on a horizontal surface (extra-terrestrial radiation) is given by the following equation [26] and solar radiation reaching the ground on a clear day can be calculated using the following [6]

*Energy Balance in GH*

Transmitted radiation through the cover – $(1-\rho)\tau S_t$

Portion of radiation falling on the north wall – $F_n(1-\rho)\tau S_t$

Portion lost to the ambient air through the north wall – $F_n(1-\rho)^2\tau^2 S_t$

Portion reflected to the inside air – $\rho F_n(1-\rho)\tau S_t$

Portion absorbed by the plants – $\alpha_p(1-F_n)(1-\rho)\tau S_t$

Portion absorbed by the flow – $\alpha_g(1-\alpha_p)(1-F_n)(1-\rho)\tau S_t$

*Greenhouse Plant*

The plants receive some of the solar radiation transmitted into the GH, which rises the temperature of the plants. The energy balance of the plants is thus given as in [24], [27].

$$\alpha_p(1-\rho)(1-F_n)\tau S_t = M_p C_p \frac{dT_p}{dt} + h_{pr} A_p (T_p - T_R) + h_r A_p (T_p - T_R) \quad (1)$$

[rate of energy absorbed by the plats surface] = [rate of energy used to raise the plants temperature] + [rate of thermal energy convected and evaporated from the plants to the enclosed air] + [rate of thermal energy radiated from the plant to the enclosed air].

The heat transfer coefficient can be expressed as in [28], [24].

*Greenhouse Floor*

Portion of the transmitted solar radiation is collected by the GH floor. This includes sum of the rate of energy loss from the soil surface to the room air and, the rate of energy loss from the soil surface to the bottom of the soil, the energy balance equation for the soil surface in a steady state condition is as in [24].

$$\alpha_g(1-\alpha_p)(1-\rho)\tau S_t(1-F_n) = h_p A_g (T_g - T_o) + h_a A_g (T_g - T_R) \quad (2)$$

[The rate of heat energy collected by the GH floor] = [rate of heat energy lost from the floor to the ground under it] + [rate of heat energy lost from the floor to the air inside the GH].

*Greenhouse Air*

The air temperature of the greenhouse is one of the most important criterion affecting the growth of plants. The air temperature serves as a balance between the energies entering and leaving the GH, which means, energy exchange between the GH air and all the items in the greenhouse i.e plant, GH structures, equipment's and the energy conducted or infiltrated by the GH cover, doors ground floor and ventilation system. The energy balance equation for GH air is as in [24], [27].

$$A_p h_{pr}(T_p - T_R) + A_p h_r (T_p - T_R) + A_g h_a (T_g - T_R) + (1-\alpha_g)(1-\alpha_p)(1-\rho)(1-F_t)\tau S_t$$
$$+\rho F_n \tau S_t (1-\rho) = M_a C_a \frac{dT_R}{dt} + U_{tc} A_c (T_R - T_a) + h_d A_d (T_R - T_a) + E_v \quad (3)$$

*Heat Transfer through Ventilation and Infiltration*

$$E_V = \frac{h_V}{\lambda \gamma_o}(P_R - P_a) \quad (4)$$

*Heat gain inside the GH*

The total excessive heat in the GH is removed as shown by (Sethi and Sharma, 2007).

$$Q_p = q \times A_c \quad (5)$$

*Energy generated by the STPV Roof*

The electrical energy generated from the roof and the extended hangout covered with STPV is calculated as given by [29].

$$E = \eta_c A_c S_c \quad (6)$$

Net electric energy produced is given as in [29].

$$E_{net} = E - P_{fan} \quad (7)$$

## IV. RESULT AND DISCUSSION

The GH inside air, GH plants and the outside temperature varies between 27° and 39° while the outside temperature varies between 28° to a maximum of 44° throughout the day depending on the time of the day or night. However, their temperature remained closely the same at night and during morning hours, but mostly varies during the peak hours of the day. The outside temperature is higher than the inside air and plants temperature during the peak hours of the day. The excessive heat inside the GH that should be removed for conducive plants growth is about 23.22 kW.

The total electric energy produced from the roof covered with STPV is 21.98 kWh $yr^{-1}$. Hence, the electrical energy generated will be used to the keep maintained 95% of the energy needs of the GH conducive for plants growth. Figure 3 shows the energy balance inside the GH.

Due to the hot climate In Nigeria at latitude 11.9° during dry season, the total solar radiation incident on the STPV roof is considerably high during those periods. However, the total solar radiation transmitted inside the GH is 35723.68 kW $yr^{-1}$. Some part of the energy transmitted is absorbed by the GH plants, floor, other portions is transmitted into the ground beneath, as shown in figure 3.

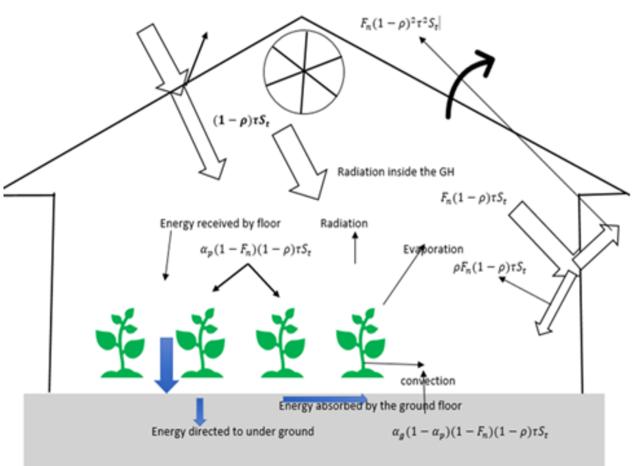


Figure 3: Energy Flow inside GH

The monthly daily average global solar radiation obtained from Nigeria meteorological and weather forecasting agency, for Maiduguri located at latitude 11.9 by [30] and the estimated monthly average interpolated satellite data of the same location, the calculated data is slightly lower than measured data as shown in figure 4, it is therefore adopted for the analysis.

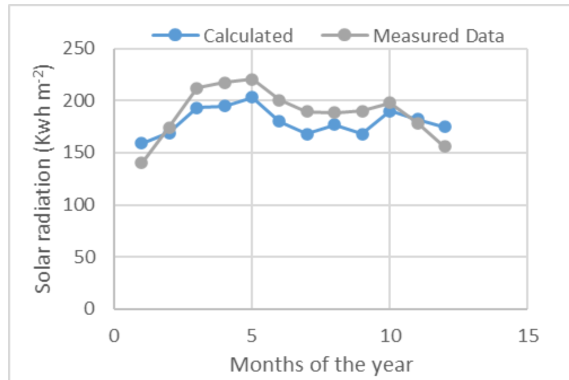


Figure 4: Measured and Calculated Solar Radiation in Nigeria, latitude 11.9°N

The daily monthly average solar radiation received by the GH roof covered with STPV and the energy transmitted through the roof into the GH cavity was computed using excel spreadsheet for all year round using Nigerian climate condition located at latitude 11.9° N. The energy received and transmitted into the GH is as shown in figure 5. While, the transmitted energy and the energy produced by the STPV is as shown in figure 6.

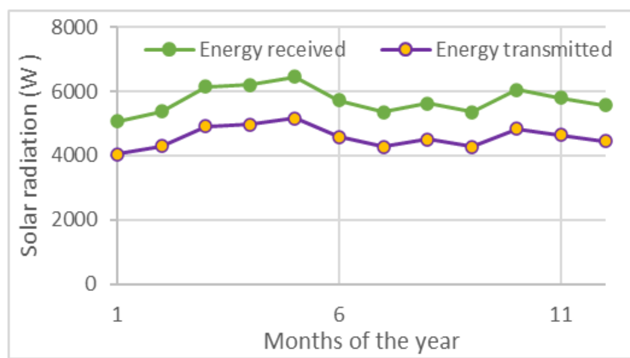


Figure 5: Energy Received and Transmitted into the GH Structure.

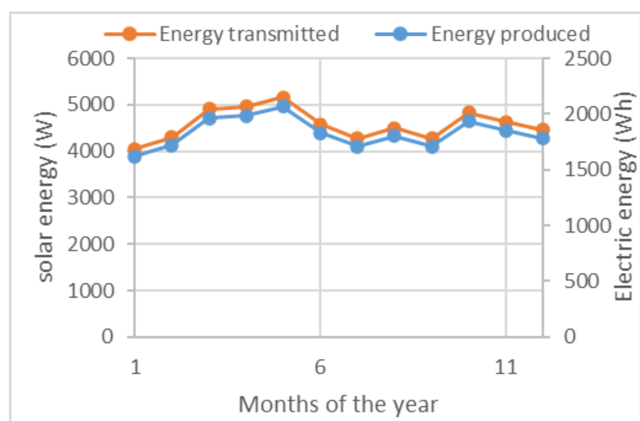


Figure 6: Solar Radiation Transmitted into the GH, in Nigeria latitude 11.9°N.

## V. CONCLUSION

Based on the result obtained from this research, the following conclusion can be drawn.

1. The new configuration implementing STPV as cover for 100% of the roof can be used for GH application, to maximize the use of solar radiation incident on the roof for electrical energy generation.
2. The energy balance of the GH shows that, the excessive energy in the GH cavity leads to an increase in the air temperature inside the GH. The electric energy generated is used to keep the inside air, plants and outside temperatures favourable for GH farming in a control environment.
3. The performance of the new configuration implementing STPV roof in Nigerian climatic condition located at latitude 11.9ºN, can generate 94% of the energy needed to control the microclimate of the GH for conducive plants growth.

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**NOMENCLATURE**

$A_c$ area of GH cover ($m^2$)
$A_d$ area of the door ($m^2$)
$A_g$ area of the ground ($m^2$)
$A_p$ plants total surface area ($m^2$)
$A_V$ area of the ventilator ($m^2$)
$C_p, C_a$ Specific heat of the plants, air ($J\ kg^{-1}\ K^{-1}$)
$F_n$ ratio of solar fraction falling on the north wall over the total incoming solar radiation at the same time (dimensionless)
$F_{PR}$ shape factor between plant and GH room (dimensionless)
$h_a$ convective heat transfer coefficient between the GH floor and inside air ($W\ m^{-2}\ K^{-1}$)
$h_b$ bottom heat transfer coefficient between the GH floor and the ground beneath ($W\ m^{-2}\ K^{-1}$)
$h_d$ heat transfer coefficient from the greenhouse door to the ambient air ($W\ m^{-2}\ K^{-1}$)
$h_p$ convective heat transfer coefficient from the plant to the inside greenhouse air ($W\ m^{-2}\ K^{-1}$)
$h_{pr}$ total convective and evaporative heat transfer coefficient from the plant to the inside air ($W\ m^{-2}k^{-1}$)
$h_r$ radiation heat transfer coefficient between plant and inside air ($W\ m^{-2}\ K^{-1}$)
$h_V$ coefficient of sensible heat transfer due to air renewal in ($W\ m^{-2}\ K^{-1}$)
$I_b,\ I_d,\ I_g$ direct, diffuse and global solar radiation ($W\ m^{-2}$)
$M_p, M_a$ total mass of plants, air in the GH (kg)
$n$ day of the year (January 1 = 1)
$S_t$ total solar radiation incident on the GH at each of the wall, roof and hangout ($Wm^{-2}$)
$T_a, T_o, T_p, T_r$ ambient, underground annual, plant and GH room temperature ($^{O}C$)
$U_t$ overall heat transfer coefficient of the greenhouse ($W\ m^{-2}\ k^{-1}$)
$v$ wind velocity ($m\ s^{-1}$)

Some Greek letters;

$\tau_b$ transmissivity of the atmosphere to direct radiation (dimensionless)
$\tau_d$ transmissivity of the atmosphere to diffuse radiation (dimensionless)
$\alpha_p$ absorptivity of plants (dimensionless)
$\alpha_g$ absorptivity of the ground (dimensionless)
$\beta$ slope of the surface with horizontal (degrees)
$\gamma_r$ relative humidity
$\gamma_o$ psychrometric constant ($kPa\ ^oC^{-1}$)
$\varepsilon$ emissivity of the plants (dimensionless)
$\rho$ reflectivity of the GH cover (dimensionless)
$\rho_a$ density of air ($kg\ m^{-3}$)
$\lambda$ latent heat of vaporization of water ($kJ\ kg^{-1}$)
$\sigma$ Stephen Boltzman's constant ($W\ m^{-2}\ k^{-4}$)