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Theoretical Modeling of PV Integrated Greenhouse for Fish Farming

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Variation of temperature due to climatic changes affects the yield and growth of the fish in cold climatic condition. This will impact the supply of protein rich food due to reduction in aquaculture production; one of the prime sectors for providing large scale employment. In this paper, the theoretical framework using Greenhouse and photovoltaic model is presented to maintain desired temperature in the fish water pond (18˚C to 35˚C). The controlled environment is maintained inside the greenhouse for the survival of fish in harsh weather. Greenhouse room air is heated using solar radiation to minimize evaporation and conduction losses from the surface of water pond as temperature inside greenhouse is high in comparison to atmospheric temperature. Photovoltaic modules produce electrical power which is used in various applications. Various packing factors have been taken to optimize the controlled condition inside system. It has been observed that desired temperature and maximum electrical power is achieved with 0.8 packing factor. It is clear that the proposed structure not only improves fish growth rate, promotes clean environment as renewable energy is used but also provides livelihood to fish farmers.

Keywords: Fish water pond, Greenhouse, Photovoltaic module, Solar energy, Aquaculture

1 Introduction

To cater the increased demand of food due to increased population, global food production becomes a challenge now[1]. Over the last few decades, food security, climate change and complex interactions are being addressed worldwide considering the severity of this changing scenario. Moreover, rapid increase in human population further exaggerates this burning issue. Mother nature is deteriorating by increase in greenhouse gases emission day by day in the atmosphere. Climatic variations such as cyclone, drought, flood, etc. occurs in a repetitive manner. This climatic variation may be limited to a particular region or may occur across the globe. Due to this, ecosystem as well as aquatic animals suffered adversely by these variations in climatic condition due to change in the mean temperature of water and air[2]. It directly affects the growth pattern and physiological behavior of aquatic animals. Hence, variation in temperature subsequently decreases reproductive capacity and may be one of the prime reasons of mortality of aquatic animals. This has a significant impact on the financial condition of fish farmers which hampers their regular livelihood. Considering the depth of the global impact, affordable and clean energy, climate action and life below water are included in The Sustainable Development Goals (SDGs) also known as the Global Goals, adopted by the United Nations in 2015 to provide better and sustainable future by 2030[3].

Aquaculture is one of the fast-growing sectors in India and has immense potential for large scale employment for fish farmers. In India, majorly fishes like Rohu, Catla, Rani, Rawas etc. are being produced and consumed for various purposes[4]. Fish farmers are adopting traditional technologies such as reservoirs, lakes, manmade water ponds for fish cultivation which results in low productivity[5]. Fish growth is particularly impacted in the areas where the difference of temperature in day and night is large. The optimum temperature for the fish to thrive is in the range of 18°C - 35 °C[6]. Large variation of temperature of water pond slows down the yielding and growth of fish. As a result, the price of fish increases 50-80 % from regular price in winter season[7].

One of the techniques to enhance the growth of fish is to maintain temperature by heating of fish water pond. This can be done using fossil fuel which increases greenhouse gases in an environment. At present, approximately 80 % of global energy demand is met by non-renewable fossil fuel resources[8]. Since the effects of global warming have become more severe globally, it is imperative that countries work together to develop renewable energy sources to cut greenhouse gas emissions[9-10]. According to the

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International Environmental Agency, approximately 25 % of global electricity generation is expected to come from photovoltaic panels by 2050[11]. This electrical energy can be stored in battery energy storage system (BESS) which is having ability to provide this energy for later use[12]. Capturing of solar thermal energy to heat the water inside fish water pond is the most excellent scientific approach for clean environment. This is achieved by using close structure as cage method made of wood, plastic etc. which traps the Sun energy to heat the water and maintain the temperature inside the fish water pond to increase the quantity and quality for culturing fish[13]. Fish cages are insulated to minimize heat losses during off sunshine hours and manage water temperature of fishpond for longer duration[14]. Evaporative loss (heat) in the atmosphere has been minimized by covering the water surface using canopy covers made by plastic materials[15].

Few researchers have attempted the issue of maintaining the temperature of water pond so that almost constant temperature is provided to the fishes irrespective of varied climatic conditions. In the proposed system, an innovative and cost-effective approach is suggested to maintain the optimum temperature using greenhouse and photovoltaic module integrated together for fish farming. Greenhouse structure helps to trap the heat coming from Sun and increases the temperature of fish water pond.

Also, this proposed system maintains the temperature of water pond in off sunshine hours to the desired level, give thermal comfort to the fish even in cold climate and increase yielding and production of fish to meet the high demand due to increase in population. Photovoltaic module aid to maintain clean environment and provide electrical energy which is used by the farmers to run various appliances as fan, light, pump etc. and to optimize the evaporation and heat losses, promoting sustainability. As the proposed system is independent of grid supply, this configuration will be a boon to small fish farmers in rural areas for increasing their livelihood which is the prime goal of one of SDGs.

2 System Description

The proposed system is designed to enhance production of Indian fisheries of length up to 60 centimeters in extremely cold climatic condition for the month of February in Ladakh. The schematic diagram of water pond with dimension as 24.4 m x 12.2 m x 1.8 m is used for production of fish in which photovoltaic module are used as shown in Fig. 1. Water pond absorbs solar radiation during sunshine hours and convert solar radiation into heat energy during daytime, increases the temperature of water pond to the desired value required for growth of fish[16]. The losses shown in Fig. 1 will act as gain using greenhouse technology as passive system.

In this proposed system, greenhouse and photovoltaic module is used. South roof of uneven shape of greenhouse is covered with photovoltaic module to receive maximum solar radiation in sunshine hours. Greenhouse receives two gain as direct and indirect gain as shown in Fig. 1. Direct gain is achieved from solar radiation through PV modules' non packing area and indirect gain is obtained from the bottom of PV module in terms of thermal energy. Thus, the water of fish water pond gets heated from both direct and indirect gain. The greenhouse helps to reduce the heat loss of water to the environment as ambient temperature is always less than that of the greenhouse temperature as shown in Fig. 1.

Photovoltaic module provides an electrical energy which can be used by fisherman for running the appliances. The temperature of water of fish water pond is maintained in desired range during off shine hours to provide thermal comfort to fish in the pond. Table 1 shows the design parameters and specifications used for greenhouse technology integrated with photovoltaic thermal system for growth of fish.

3 Modeling and Methodology of Proposed System

A theoretical model has been developed in the present analysis for the fish water pond using hourly average data of solar radiation intensity during sunny hours (from 7.00 am till 5.00 pm), atmospheric temperature, velocity of wind etc. obtained from meteorological department for the month of February

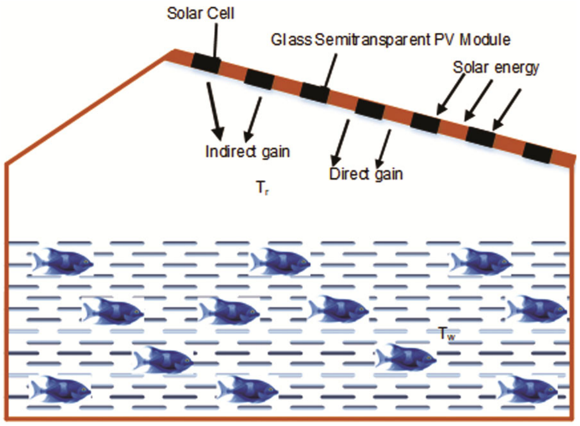

Fig. 1 — Greenhouse and photovoltaic module integrated together in fish water pond

Table 1 — Design parameters and Specification of Greenhouse and Photovoltaic module integrated together for Fish Farming[7, 8, 13, 14]

Aperture area of south side photovoltaic module mounted on roof (A_{pp})	245.05 m^2
Specific heat of fish water pond (c_w)	4190 J/kg
Heat transfer coefficient from water surface of fish water pond to greenhouse room (h_{tc})	5.7 W/m^2 °C
Thermal conductivity of glass (Kg)	0.816 W/m K
Glass cover thickness (L_g)	0.003 m
Mass of water in fish 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 in photovoltaic module (P_{Vpf1})	0.3782
Penalty factor obtained due to absorptive plate placed at the bottom of photovoltaic module (P_{Vpf2})	0.7805
Surface area of fish water pond (A_{fwp})	37.12 m2
An overall heat transfer coefficient from the bottom of photovoltaic module to greenhouse room from transparent glasses (V_{bcr})	5.6789 W/m^2 °C
An overall heat transfer coefficient from the top of photovoltaic module to atmosphere from transparent glasses (V_{tca})	9.1794 W/m2 °C
Absorption coefficient of photovoltaic module (app)	0.9
Packing factor of photovoltaic module (β)	0.8
Under Ground temperature beneath the fish water pond (T_0, g)	10°C

of Ladakh. The average ambient temperature of Ladakh in the month of February is 10°C.

Assumptions are considered for greenhouse and photovoltaic module integrated together for fish farming system and characteristic equations are developed from energy balance equations. They are as:

i The proposed system is based on quasi state condition by considering hourly variation obtained from meteorological department, Pune, India.
ii Optimizing the design parameters by creating a thermal characteristic equation.
iii Maximizing a roof PV module's packing factor to achieve the required thermal and electrical energy.
iv Designing greenhouse integrated with photovoltaic system for aquaculture.

3.1 Photovoltaic Thermal Module Mounted on South Roof of Greenhouse

The energy balance equation for photovoltaic thermal module which is mounted on the greenhouse south roof is given as the rate of absorption of solar energy by photovoltaic thermal module is equal to the rate of thermal energy lost from photovoltaic thermal module to greenhouse from the back of glass, rate of thermal energy lost from photovoltaic thermal module to atmosphere from the top of glass and the rate of electrical energy generated by photovoltaic thermal module.

The energy balance equation for the photovoltaic thermal module which is mounted on south roof of greenhouse is written as[17]:

$$\alpha_{pp}\tau_{pp}\beta A_{pp}I_s(t)=V_{tca}(T_{pv}-T_a)A_{pp}+V_{bcr}(T_{pv}-T_{gh})A_{pp}+\eta_{pp}\tau_{pp}\beta A_{pp}I_s(t) \quad \ldots (1)$$

The temperature of photovoltaic thermal module (T_{pv}) is calculated using Eq. (1) as:

$$T_{pv}=\frac{\tau_{gg}\beta(\alpha_{pp}-\eta_{pp})I_s(t)+V_{tca}T_a+V_{bcr}T_{gh}}{V_{tca}+V_{bcr}} \quad \ldots (2)$$

3.2 Greenhouse Room Air Energy Balance Equation

Greenhouse room air energy balance equation is the addition of rate of gain of thermal energy obtained from photovoltaic thermal module to greenhouse room air from the bottom of the glass and the rate of gain of thermal energy from the top surface of fish water pond from greenhouse room air to atmosphere through the glass walls and north glazed roof.

The greenhouse room air energy balance equation can be formulated[18] as:

$$V_{bcr}(T_{pv}-T_a)A_{pp}+h_{tc}(T_{fwp}-T_{gh})A_{fwp}=\sum_{i=1}^{5}A_iV_i(T_{gh}-T_a) \quad \ldots (3)$$

Greenhouse room air temperature is obtained using Eqs. (1) and (2) as:

$$T_{gh}=\frac{PV_{PF1}\beta A_{pp}(\alpha_{pp}-\eta_{pp})I_s(t)+h_{tc}A_{fwp}T_{fwp+}V_{ra}A_{pp}T_a+\sum_{i=1}^{5}A_iV_iT_a}{h_{tc}A_{fwp}+V_{ra}A_{pp}+\sum_{i=1}^{5}A_iV_i} \quad \ldots (4)$$

where

$$PV_{pf1}=\frac{V_{bcr}}{V_{bcr}+V_{tca}}$$

Here PV_{pf1} is known as penalty factor of PV module made of glass.

3.3 Fish Water Pond Energy Balance Equation

Water pond itself is a good collector of thermal energy obtained from Sun. The Sun radiation intensity is absorbed by fish water pond and stored as thermal energy called as direct gain given as[19]:

$$Q_{fwp} = \alpha_{fwp} I_s(t) A_{fwp} \quad \ldots (5)$$

where $\alpha_{fwp}$is the absorptivity of fish water pond, (t) is total solar radiation intensity in sunshine hours (beam + diffused) and A_{fwp} is the area of fish water pond.

The summation of rate of thermal energy transmitted from ground level to fish water pond, the rate of Sun irradiation transfers to fish water pond as direct gain from the non-packing area of photovoltaic module and the rate of solar irradiation transmitted from glass walls to water pond of fish must equalize to the addition of the rate of thermal energy which is stored in fish water pond and the rate of thermal energy transferred from greenhouse room air to fish water pond. The fish water pond energy balance equation can be written as[20]:

$$\sum_{k=1}^{5} A_k V_k (T_{0,g} - T_{fwp}) + \tau_{pp}^2 (1-\beta) A_{pp} I_s(t) + \tau_{pp}^2 \sum_{j=1}^{3} A_j I_j = M_{fwp} C_w \frac{dT_{fwp}}{dt} + h_{tc}(T_{fwp} - T_{gh}) A_{fwp} \quad \ldots (6)$$

Here $\tau_{pp}^2 \sum_{j=1}^{3} A_j I_j$ is considered as 0 as it's assumed as complete absorbed Sun radiation is exposed either using opaque walls of greenhouse or using north roof[21].

Equation (6) can be rearranged using Eqs. (2) and (4) as:

$$\frac{dT_{fwp}}{dt} + S_{fwp} T_{fwp} = S(t) T_a \quad \ldots (7)$$

Where

$$S_{fwp} = \frac{(VA)_{fwp} + \sum_{k=1}^{5} A_k V_k}{M_{fwp} C_w}, S(t) = \frac{(MA)_{11} + (MA)_{22} T_a}{M_{fwp} C_w} \quad \ldots (8)$$

Where

$$MA_{11} = \left\{ \tau_{pp}^2 (1-\beta) A_{pp} + PV_{pf2} A_{pp} (\alpha\tau)_{wfp,eff} \right\} I_s(t) + \tau_{pp} \sum_{j=1}^{3} A_j I_j \quad \ldots (9)$$

and

$$(MA)_{22} = (VA)_{fwp} + \sum_{k=1}^{5} A_k V_k \;,$$

$$(VA)_{fwp} = \frac{h_{tc} A_{fwp} (V_{ra} A_{pp} + \sum_{i=1}^{5} A_i V_i)}{h_{tc} A_{fwp} + V_{ra} A_{pp} + \sum_{i=1}^{5} A_i V_i}$$

$$(\alpha\tau)_{wfp,eff} = PV_{pf1} \tau_{pp} \beta (\alpha_{pp} - \eta_{pp}) \quad \ldots (10)$$

$$PV_{pf2} = \frac{h_{tc} A_{fwp}}{h_{tc} A_{fwp} + V_{ra} A_{pp} + \sum_{i=1}^{5} A_i V_i} \quad \ldots (11)$$

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 calculated as:

$$T_{fwp} = \left[\frac{(MA)_{11}}{(MA)_{22}} + T_a \right] \times (1 - e^{-at}) + T_{fwp0} e^{-at} \quad \ldots (12)$$

Theoretically, temperature of greenhouse room air and photovoltaic cell can be obtained using Eqs. (2) and (4), after knowing fish water pond temperature using Eq. (12).

3.4 Instantaneous Electrical Efficiency, Energy and Exergy

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

$$\eta_{elect,pv} = \tau_{pp} \eta_{pp} \left[1 - \beta (T_{fwp} - 18) \right] \quad \ldots (13)$$

where η_{pp} is the standard photovoltaic cell electrical efficiency considered as 0.15[23, 24]. The shape of the greenhouse structure affects the capture of solar radiation[25].

The copper losses between the photovoltaic cells are considered negligible. The PV module's hourly electrical energy output also gets affected with installation of photovoltaic cell and greenhouse structure[26, 27] and is given as:

$$E_{pv,hourly} = \eta_{elect,pv} \times I_s(t) \times \beta \times A_{pp}(W) \quad \ldots (14)$$

The daily electrical energy generated by PV module is calculated in Wh as[28]:

$$E_{pv,daily} = \sum E_{pv,hourly} \quad \ldots (15)$$

The overall daily exergy is the combination of hourly thermal energy ($Q_{thermal}$) and hourly electrical energy ($E_{pv,hourly}$). $Q_{thermal}$ (hourly) is calculated as:

$$Q_{thermal} = M_{FWP}c_w[(T_{FWP} - T_{FWP,0}) - (T_a + 273) In \frac{T_{FWP,\max} + 273}{T_{FWP,\min} + 273} \quad \ldots (16)$$

and overall daily exergy is given as[29]:

$$E_{exergy} = Q_{thermal} + E_{pv,hourly} \quad \ldots (17)$$

4 Results and Discussion

The Indian Meteorological Department (IMD), located in Pune, India, provided the meteorological data for Ladakh. The hourly global solar radiation as I_s (t) is shown in Fig. 2 and atmospheric air temperature as T_a is shown in Fig. 3. The minimum temperature of Ladakh is 8˚C in nighttime and maximum temperature is 18˚C in daytime for the month of February as depicted in Fig. 3. The mean value of atmospheric temperature and solar intensity is computed to obtain theoretical temperature parameters. Moreover, substantial amount of heating is needed to increase the temperature of water of fish water pond for survival of fish in this cold weather condition. The solar radiation received only for 8 hours is shown in Fig. 2. Water stores sufficient thermal energy to maintain the temperature of water to desired range as 18˚C - 35˚C in off sunshine hours for survival of fish as water takes longer duration to cool down due to larger volume.

Water can be used as a thermal energy storage material and this energy is calculated using Eq. (5) as water has fluid properties which does not undergo a chemical change when it is heated[30]. In this regard, Eq. (13) is used for calculating the temperature of fish water pond used for aquaculture by considering climatic variations and design parameters by outlined in Table 1. Initially a huge amount of thermal energy is needed to raise the temperature of fish water pond. Since the solar intensity is available after 7:00 am and very low when sun rises and increases as the day progresses, increases the temperature of water pond to maximum value as 35˚C with minimum value as 16˚C which is the best suited temperature for fish survival as shown in Fig. 4. Water pond temperature drops slowly in off sunshine hours due to large volume of water as it will take more time to lose its thermal energy. Temperature of water pond will again gain thermal energy as Sun will come again and maintain the water temperature as above 16˚C-17˚C.

These calculations are presented in Figs. 4 and 5 for variable packing factor β. Figs. 4 and 4 shows the suitable result for pisciculture for optimum temperature for survival and growth of fish for packing factor β=0.8.

Hourly varied photovoltaic cell temperature and greenhouse air temperature is estimated using Eqs. (2) and (3) and Fig. 4 shows the corresponding experimental results obtained after simulation using MATLAB 2015a. It is visible from the Fig. 4 that the photovoltaic cell maximum temperature is 55˚C in sunshine hours and 10˚C in off sunshine hours. This show as the consumer has to decide its priority based on application between thermal and electrical energy before PVT installation.

However, temperature of greenhouse room air is approximately same as the fish water pond temperature due to the low heat capacity of air. Furthermore, temperature of greenhouse room air is more than that

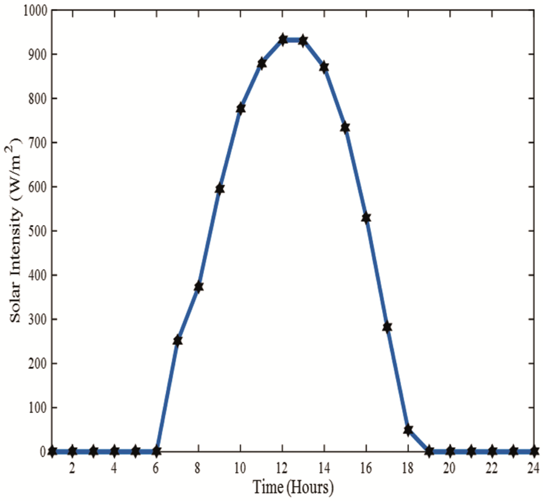

Fig. 2 — Hourly variation of solar intensity for February month of Ladakh

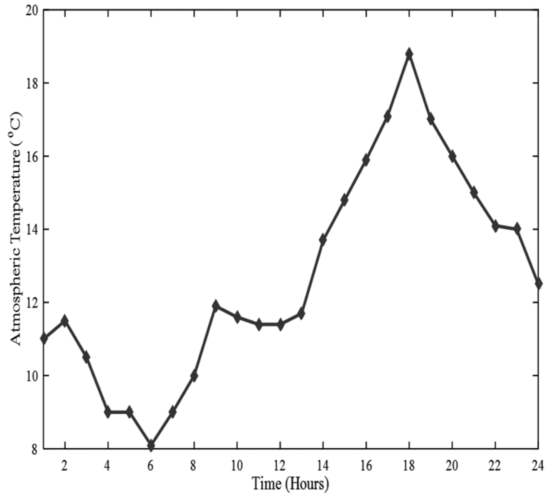

Fig. 3 — Hourly variation of atmospheric temperature of February month of Ladakh

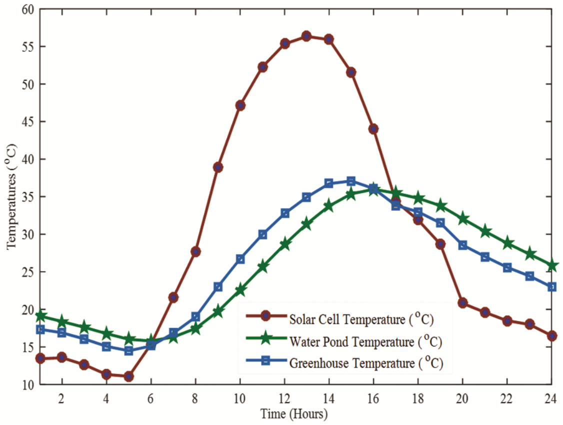

Fig. 4 — Temperature of solar cell, fish water pond and greenhouse room air

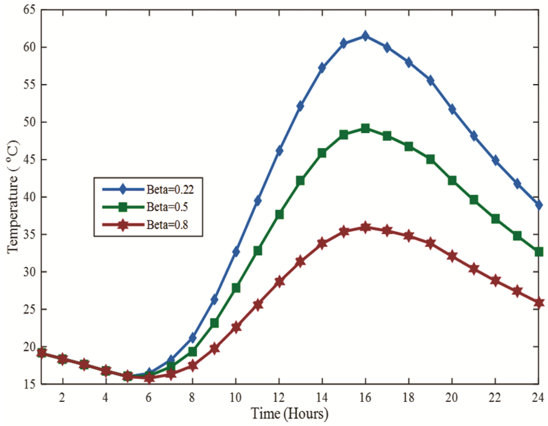

Fig. 5 — Temperature of fish water pond for variable packing factor

of atmospheric temperature and acts as hot cover to the water pond and it reduces evaporation and conduction losses as a result. Greenhouse acts as a blanket for water pond to store the thermal energy for a longer duration in off sunshine hours, even when the atmosphere temperature is below 10˚C as shown in Figs. 3 and 4. Also, the indirect losses coming in terms of heat from back surface of photovoltaic thermal increases the temperature of greenhouse as in Fig. 4.

Figure 6 present the hourly and daily variation of the electrical energy without grid, obtained using Eqs. (15) & (16). Figure 7 show the efficiency of the proposed system calculated using Eq. (14). It is observed that the higher value of solar cell temperature, which is greater than 55 °C as illustrated in Fig. 4, makes the significant electrical power obtained after 12 noon more practical and beneficial. The partial electrical power obtained during sunny hours can be stored in the battery so that it can be used during nighttime by farmers in rural areas for running appliances. The maximum efficiency of the proposed system is also seen after 12 noon.

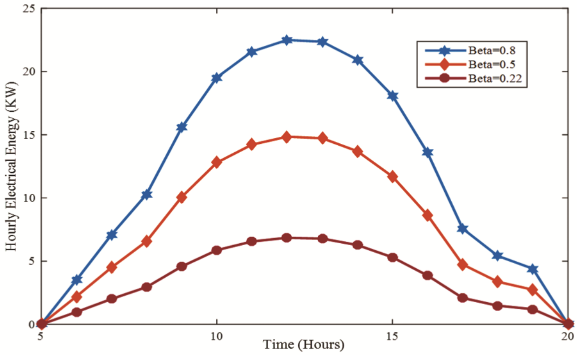

Fig. 6 — Hourly electrical energy for variable packing factor

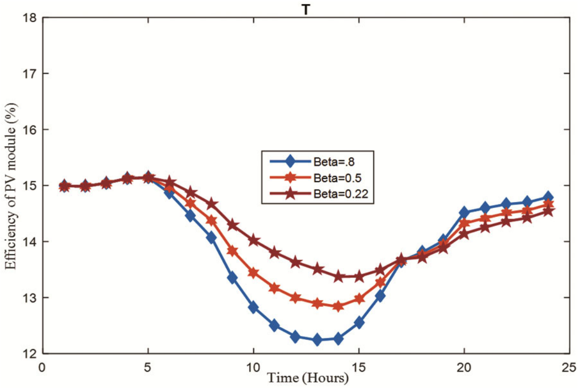

Fig. 7 — Efficiency for variable packing factor

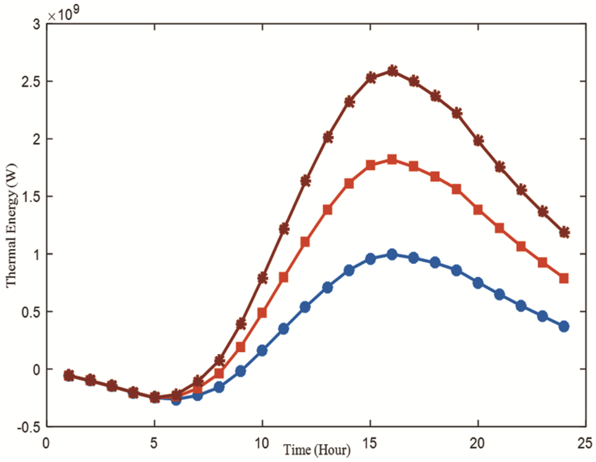

Fig. 8 — Thermal energy for variable packing factor

In the proposed system, the thermal energy calculated using Eq. (17) is having higher priority as compared to electrical energy to heat the water of fish water pond. The maximum thermal energy is achieved for the packing factor of 0.8 as depicted in Fig. 8. Further, Fig. 9 shows that exergy increases with decrease of packing factor due to more generation of

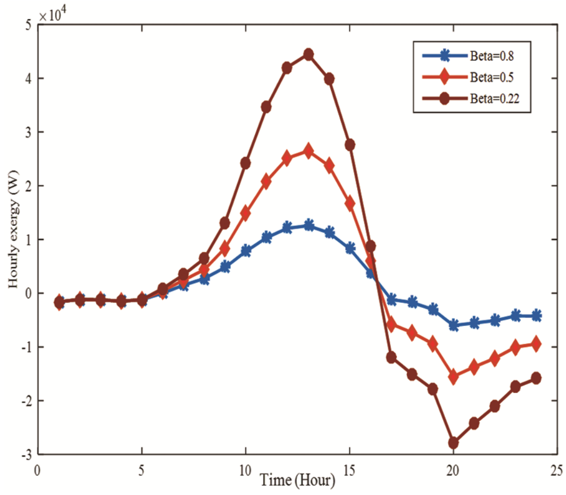

Fig. 9 — Energy for variable packing factor

electrical energy. Also hourly exergy dominates at lower value of packing factor, but exergy shows less variation at 0.8 packing factor in off sunshine hours as shown in Fig. 9.

5 Conclusion

Fish flourish in a controlled and steady temperature environment, which enhances their digestion and metabolic rate. The primary objectives of this proposed Greenhouse and Photovoltaic Module integrated system is to make it self-sustainable in terms of electrical and thermal energies to meet the requisite of pisciculture. Following conclusion is drawn for the proposed system based on the observed findings:

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 for packing factor β=0.8.

ii The result shows that optimized greenhouse can capture sufficient Sun radiation in winter in Ladakh region which can act as blanket for survival and growing fish to meet the demand of protein rich food.

iii Optimized temperature inside greenhouse slow down the cooling process of water pond due to large variation between atmospheric temperature and greenhouse room air temperature.

iv It is observed that solar cells temperature (55˚C) was higher compared to greenhouse room air temperature (36˚C) as expected in sunshine hours.

v Due to zero solar intensity after sunshine hours, the temperature of the solar cell is less than the temperature of the greenhouse air and aqua pond water.

vi Maximum electrical energy (23 KW) is obtained for the time duration of 8 hours in sunshine hours for packing factor β=0.8 as shown in Fig. 6. This energy is used by the farmers for running appliances.

Although the proposed glasshouse-integrated PV system demonstrates promising performance in maintaining optimal pond temperatures and enhancing energy generation, the present study is primarily based on thermal modeling and simulation results. The present work is also having the application as outdoor swimming pool. Comprehensive real-time experimental validation under diverse climatic zones and seasonal variations remains to be conducted.

Future research should therefore focus on extensive experimental investigations to validate the model predictions and assess the long-term reliability, durability, and techno-economic feasibility of the system across different climatic and geographical regions.

Nomenclature

T_a: Atmospheric temperature (˚C)
T_{pv}: Photovoltaic module temperature
T_{gh}: Greenhouse room temperature
T_{fwp}: Fishpond water temperature
$I_s(t)$: Solar Intensity received by Photovoltaic module mounted on south roof (W/m^2)
$E_{H.FSH}$: Hourly thermal energy of fish water pond (W/m^2)
$E_{H,Thermal}$: Hourly thermal exergy of fish water pond (W/m^2)
$E_{xH,thermal}$: Overall Hourly thermal exergy (W/m^2)
P: Water density (kg/m3)
Z_{pp}: Conversion factor (thermal energy to electrical energy)
η_0: Photovoltaic module electrical efficiency under standard test conditions
$\eta_{elect,pv}$: Instantaneous Electrical efficiency of Photovoltaic module

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