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Design of Eco-Sustainable Renewable Energy Systems for Fish Farming

Manju Bhardwaj[a], Shikha Singh[b*], Ram Gopal Singh[c]

[a]*Center for Research and Advanced Studies, Shri Ramswaroop Memorial University, Tindola, Barabanki, INDIA*
[b]*Department of Electrical Engineering, Madan Mohan Malaviya University of Technology, Gorakhpur, INDIA*
[c]*Department of Physical Sciences, Shri Ramswaroop Memorial University, Tindola, Barabanki, INDIA*

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A B S T R A C T

Aquaculture is one of the prime sector; affected by climatic variations and environmental pollution. In this research, a renewable energy based solution is proposed by integrating photovoltaic (PV) modules with a glasshouse structure to provide a controlled environment for fish ponds, ensuring production regardless of climatic fluctuations. Furthermore, this study analyzes the performance of two commonly used solar cell materials; crystalline silicon (c-Si) and nanocrystalline silicon (nc-Si) within glasshouse-integrated PV system to maximize electrical energy output. The results demonstrate that c-Si and nc-Si shows similar temperature (16˚C-35˚C) of fish pond. Additionally, c-Si is 2% more efficient than nc-Si, which increases monthly electrical energy generation by 20% to a maximum of 2000kW in January. The choice of solar cell materials for the glasshouse integrated PVT system should be optimized in accordance with the expected lifespan and performance requirements of the respective greenhouse type, as the life of glasshouse materials varies from 5 to 30 years. Therefore, this study recommends appropriate solar cell materials for specific glasshouse designs by evaluating Energy Payback Time (EPBT) and Life Cycle Conversion Efficiency (LCCE), considering thermal exergy range from 7.5 years to 9 years and 12% to 21%.

1. Introduction

Climate change is projected to impact broadly across ecosystems, economies and societies. This increase the pressure on all food supplies and livelihoods, including those in the aquatic and fisheries industry. Food supply will become an increasingly vital challenge in the coming years [1]. Fish is the rich source of protein, become an economical and vital seafood product that corresponds to approximately 15% of the total value of the world's traded seafood products [2]. Aquaculture continues to significantly expand its production of fish stands out as the fastest-growing

*Corresponding Author Email:ishikha.singh@gmail.com

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food production sector globally [3]. Apart from preventing the overexploitation of natural fishery stocks, aquaculture also possesses the most significant capability to meet the rising demand of global fish food [4].

Cage fish farming satisfy the growing demand for fish due to growing global population [5]. The internal environment's microclimatic parameters are regulated by the use of cage fish farming (i.e., air temperature, relative humidity, PH level, CO_2 concentration), influencing fish quality and quantity [6]. Cage fish farming as greenhouses use solar radiation as input to provide control internal environment [7]. Depending on the season, cage fish farming and greenhouse construction provide shielding to the fish from high temperatures in the spring and/or summer season as well as from low temperatures at night in the winter season [8]. Cage farming significantly increases fish production, thereby strengthening the country's economy, employment opportunities, and improved food security [9]. This aligns with the United Nations Sustainable Development Goals (SDGs), particularly the goal of promoting sustainable economic growth and supporting livelihood opportunities for communities dependent on fisheries [10].

India is a developing country and its priority to improve the quality of life for farmers in rural areas [11]. One effective way to achieve this is through the adoption of renewable energy sources such as solar energy [12]. This clean energy solution can provide reliable and affordable electricity for fish farmers, reducing their dependence on costly conventional power sources [13]. Electrical output can further enhance by integrating a hybrid energy system [14]. The incorporation of solar collector can further boost system performance by improving thermal energy capture under low-temperature conditions [15]. By ensuring a cleaner environment and sustainable energy supply, renewable technologies not only support fish farming activities like lighting of bulb, running fan, aeration, pumping but also contribute to rural development, improved livelihoods, and long-term food security [16]. Table 1 summarizes the research work carried out on greenhouse and photovoltaic thermal (PVT) systems across different regions. The available literature indicates that limited research has been conducted on Indian fish species suited for the cold climatic conditions of Ladakh using greenhouse structure [17]. Further, a very few attempts have been done by researchers to maximize the solar cell efficiency, stability and its life time [18]. Integrating greenhouse with PVT system requires detailed analysis as glass-based greenhouse structure has specific service life and the selection of solar cell material need to be optimized accordingly. Due to different life span of glass house and solar cell material, it is essential to identify the most suitable solar cell material to support structural integration, ensures the required thermal environment for Indian fish species in the cold climate of Ladakh, India and to deliver maximum electrical output simultaneously [19].

Therefore, there is a critical need to study the inside temperature of glasshouse integrated with PVT onto the roof which directly affects fish yielding and growth, as well as the energy metrics of different solar-cell materials to identify the most suitable material. Maintaining the optimum water temperature is also critical for fish farming as it directly affects the metabolic rate, feed conversion efficiency, growth performance, and overall survival of fish. Indian carps require a temperature range of approximately 18°C-35°C and any significant deviation from this range can lead to thermal stress, disease susceptibility, mortality, and substantial economic losses for farmers, ultimately impact the local livelihoods and economy of the country [20]. Therefore, precise thermal regulation of the fish culture environment is essential. To support this requirement while simultaneously reducing the energy burden on farmers, the integration of photovoltaic–thermal (PVT) systems with greenhouse-based aquaculture offers a sustainable solution. The proposed work aims to combine greenhouse technology with a PVT system specifically designed for the cold climatic conditions of the Ladakh region, ensuring both temperature maintenance for fish growth and reliable renewable electricity generation. The proposed concept involves installing PV panels on a glasshouse structure, which simultaneously acts as a greenhouse for fish farming. This dual-purpose design offers multiple benefits:

a. It maintains the pond temperature to promote fast growth and high yield of fish in the cold climatic conditions of Ladakh, India.
b. It also generates renewable electricity for the farmers.

The electricity produced can be utilized for essential operations such as water pumping, aeration, and cold storage, thereby reducing dependence on conventional energy sources and lowering operational costs. The

Table 1. Various Greenhouse Systems

S.No	Solar cell material used/PVT	Applications /Weather conditions	Observations	Reserach Gap	Reference
1.	Greenhouse made with glass and green jute Semi-transparent photovoltaic thermal (SPVT)	Plants/hot climatic condition	• Plant temperature decrease with increase in air temperature. • The temperature of air for growth of plant reduce by 9 °C to 10.5 °C.	• Not for aquaculture • Proposed system for hot climate • Efficicency (solar cell) based performance evalation is absent	[21]
2.	Greenhouse A-Slope made with glass glazed PVT solar collectors and drying system	Crops drying/ winter climatic condition	• Temperature controllability is superior then other drying systems. • By altering the air mass flow rate and PV module packing factor, a single drying system may be used for various applications.	• Not for aquaculture • Efficicency (solar cell) based performance evalation is absent • No electrical generation using renewable energy for farmers	[22]
3.	Ridge and furrow type green house Uneven PVT system	Off season crop/ cold climatic condition	Following conditions provide maximum crop yielding: • Packing factor area is 25% of total area of semi-transparent PV module. • The ratio of sand, soil and organic fertilizer as 40%, 40%, and 20% respectively. • Burning dung cake maintains CO_2 level. • Heat loss minimization.	• Not for aquaculture • Efficicency (solar cell) based performance evalation is absent • Comparative analysis of different solar cells are not done	[23]
4.	Glass based greenhouse spherical micro-PV cells	Crop/cold climatic condition	• Improve agricultural production. • Quality improvement. • Reducing fuel consumption. • Reduce grid electricity usage.	• Not for aquaculture • Efficicency (solar cell) based performance evalation is absent • Comparative analysis of different solar cells are not done	[24]
5.	Plastic based greenhouse solar based hot air aerator	Fish/ Mediterranean	• Fast fish growth.	• No PVT (Only greenhouse) • No electrical energy generation	[25]

long lifespan of glass enhances system durability, while the careful selection of solar cells ensures reliable performance under local environmental conditions. In this study, an attempt has been made to analyze key energy metrics, estimate the lifespan of the PV modules, and evaluate the payback period to determine the overall economic feasibility of the system. The proposed model not only helps farmers increase their income through improved fish productivity but also enables significant savings through renewable energy generation, ultimately contributing to rural development and supporting the achievement of several United Nations Sustainable Development Goals (SDGs).

2. System Description of Proposed System

Figure 1 show the proposed glasshouse integrated with PVT system. Here an uneven shape of the glasshouse is considered as shown in Figure 1.

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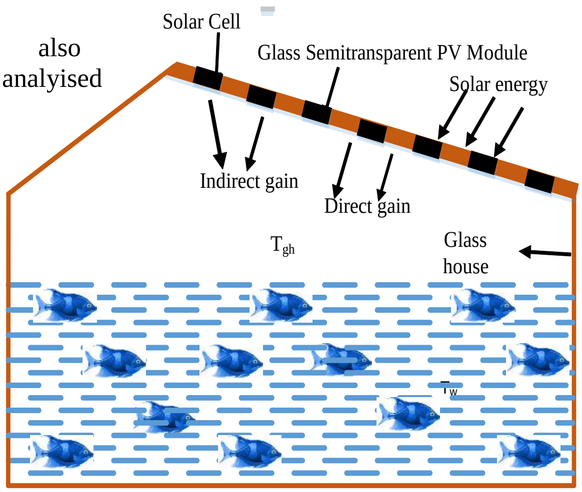

Figure 1. View of uneven glasshouse integrated with PVT system.

In the freezing temperature of the Ladakh region, the semi-transparent PV module has been employed onto the south roof to obtain maximum solar radiation that can be used as direct gain within the glass house through a non-packing section of the PV module for thermal heating as [19]:

$$Q_{pw} = \alpha_{pw} I_{irr}(t) A_{pw} \tag{1}$$

Also semi-transparent PV module's temperature rises because incident solar radiation that strikes its packing area after being transmitted from the top glass cover is partially converted into DC power and the remainder is used to heat the PV modules. An indirect gain is observed due to increase in the temperature of PV modules to glass room air of the glasshouse integrated with PVT which provide thermal energy and maintain the temperature more than atmospheric temperature, further help in providing thermal comfort to fish in extreme cold weather of Ladakh. Further indirect gain in the glass house reduces the evaporation loss and maintains the temperature of water of fish water pond even in off sunshine hours. Also, due to the low range of operating temperature of PV module, the electrical efficiency of the solar cell in the PV module will be at its maximum when there is a maximum thermal energy loss from the solar cell to both the area as atmosphere and glasshouse air. The details of the design of glasshouse integrated with PVT system have been given in Table 2 [17, 19, 20, 21].

3. Mathematical Modeling of Proposed System

To create a characteristic equation of the proposed un-even glasshouse integrated with PVT system and to develop an energy balance equation, the following presumptions have been made:

1. Electrical and thermal analysis has been done under quasi-steady state conditions.
2. Ethyl Vinyl Acetate (EVA) possesses a transitivity of almost 100% as its the thinnest material.
3. The electrical losses are considered negligible between the connections of two solar cells. This is due to use of copper material for connection.
4. Negligible heat capacity is considered for each material of glasshouse integrated with PVT system, except water heat capacity.
5. The underground temperature is assumed to be same as that of atmospheric temperature.

Table 2. Design Parameters for Proposed System

Design Parameters	Values
Specific heat of fish water pond (c_{fwp})	4190 J/kg
Heat transfer coefficient (h_{tc})	5.7 W/m^2 °C
Mass of water of water pond (M_{fwp})	2 Kg/s
Volume of water in fish water pond (V_{fwp})	100-535 m^2
Penalty factor due to transparent glass used in photovoltaic module (PV_{pf1})	0.3782
Penalty factor due to absorptive plate at the bottom of photovoltaic module (PV_{pf2})	0.7805
Surface area of fish water pond (A_{fwp})	37.12 m^2
An overall heat transfer coefficient (V_{tca})	9.1794 W/m^2°C
Absorption coefficient of module (a_{pp})	0.9
Packing factor of photovoltaic module (β)	0.8
Under ground temperature (T_{pw0})	10°C

According to the aforementioned hypotheses, the fundamental energy balance equation for every component of uneven glasshouse integrated with PVT system is expressed as follows:

The PVT installed on the south roof of glasshouse has the energy balance equation as [26]:

Total Sun irradiation solar cell absorbs	=	Heat energy into electrical energy	+	Lost of heat energy of solar cell into atmosphere	+	Loss of heat energy from bottom of solar cell to the glasshouse room

and can be written as:

$$\alpha_{pp}\tau_{pp}\beta A_{pp} I_{irr}(t) = V_{tca}(T_{pvt} - T_{pa})A_{pp} + V_{bcr}(T_{pvt} - T_{glh})A_{pp} + \eta_{pp}\tau_{pp}\beta A_{pp} I_{irr}(t) \tag{2}$$

Table 3 listed the energy density, temperature coefficient, embodied energy, and electrical efficiency under standard test conditions (STC) for c-Si and nc-Si solar cells materials.

The temperature of PVT (T_{pvt}) using above equation (2) is computed as:

$$T_{pvt}=\frac{\tau_{gg}\beta(\alpha_{pp}-\eta_{pp})I_{irr}(t)+V_{tca}T_{pa}+V_{bcr}T_{glh}}{V_{tca}+V_{bcr}} \quad (3)$$

The glasshouse helps to maintain the temperature inside the glasshouse and fish water pond with respect to ambient temperature. The temperature of fish water pond will be maintained for longer duration as glasshouse temperature is always more than the ambient temperature. All losses are taken into account while creating the energy balance equation of glasshouse as [19]:

$$V_{bcr}(T_{pvt}-T_{pa})A_{pp}+h_{tc}(T_{fwp}-T_{glh})A_{fwp}=\sum_{i=1}^{5}A_iV_i(T_{glh}-T_{pa}) \quad (4)$$

Glasshouse temperature is obtained using equation (2) and (4) as:

$$T_{glh}=\frac{PV_{PF1}\beta A_{pp}(\alpha_{pp}-\eta_{pp})I_{irr}(t)+h_{tc}A_{fwp}T_{fwp}+V_{ra}A_{pp}T_{pa}+\sum_{i=1}^{5}A_iV_iT_{pa}}{h_{tc}A_{fwp}+V_{ra}A_{pp}+\sum_{i=1}^{5}A_iV_i} \quad (5)$$

where

$$PV_{pf1}=\frac{V_{bcr}}{V_{bcr}+V_{tca}} \quad (6)$$

The fish water pond's energy balance equation is computed as follows:

$$\sum_{k=1}^{5}A_kV_k(T_{0,g}-T_{fwp})+\tau_{pp}^2(1-\beta)A_{pp}I_{irr}(t)+\tau_{pp}^2\sum_{j=1}^{3}A_jI_j=M_{fwp}C_{fwp}\frac{dT_{fwp}}{dt}+h_{tc}(T_{fwp}-T_{glh})A_{fwp} \quad (7)$$

Here $\tau_{pp}^2\sum_{j=1}^{3}A_jI_j$ is considered as 0 as it's assumed as complete absorbed Sun irradiation is exposed either using opaque walls of glasshouse or using north roof.

The above equation is solved by considering all initial conditions as $T_{fwp}=T_{fwp0}$ at t=0. The water temperature of fish water pond is computed as:

$$T_{fwp}=\left[\frac{(MA)_{11}}{(MA)_{22}}+T_{pa}\right]\times(1-e^{-at})+T_{fpw0}e^{-at} \quad (8)$$

In the current study, the monthly average variation of temperature of fish water pond, solar cell, and glasshouse air temperatures is evaluated using equations (4) to (8), which are applicable to the majority of blue sky clear climatic conditions. For experimental validation, the daily hourly variation of fish water pond, solar cell, and glasshouse air temperatures is evaluated using the given hourly solar intensity and ambient air temperature.

The PVT temperature can be obtained using equation (3) after substituting the value of T_{glh} from equation (5).

4. Electrical and Thermal Energy of Proposed System

4.1. Electrical Energy

The percentage of sunlight that a PV module converts into usable electricity is known as its electrical efficiency. A number of variables, including the type of solar cell material, cell design, and operating circumstances, affect its efficiency [27].

An instantaneous PV module electrical efficiency mounted onto the roof of glasshouse is calculated as:

$$\eta_{elect,pv}=\tau_{pp}\eta_{pp}\left[1-\beta(T_{fwp}-18)\right] \quad (9)$$

where η_{pp} is the standard photovoltaic cell electrical efficiency considered as shown in Table. 3 for c-Si & nc-Si [21, 22, 24].

Monthly electrical energy can be obtained using above equation (9) of efficiency of PV module as:

$$E_{mon}(KWh)=\frac{\eta_{pvt}\times I_{irr}(t)\times A_m\times N_{pv,mod}\times N_{sunshine,hours}\times N_{month,days}}{1000} \quad (10)$$

where $N_{pv,mod}$ is the number of PV module installed on the south roof of proposed system, $N_{sunshine,hours}$ is the number of suntime in hours in a day and it varies as per geographical location and $N_{month,days}$ are the number of days in the month.

Yearly electrical energy can be computed as:

$$E_{year}(KWH)=\sum_{M=1}^{12}E_{mon} \quad (11)$$

Table 3. Specification of c-Si and nc-Si solar cell Material

Solar Cell Construction Material	Crystalline Silicon(c-Si)	Nano-Crystalline Silicon(nc-Si)
PV module efficiency (%)	16	12
Ein	8449	433.1
Expected Life time (Years)	30	25
Average Temperature Coeefficient(β)	0.00535	0.0036

4.2. Thermal Exergy

The yearly average thermal exergy ($Q_{year,exergy}$) is computed as

$$Q_{year,exergy} = M_{fwp} c_{fwp} [(T_{fwp} - T_{fwp0}) - (T_{pa}+273) In \frac{T_{fwp,max}+273}{T_{fwp,min}+273} \quad (12)$$

where $T_{fpw,max}$ and $T_{fpw,min}$ can acquire from analytical expression of temperature of fish water pond using equation 8 for the given climate and design parameters.

Total yearly exergy of proposed system can be computed using above equation as:

$$E_{total,exergy} = E_{year} + Q_{year,exergy} \quad (13)$$

5. Energy Matrices of Proposed System

The three primary energy matrices for assessing the performance of energy systems especially renewable energy technologies are the energy payback time as EPBT, energy production factor as EPF and life cycle conversion efficiency as LCCE. These indicators aid in evaluating a system's overall lifespan energy balance and efficiency. In this paper, these matrices have been evaluated for two solar cell materials as c-Si and nc-Si in the subsection that follows, both with and without thermal exergy.

5.1. Computation of EPBT

The amount of time needed for an energy technology to produce enough energy to meet its life cycle energy needs is defined as energy payback time, or EPBT [28].

$$EPBT = \frac{Embodied\ energy\ (E_{in,T})}{Yearly\ electrical\ outpu(E_{yearly})} >> 1$$

$$Eyearly \times Life\ of\ PV\ system\ Ein,T\ > 1$$

$$EPF = \frac{E_{yearly} \times Life\ of\ PV\ module}{Embodied\ energy\ (E_{in,T})} > 1$$

$$LCCE = \frac{E_{yearly} \times Life\ of\ PV\ module - Embodied\ energy\ (E_{in,T})}{Life\ of\ PV\ module \times yearly\ solar\ irradiation} \prec 1 \quad (14)$$

The amount of electricity required for all activities associated with manufacturing, transportation to the construction site, and building throughout life is known as the embodied energy [29].

It is basically a gauge of the "hidden" energy cost associated with the manufacturing of solar panels and calculated as:

$$E_{in,T} = PV\ modules\ in\ south\ roof \times an\ area\ of\ one\ PV\ module\ \left(m^2\right) \times embodied\ energy\ E_{in}\left(kWh\right) \quad (15)$$

The embodied energy of a solar system should be as low as feasible. Here, the embodied energy for a given design of glasshouse integrated with PVT system is constant for different solar cell materials. The embodied energy, E_{in}(kWh), for the PV module of 0.71 m^2 for different solar cell materials is given in Table 2.

5.2. Computation of Energy Production Factor (EPF)

EPF is a crucial metric for assessing the performance and cost-effectiveness of proposed system. The complete life of proposed system known as energy production factor, EPF depends on whole life of PV modules, yearly electrical energy and embodied energy. EPF of proposed system is estimated as:

$$EPF = \frac{E_{yearly} \times Life\ of\ PV\ module}{Embodied\ energy\ (E_{in,T})} > 1 \quad (16)$$

EPH must be as maximum as possible as it shows higher efficiency rating.

5.3. Computation of LCCE

LCCE refers to the overall efficiency of converting input energy into a useful output over the entire lifespan of a system or process. It's a key metric in evaluating the sustainability and effectiveness of energy technologies, especially renewable energy systems like solar power. LCCE considers various factors throughout the system's life, including energy inputs for manufacturing, operation, and eventual disposal or recycling [30].

In the proposed system, LCCE depends on yearly electrical energy (E_{yearly}), life of PV module, and embodied energy ($E_{in,T}$) along with yearly solar irradiation.

The LCCE is defined as:

$$LCCE = \frac{E_{yearly} \times Life\ of\ PV\ module - E_{in,T}}{Life\ of\ PV\ module \times yearly\ solar\ irradiation} \prec 1 \quad (17)$$

6. Results and Discussions

The average value of ambient air temperature and sun intensity of the whole year has been taken from Indian Meteorological Department (IMD), located in Pune, India as plotted in Figure 2 and Figure 3 for Ladakh region. Using MATLAB, numerical calculations and simulation were performed using the design parameters given in Table 2 and Table 3 for two solar cell materials as c-Si and nc-Si for varying climatic conditions of Ladakh as displayed in Figure 3 for whole year. Ladakh endures exceptionally low temperatures due to its harsh desert climate throughout the year, particularly during the winter months.

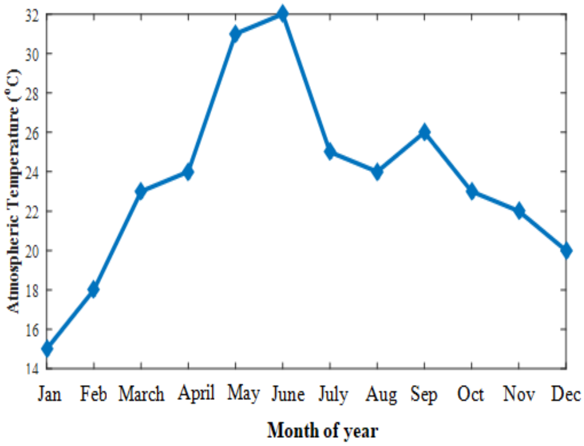

Figure 2. Yearly variation of atmospheric temperature of Ladakh, India

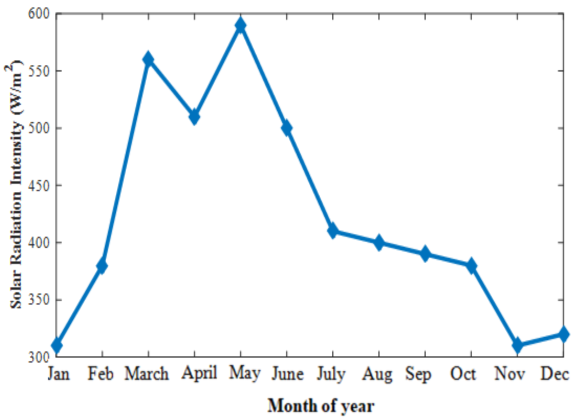

Figure 3. Yearly variation of solar intensity of Ladakh, India

The winters are harsh and lengthy, with significant snowfall and below-freezing temperatures, while the summers are brief and chilly. The area is known as a "cold desert" and receives relatively little rainfall is plotted in Figure 3. The solar intensity receive in this region is low in winters and maximum in the month of May to July as shown in Figure 3.

Figure 4 shows that the temperatures of each individual solar cell do not differ significantly. In Figure 4, PV module temperature of proposed system for c-Si and nc-Si solar cell material might result from the PV module material's having extremely low heat capacity. The PV module achieved maximum temperature as 65˚C approximately in the month of May (summer season) and minimum temperature as 35˚C approximately in the month of January (winter season) as shown in Figure 4.

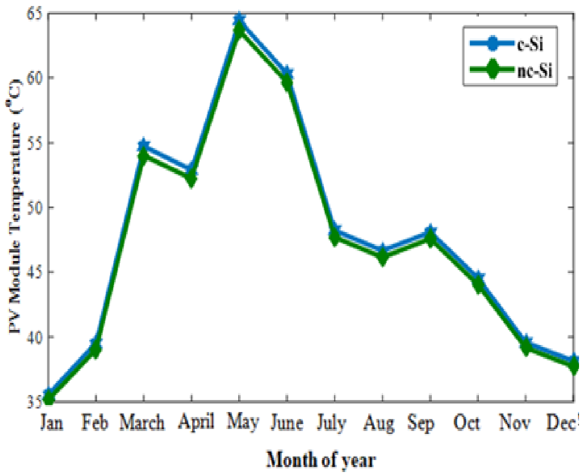

Figure 4. PV module temperature of proposed system for c-Si and nc-Si solar cell material

According to Figure 5, the mean monthly variation of temperature of fish water pond of the proposed system shows a very small variation for two PV module as c-Si and nc-Si. The maximum temperature as approximately 35°C in July/August month due to clear sky and sunshine hours and the minimum temperature is 16°C in month of January due to extremely cold weather. Figure 5 of proposed system shows the suitable result for yielding and growth of fish as they need the temperature range as 18°C to 35°C for survival.

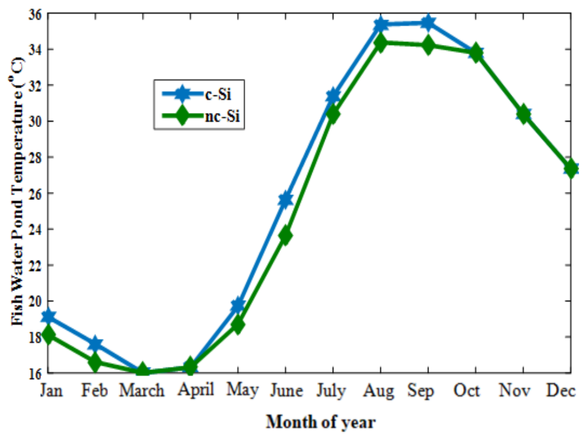

Figure 5. Fish pond temperature of proposed system for c-Si and nc-Si solar cell material

The Figure 6 illustrates the variation in water temperature for a greenhouse and a glasshouse integrated with a PVT system for c-Si and nc-Si. It can be observed that glasshouse with PVT maintains relatively higher and more stable temperatures compared to the conventional greenhouse. This improved temperature indicates that the glasshouse integrated with PVT is more suitable thermal conditions for fish yielding and growth.

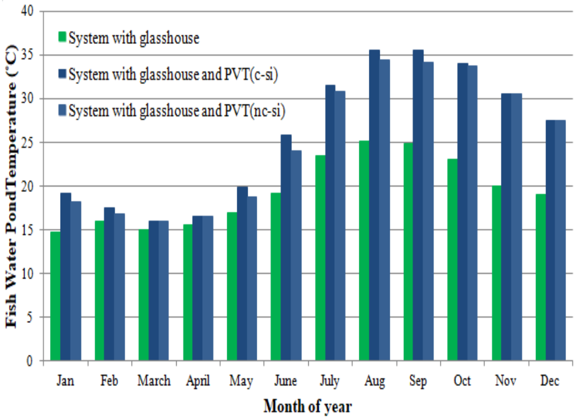

Figure 6. Comparative analysis of greenhouse system and proposed system (c-Si & nc-Si)

The Figure 7 presents a comparative analysis of Thailand and Ladakh [31]. Thailand shows a different geographical condition as shown in figure. The atmospheric temperature range of Thailand for a day is 20°C to 35°C, suitable for warm-water aquaculture, whereas Ladakh experiences significantly lower temperatures as 8°C to 18°C, which are inadequate for fish survival. The comparative analysis shows that the glasshouse integrated with PVT shows the promising result for fish survival by maintaining the temperature in cold climate of Ladakh and providing a thermal environment for sustained fish growth and survival.

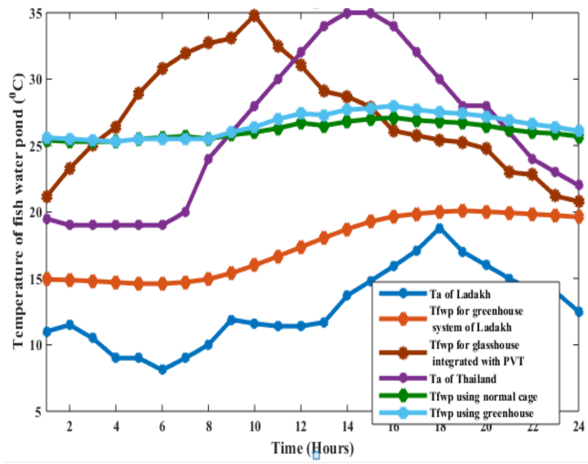

Figure 7. Comparative analysis of greenhouse existing system and proposed system

An average monthly variation of glassroom integrated with PVT system glass room air temperature for different solar cell materials is shown in Figure 7, which is lower than the solar cell temperature as in Figure 4 and higher than fish pond temperature as in Figure 5 as computed theoretically. An average monthly variation of glassroom integrated with PVT system glass room air temperature for different solar cell materials is shown in Figure 8, which is lower than the solar cell temperature as in Figure 4 and higher than fish pond temperature as in Figure 5 as computed theoretically.

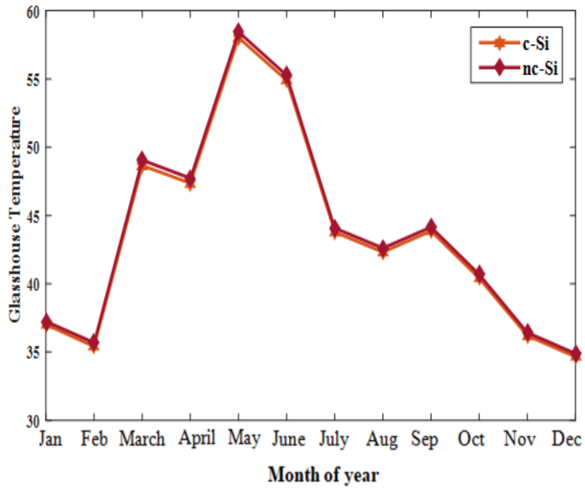

Figure 8. Glasshouse temperature of proposed system for c-Si and nc-Si solar cell

An average monthly variation of glassroom integrated with PVT system glass room air temperature for different solar cell materials is shown in Figure 8, which is lower than the solar cell temperature as in Figure 4 and higher than fish pond temperature as in Figure 5 as computed theoretically.

The Figure 4, Figure 5 and Figure 8 show that temperature of solar cells, fish water pond and glasshouse depends onto the solar intensity and atmospheric temperature. C-Si solar cells material shows better result compare to nc-Si solar cell material as in Figure 4, 5 and 7.

Figure 9 shows the solar cell efficiency which is lower in summer due to higher temperatures and higher in winter due to cooler temperatures. Further, the overall energy production is affected by both sunlight intensity and temperature. Figure 10 shows generation of monthly electrical energy which decreases during specific months due to variation in atmospheric conditions, solar intensity and sun's angle with respect to the Earth which serves as the main energy source for solar panel.

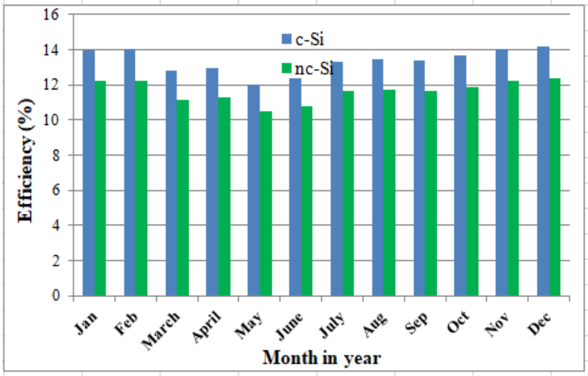

Figure 9. Average monthly variation of electrical efficiency of c-Si & nc-Si solar cell materials

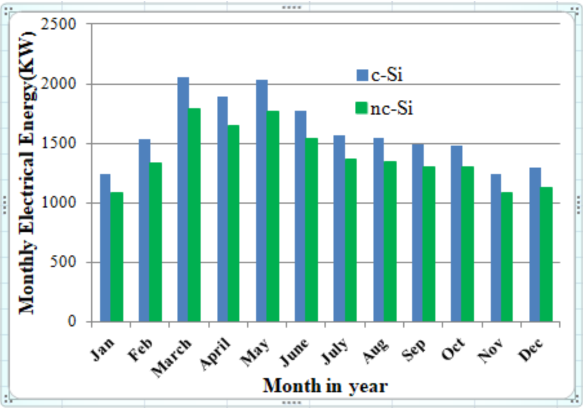

Figure 10. Average monthly variation of electrical energy of c-Si and nc-Si solar cell materials

However, the annual electrical energy for c-Si solar cells is at its highest as 2100 kWh and lowest as 1200 kWh, whereas nc-Si solar cells shows its highest value as 1800 kWh and lowest as 1100 kWh, respectively as illustrated in Figure 10.

Figure 11 and Figure 12 shows the average monthly variation of thermal energy and exergy in c-Si and nc-Si solar cells which is influenced by ambient temperature and solar irradiance, with higher temperatures generally leading to increased thermal energy loss and decreased exergy (useful energy). C-Si solar cells exhibit a higher temperature coefficient of power, meaning their efficiency decreases more rapidly with increasing temperature compared to nc-Si solar cells.

Furthermore, EPBT, EPF and LCCE of the two solar PV system as c-Si and nc-Si is reviewed with some latest PV technologies as tabulated in Table.4. This is important in making decisions of economic viability and selection of a PV module between c-Si and nc-Si material. Crystalline modules have good conversion efficiency but the primary energy they require is very high and corresponding EPBT and greenhouse gases emissions are also high whereas thin film PV modules consume less primary energy and have lower EPBT and greenhouse gases emission but their efficiency is low. A set of parameters like manufacturing process, material used, conversion efficiency, life expectancy is responsible for the variability in the performance of different installations.

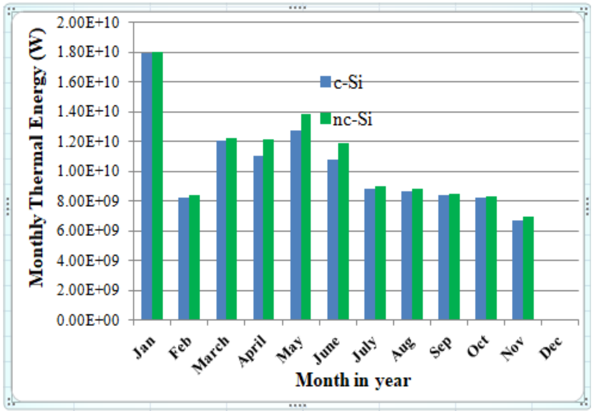

Figure 11. Monthly average variation of thermal energy of c-Si & nc-Si solar cell materials

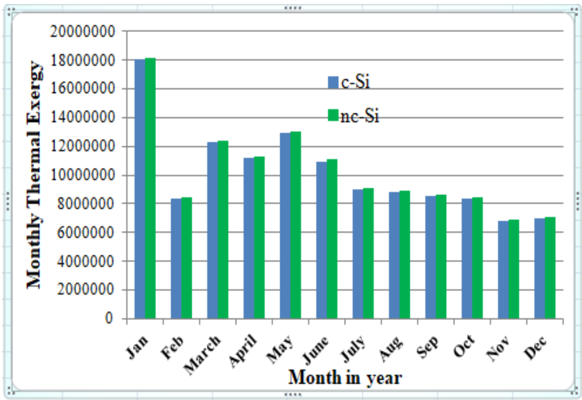

Figure 12. Monthly average variation of thermal exergy of c-Si & nc-Si solar cell materials

Table 4. Energy Metrics and Life of PV Module

Energy Matrice	Without Thermal Exergy	With Thermal Exergy	Life of PV module, n_{PV} (Yrs)	Life of PV module, n_{PV} (Yrs) Without Thermal Exergy	Life of PV module, n_{PV} (Yrs) With Thermal Exergy
C-Si					
EPBT	7.96	4.46			
EPF	3.77	6.72	30	22.04	25.54
LCCE	6.39	13.21			
nc-Si					
EPBT	8.22	5.61	25	16.78	19.39

It is visible from Table 3 that the nc-Si solar cell has a lesser energy payback time as 8.22 years compared with c-Si which shows 7.40 years. However, the life of nc-Si solar cell and c-Si solar cell is 25 years and 30 years respectively. The observation from Table 3 shows that c-Si can work 22.6 more in addition to its EPBT of 7.40 years. This means that the c-Si PV module system cost will be recovered in 7.40 years and c-Si PV solar module will generate profit for the remaining 22.5 years of its lifespan. Also c-Si solar panel needs to be replaced after every 30 years of duration which is a long time than that of glasshouse life span. Therefore, the c-Si PV module is most suitable for low-cost glasshouse.

7. Conclusions

The main objective is to design this glasshouse integrated with PVT system, a self sustainable system for cage farming of fish is required for rural areas where grid connectivity is not available. Thermal modeling of such system is not only helps in increasing the yielding and growth of fish by maintaining temperature (18˚C- 35˚C) of fish water pond in extreme cold climate of Ladakh region but also provide electrical energy to help farmers to run their daily appliances and to make their life easier and comfortable. Further from present theoretical and simulation analysis of embodied energy, energy payback time, energy production factor and LCCE analysis of the PVT modules installed onto the south roof, the following conclusions have been drawn:

i. Optimize water temperature (18˚C-35˚C) for fish survival and growth is achieved in sunshine and off sunshine hours in extreme cold climatic conditions.
ii. The result shows that optimized glasshouse structure can capture sufficient Sun radiation in winter in Ladakh region.
iii. The glasshouse temperature is more than atmospheric temperature (35˚C-58˚C) as observed from Figure 6. This acts as blanket to fish water pond and minimize the evaporation and conduction losses, maintains the temperature of water in fish water pond for longer duration which help to provide thermal comfort to fish.
iv. It is observed that solar cells temperature was higher compared to greenhouse room air temperature as expected in sunshine hours. Heating of photovoltaic increases the indirect gain to the greenhouse which further increases the greenhouse temperature in the proposed system. This slow down the cooling process of fish water pond.
v. Due to zero solar intensity after sunshine hours, the temperature of the solar cell is less than the temperature of the greenhouse and fish pond. Efficiency, electrical energy and exergy is also less in off sunshine hours as shown in Figure 7, Figure 8, Figure 9 and Figure 10.
vi. The performance of energy matrices of c-Si and nc-Si solar cell materials was assessed to determine their suitability for glasshouse integrated with PVT system.
vii. The energy payback time of c-Si PV solar module is 3.73 years for thermal energy and is 7.40 years for electrical energy whereas for nc-Si, the energy payback time is 5.61 years for thermal energy and is 8.22 years for electrical energy.

Although the proposed glasshouse-integrated PV system demonstrates promising results in maintaining optimal pond temperatures and improving energy generation, the study primarily relies on thermal modeling and simulation-based data. Real-time experimental validation across different climatic regions and seasonal conditions is yet to be performed. Factors such as long-term material degradation, humidity effects, dust accumulation, and economic scalability under field conditions were not considered in the present analysis.

Future, this research should be experimentally validated to verify model predictions and evaluate system reliability under varying climatic and geographical conditions. Hybrid configurations as integrating PVT with biogas systems can be explored to improve energy resilience. Advanced solar cell materials such as perovskite and bifacial PV modules may enhance spectral efficiency and operational longevity. Additionally, comprehensive techno-economic and environmental impact assessments at larger scales will provide valuable insights for sustainable and commercially viable aquaculture applications.

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Nomenclature and Greek Letters

A_{fwp}	Surface area of fish water pond (m^2)
A_{pp}	Area of south roof semi-transparent PV module roof (m^2)
C_{fwp}	Specific heat of water, (J/kg˚C)
E_{mon}	Monthly electrical energy (KWh)
E_{year}	Yearly electrical energy (KWh)
$E_{total,exergy}$	Total yearly exergy
EPF	Energy Production Factor

EPBT	Energy payback time
LCCE	Life cycle conversion efficiency
h_{tc}	Total heat transfer coefficient from water surface of pond to Uneven CE greenhouse room air (W/m^2 ˚C)
I_{irr}	Solar irradiation received by south roof semi-transparent PV module (W/m^2)
M_{fwp}	Mass of water in the fish pond (kg)
T_{pa}	Atmospheric temperature (˚C)
T_{pvt}	Photovoltaic module temperature (˚C)
T_{glh}	Temperature of glasshouse (˚C)
T_{fwp}	Temperature of water of fish pond (˚C)
V_{bcr}	Overall heat transfer coefficient (bottom) from back of solar cell to un-even CE glasshouse air from glass cover (W/m^2 ˚C)
$Q_{year,exergy}$	Yearly average thermal exergy
Greek letters	
α_{pp}	Absorption coefficient of PV module
β	Packing factor
τ_{gg}	Conversion factor (thermal energy to electrical energy)
η_p	Electrical efficiency of Photovoltaic module under standard test conditions
$\eta_{elect,pv}$	Instantaneous PV module electrical efficiency

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