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CARBON EMISSION AND MITIGATIONS ANALYSIS OF MULTI-CRYSTALINE SILICON BASED GREENHOUSE INTEGRATED SEMITRANSPARENT PHOTOVOLTAIC SYSTEM INTEGRATED WITH SOLAR COLLECTORS

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Abstract: The impact of increased CO_2 in environment is a major factor of climate change and has cascading effects on ecosystem, human societies and agriculture. Increased CO2 levels can affect crop yield and food security. This paper aims to examine carbon credit of a greenhouse integrated solar photovoltaic thermal (GiSPVT) system that uses Multi crystalline solar cell material with semitransparent (SPVT) collectors for control environment while promoting the friendly atmosphere. GiSPVT-integrated air collectors supply thermal and electrical energy, which is used to regulate the structure's humidity and temperature.

In this paper analytical calculations are done to derive the expressions that can find temperature of the plant and air within the greenhouse, solar cell temperature, also the efficiency of electrical energy of the GiSPVT system along with the collectors. The expressions are derived with the help of climatic variables like solar irradiations and ambient air temperature, as well as some design parameters such as temperature coefficients, heat transfer coefficients, area of the PV module, electrical efficiency under standard test conditions (STC). The performance of the proposed system is evaluated using different energy performance indicators, namely energy payback time (EPBT), energy production factor (EPF), and life cycle conversion efficiency (LCCE). Thermal modelling is specifically carried out for a multi-crystalline silicon (mc-Si)–based GiSPVT system integrated with air collectors. The total electrical and thermal energy outputs of the system are estimated in order to assess these energy matrices. In addition, the total carbon emissions, carbon mitigation, and carbon credits associated with the proposed system over its entire lifetime are also evaluated.

Keywords: Multi crystalline silicon, semitransparent collector, GiSPVT , CO_2, LCCE

1. Introduction

Rapid population growth, environmental degradation, and the continuous reduction of cultivable land have posed serious challenges to global food and energy security, particularly in developing and underdeveloped countries where the population is increasing by more than 90 million per year. At the same time, rapid industrialization is leading to a steady decline in available agricultural land. As a result, the per capita demand for both food and energy have increased substantially in recent years.

To meet these growing demands, it has become essential to enhance agricultural productivity while simultaneously increasing clean energy production using the same land resources [1-6]

In this context, protected cultivation using greenhouse technology has emerged as an effective approach to improve crop yield and protect plants from extreme climatic conditions [7]. However, conventional greenhouses require a substantial amount of external energy to maintain optimal temperature, humidity, and light conditions. Therefore, there is an urgent need to upgrade traditional farming practices by integrating renewable energy–based technologies into greenhouse systems. One such promising solution is the greenhouse-integrated semitransparent photovoltaic thermal (GiSPVT) system, which all together enables crop production and electricity generation while maintaining a controlled indoor microclimate [8-10].

In a GiSPVT system, semi-transparent photovoltaic (PV) modules are installed on inclined roof of greenhouse, where they generate electrical and thermal energy simultaneously. The produced electrical energy can be utilized to operate auxiliary systems such as fans, pumps, and lighting, thereby making the system self-sustaining—particularly suitable for rural and remote regions with limited grid connectivity. At the same time, the thermal energy contributes to maintaining favorable greenhouse conditions, while the PV modules partially shade the crops from excessive solar radiation, thereby improving overall plant productivity [11-13].

The selection of greenhouse construction material is crucial as it determine the system's lifespan, which typically varies from 5 to 30 years. Accordingly, the choice of photovoltaic technology should be compatible with the expected lifetime of the greenhouse structure. Different solar cell materials—such as (c-Si), (mc-Si), (a-Si), (CIGS), and (CdTe) exhibit significantly different thermal coefficients, conversion efficiencies, energy densities, and operational lifetimes. It is also well established that semitransparent PV modules are particularly suitable for uneven-type greenhouse structures [14].

Thermal coefficient of a PV module is one of the most sensible parameters influencing its electrical performance, as PV efficiency decreases with increasing cell temperature. Numerous studies have focused on improving the efficiency, stability, and service life of photovoltaic and photovoltaic–thermal (PVT) systems to enhance their techno-economic feasibility [15]. Furthermore, the implementation of renewable energy technologies has become essential to mitigate rising atmospheric CO_2 concentrations, which have increased dramatically since the post–World War II industrial era due to rapid industrialization and population growth [16-17].

Several researchers have investigated different aspects of greenhouse materials and PV technologies. Lee et al [18]. examined the thermal atmosphere within the single-span greenhouses covered with glass, polycarbonate, and plastic film and reported that polycarbonate performed better for heat retention during winter, whereas glass performed better for cooling during summer. Makolli et al. demonstrated that the increasing share of renewable energy, significantly affects energy performance pointers such as energy payback time (EPBT). Some researchers [19-20] highlighted that PV material selection is a key factor governing electrical efficiency, system durability, and economic feasibility.

Practical implementation of GiSPVT systems has also been reported in the literature. Tiwari and Tiwari installed a 30 kWp GiSPVT using semitransparent single-crystalline silicon PV modules with different packing factors. Due to the long service life of approximately 30 years and compatibility with reinforced cement concrete (RCC) structures, the mc-Si–based system was categorized as a hightech greenhouse. Despite these advances, a comprehensive energetic comparison of different solar cell materials for GiSPVT applications based on standard energy performance indicators remains limited. Therefore, there is a strong requirement to investigate the effect of various photovoltaic materials on the performance of GiSPVT systems in terms of energy matrices such as life cycle conversion efficiency (LCCE), energy payback time (EPBT) and energy production factor (EPF) with and without the inclusion of thermal exergy [21-23].

Accordingly, this paper focuses on the thermal modelling and performance evaluation of a Mult crystalline silicon (mc-Si) based GiSPVT system integrated with air collectors. To predict the monthly and yearly electrical output of the system under Indian climatic conditions, an analytical expression for electrical efficiency is developed which depends on different temperatures. The estimated yearly energy generated is then used to compute relevant energy matrices. In addition, the impact of CO_2 emission mitigation achieved by the proposed system is also evaluated. Finally, the developed thermal model is experimentally justified by comparing the variations of plant, greenhouse air, and solar cell temperatures on hourly basis for a representative day.

2. Solar Cell Materials

Solar cell materials constitute the foundation of photovoltaic (PV) technology and play a decisive role in concluding the efficiency, cost, durability, reliability, and environmental impact of solar energy conversion systems. Over the past several decades, continuous advancements in material science, device physics, and manufacturing technologies have driven the rapid evolution of photovoltaic systems. This evolution has been motivated by the rising demand for clean energy worldwide, the essential to reduce greenhouse gas emissions, and the necessity to develop sustainable and energy-efficient solutions for applications such as buildings, agriculture, and controlled-environment greenhouses.

In recent years, the integration of photovoltaic systems with agricultural infrastructure, such as greenhouse-integrated solar photovoltaic thermal (GiSPVT) systems, has attracted significant attention. In such applications, the choice of solar cell material becomes even more critical, as the PV modules must simultaneously provide electrical energy, thermal energy, and controlled solar radiation transmission for crop growth. Therefore, a comprehensive understanding of solar cell materials and their technological evolution is essential for selecting an appropriate PV technology for greenhouse-integrated hybrid energy systems [13-15].

Based on technological development and material characteristics, solar cells are classified into different generations: first-generation wafer-based well known as crystalline silicon solar cells, second-generation well known as thin-film solar cells, and third-generation emerging and advanced photovoltaic technologies. Fig.1 presents the classification of solar cell materials according to their technological generations.

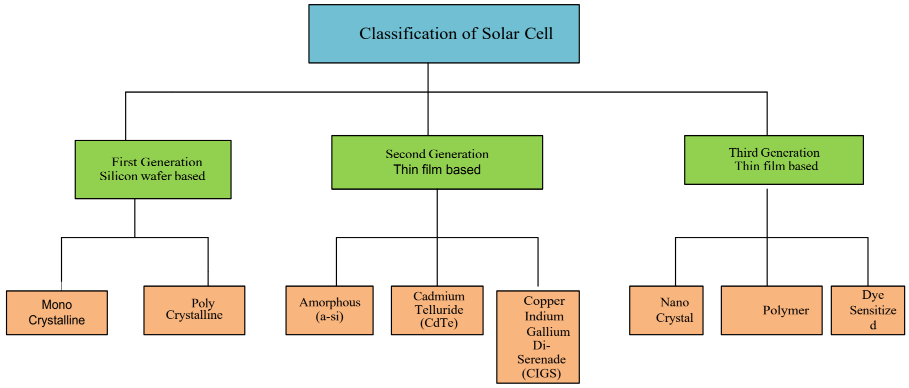

Fig.1 Solar Cell Materials Classification

2.1 First Generation (Wafer-Based /Crystalline Solar Cells)

- Monocrystalline Silicon (c-Si)
- Polycrystalline / Mult crystalline Silicon (mc-Si)

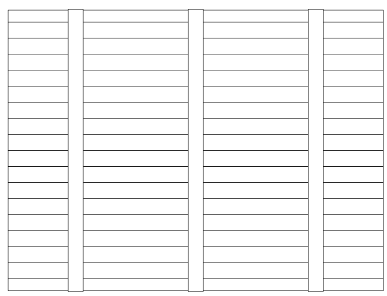

Fig. 2 Multi crystalline solar cell

Advantages:

High efficiency

Mature technology

Disadvantages:

High material and manufacturing cost

Rigid and heavy modules

2.2 Second Generation (Thin-Film Solar Cells)

- Amorphous Silicon (a-Si)
- Cadmium Telluride (CdTe)
- Copper Indium Gallium Selenide (CIGS)

Advantages

Low material usage

Low-cost fabrication

Lightweight and flexible options

Disadvantages

Lower efficiency than crystalline silicon

2.3 Third Generation (Emerging and Advanced Solar Cells)

- Perovskite Solar Cells

- Organic Solar Cells (OPV)
- Dye-Sensitized Solar Cells (DSSC)
- Quantum Dot Solar Cells
- Tandem / Multi-junction Solar Cells

Advantages:
Very high theoretical efficiency
Low-cost and low-temperature fabrication
Suitable for semi-transparent and flexible applications
Disadvantages:
Stability and large-scale commercialization still under development
Based on the critical review of different photovoltaic technologies, Mult crystalline silicon emerges as a highly suitable choice for greenhouse-integrated solar photovoltaic thermal systems. Compared to emerging technologies, Mult crystalline silicon offers:

- Proven long-term stability and durability (>25 years)
- Good efficiency–cost trade-off
- Excellent thermal and mechanical robustness
- Well-established manufacturing and supply chain
- If used in hybrid PV/T systems, electrical and thermal performance can be predicted easily

As emphasized by researchers [13-15], crystalline silicon technologies continue to dominate global PV deployment due to their reliability and techno-economic viability. For GiSPVT applications, where both electrical and thermal outputs are utilized and long-term outdoor operation is essential, Mult crystalline silicon provides a technically sound and economically feasible solution.
while efficiencies of about 12–14% have been reported for Mult crystalline silicon solar cells [11]. In the present study, a Mult crystalline silicon (mc-Si) solar cell–based system is considered to evaluate the overall lifetime efficiency and the payback time of the system.

3.Principle of Working of The Proposed System.

Fig. 3 gives the cross-sectional view of GiSPVT system integrated with Air Collectors. The proposed system is a hybrid configuration combining a greenhouse-integrated semi-transparent photovoltaic thermal (GiSPVT) system with semi-transparent photovoltaic thermal (SPVT) air collectors. To maximize solar insolation, an uneven-shaped greenhouse structure with a south-facing roof is adopted. The photovoltaic (PV) modules employed in the system are fabricated from Mult crystalline silicon (mc-Si). The greenhouse receives useful energy gains through two mechanisms: first, directly via non-packing (transparent) spaces of the structure, and second, indirectly via heat extraction from the rear surface of the PV modules.
To minimize thermal losses from the back surface of the PV modules, a semi-transparent photovoltaic (SPV) module is mounted above a blackened absorber plate, which is thermally insulated at the rear side. In the present configuration, twentyfive series connected collectors considered. Ambient air is drawn from the bottom of the greenhouse into the inlet of the first collector, where it is heated by absorbing thermal energy from the blackened absorber surface. For enhanced temperature rise, the outlet of the first collector is connected to the inlet of the second collector, and this cascading

arrangement continues up to the last collector in the series.

The heated air exiting the final collector is then supplied at the top of the GiSPVT system. As a result, the internal air temperature of the GiSPVT room increases significantly, thereby improving the thermal environment inside the greenhouse while simultaneously enabling electrical energy generation from the PV modules

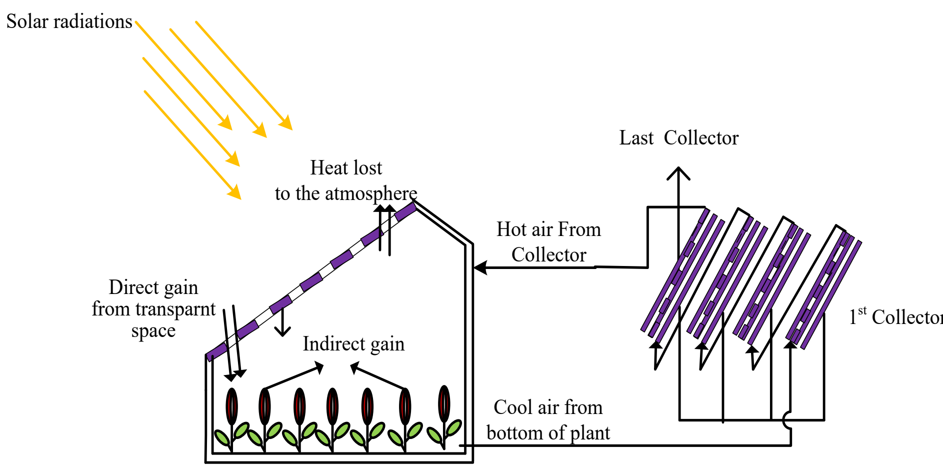

Fig. 3 Cross sectional view of GISPVT system integrated with aircollectors

In addition to the transparent walls and north roof, south roof of the semi-transparent photovoltaic arrays has a non-packing portion that provides direct gain. Inside the greenhouse room, the indirect gain comes from the PV array's packing area, which is rear of the solar cell. The south roof of GiSPVTS is at an angle to receive the most solar radiation possible during the summer months in order to generate the most electrical power possible. Additionally, if necessary, sliding walls and a roof vent are provided to transfer excess heat from the interior of greenhouse to the outside. To limit the usage of land, an EAHE is buried underground beneath GiSPVTS. As seen in Fig. 1, pipes are connected in sequence and afterwards coupled in back to back. To move hot, earth-cooled air, EAHE and GiSPVTS are connected in a closed loop. In this situation, arrangements for heating and cooling can be made in accordance with need.

4. Analysis of Proposed System.

The following formulae are derived to determine the monthly and annual variations in solar cell temperature (Tc), room air temperature (Tr), and plant temperature (Tp) based on the operation of the system described above and the Hottel-Whillier-Bliss equations [14]:

$$\overline{T}_c = \frac{\tau_g \beta(\alpha_c - \eta_0)\overline{I}(t) + U_{t,ca}\overline{T}_a + U_{b,cr}\overline{T}_r}{U_{b,cr} + U_{t,ca}} \quad (1)$$

$$\overline{T}_r = \frac{(\alpha\tau)_{gmeff}\overline{I}(t) + h_1 A_{wP}\overline{T}_p + U_{ra1}A_{RS}\overline{T}_a + (UA)_{gm}\overline{T}_a}{h_1 A_{wP} + U_{ra1}A_{RS} + (UA)_{gm}} \quad (2)$$

$$T_p = \left\{\frac{[\tau_g{}^2(1-\beta)A_{RS}+PF_3(\alpha\tau)_{gmeff}A_P]I(t)\tau_g+\sum_{j=1}^{3}A_jI_j}{[(UA)_{wa}+\sum_{k=1}^{5}A_kU_k]}+T_a\right\}(1-e^{-at})+\ T_{p0}e^{-at} \quad (3)$$

$$\dot{E}_{mi,co} = \eta_{mi,co} \times I(t) \times \beta \times N \times A_{cm}(W) \quad (4)$$

The monthly variation of ambient temperature (Ta) and solar radiation I (t) in W/m2) must be known in order to calculate the monthly variation of Tc, Tr, and Tp . The monthly average change of ambient temperature and solar radiation (W/m2) for a composite Indian climate condition is shown in Fig. 4. Using equations (1-4), the monthly fluctuation of Tc, Tr, Tp as shown in Fig. 5 and Electrical Energy (E) may be obtained from the data as shown in Fig. 4.

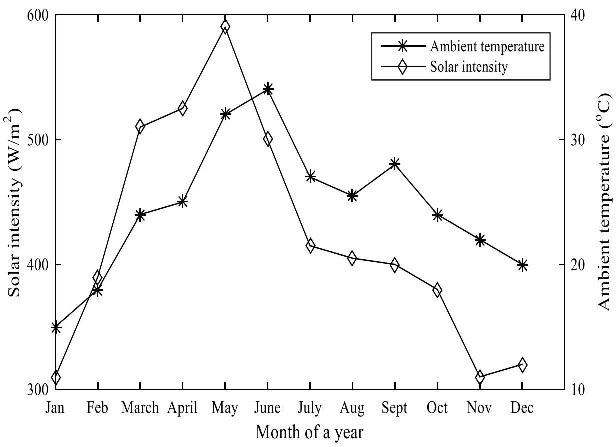

Fig. 4 Variation of solar radiation and ambient temperature on average of an Indian climatic condition

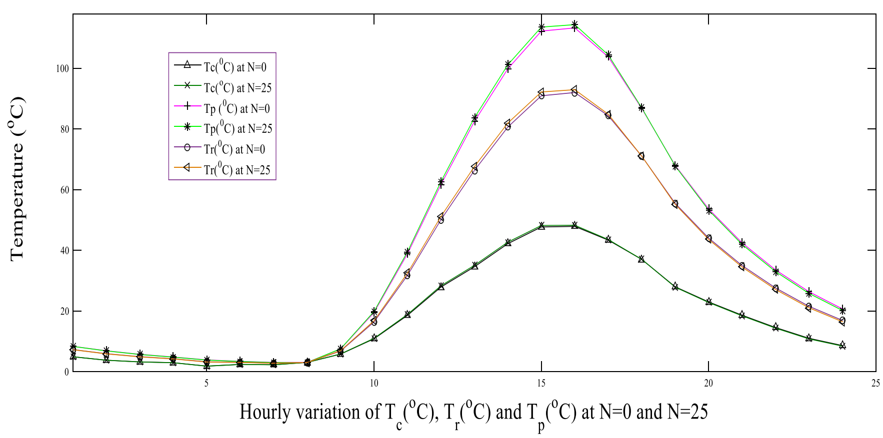

Fig. 5 Variation of Tc, Tr and Tp for N=0 and N=25

5. Assessment of Energy Matrices.

It is well established that a renewable energy system is considered viable only if the total energy generated over its operational lifetime exceeds the energy utilized during its engineering, installation, and maintenance; otherwise, the system becomes energetically unjustifiable. Energy metrics, including the energy payback time (EPBT), energy production factor (EPF), and life cycle conversion efficiency (LCCE) are evaluated to estimate the performance and sustainability of the proposed system [20]..

In present study, the total thermal and electrical output of the system is calculated by considering all the electricity-generating components. The Yearly electrical and thermal energy produced by the greenhouse-integrated solar photovoltaic thermal (GiSPVT) system and the yearly electrical energy generated by the semi-transparent photovoltaic collectors are computed separately and then added together to obtain the total annual electrical and thermal energy produced by the integrated system. Table 1 gives the value of annual electrical energy generated with and without considering the exergy and collectos.

Table 1: Yearly electrical energy with and without thermal exergy and collector in kWh

solar cell materials	Yearly electrical energy without exergy and without collector in Wh	Yearly electrical energy without exergy and with collector in Wh	Yearly electrical energy with exergy and without collector in Wh	Yearly electrical energy with exergy and with collector in Wh
mc-Si	$4.27x10^4$	$1.17807x10^2$	$4.32x10^4$	7.087 $6.6722x10^4$

Table2 gives the embodied Energy of each of the component of the system

System	Embody Energy	No. of Units	Total Embody Energy
GiSPVT	27954.7	1	27954.7
SPVT Collector	1159.49	25	28987.25
Mc-Si module	646	168	108528

Table 1: Embodied Energy of different components

By using the data in Fig.4, Table 1 and the temperatures of solar cell, room and inside air temperature. Total electrical energy generated in a year has been estimated as

Total electrical energy generated in one year =66722kWh

From the data given in Table 2 , Total embody (Ein) energy of the system is calculated as

Ein = Embodied energy of GiSPVT+ Embodied energy of 25 SPVT collectors+ Embodied energy of mc-Si module

Ein = 27954.7 +28987.25 +(168*646) = 165469.95 kWh

EPBT is the relationship between total embodied energy (Ein) and total annual energy generated by the system. The payback time should be minimum. For the proposed system, it is evaluated as

$$EPBT = \frac{Ein}{Annual\ Energy}$$

$$= 2.09 Years \quad (5)$$

EPF is the relationship between annual energy, total life of the system and the embodied energy. Total life span of the proposed system, is 30 years. The value of EPF must be high for system to be economical. It is given as

$$EPF = \frac{Annual\ Exergy * life\ span}{Ein} \quad (6)$$

$$= 11.92$$

Life cycle conversion efficiency (LCCE) is the ratio of effective energy obtained by the system to the total solar energy available in the life time of system which is given by,

$$LCCE = \frac{Annual\ Exergy * life\ span - Ein}{Yearly\ solar\ radiation * life\ of\ the\ system} \quad (7)$$

$$= 12.198\ \%$$

6.Emission and Mitigation of CO2

As we known that during production of 1kWh of electrical energy at a coal-based thermal power plant 1.01 kg of CO2 emission takes place. Furthermore, transmission, distribution and wiring losses are 40% and 20%, respectively [21]. The CO2 emission by the plant is given as follows:

$$CO2\ emission/\ year = 2.10 * \frac{Ein}{Life\ Time} \quad (8)$$

$$= 7.38\ Tones$$

CO2 emission for the whole life is estimated as=221.4Tones

Total thermal energy is required to evaluate the CO2 mitigation of system to environment. Which is the sum of thermal energy obtained by GiSPVT and thermal energy obtained by air collectors.

CO2mitigation/year =2.1* Exyearly kWh (9)

= 109.641 Tones

CO2 mitigation for entire life= CO2 mitigation/year *life time

= 3289.23Tones

For calculating the net CO_2 mitigation of the proposed system over the entire life, the effect of carbon dioxide emitted by embodied energy (Ein) need to consider . Which is given as

CO2 (net) = 2.1 × (Exyearly × total life- Ein) × 10-3 (tones)
=2867.25 tones

The carbon credit rate (CCR) is considered as $10 per tones

In entire life time, total carbon credit earned by GiSPVT-SPVT is given as

CCR*CO_2 net tones =10*2867.25 tones =28672$

Carbon credit earned per year = CCR*CO2 net tones/total years

=28672/30= 955.733$

Considering the conversion rate in Indian scenario and If 1$=90 ₹

Therefore, the system is capable of saving around =955.733*90 = ₹ 86,016 and considered as economical system.
Carbon credit earned in life time = Carbon credit earned per year x × total life = ₹ 25, 80,480/-

8. Conclusions

1. The greenhouse-integrated solar photovoltaic thermal system coupled with semitransparent photovoltaic thermal collectors demonstrates strong potential for agricultural applications by enabling substantial carbon emission mitigation and economic benefits over its operational lifetime. The proposed GiSPVT system, based on multicrystalline silicon (mc-Si) solar cells, is designed for service life of 30 years and achieves a high overall system efficiency of 25.27%, with an energy payback time (EPBT) of only 2.09 years.
2. Over its entire lifespan, the system is capable of mitigating approximately 3289.23 tonnes of CO_2 emissions, thereby significantly reducing the carbon footprint and contributing to an environmentally sustainable and eco-friendly agricultural infrastructure. In addition to its environmental benefits, the system also provides economic gains through carbon credit mechanisms. The estimated revenue from carbon credits is approximately ₹86,016 per year, amounting to nearly ₹2,580,480 over the full operational lifetime of the system.

3. Consequently, the proposed GiSPVT–SPVT system not only enhances energy sustainability and climate resilience in agriculture but also emerges as a financially attractive and transformative solution for farmers.

Declaration of competing interest: The authors declare that they have no known competing financial interests or personal relationships that would influence this paper.

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