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CONCEPT AND DESIGN OF A SOLAR POWERED FLORICULTURE GREENHOUSE WITH FUEL CELL BACK UP

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ABSTRACT

Greenhouse technology is an effective method of cultivation of flowers, vegetables and horticultural plants under controlled environment. This paper presents a typical design of a floriculture greenhouse suitable for use in hot and humid climate. Solar photovoltaic panels on part of canopy area enable the greenhouse to generate power to feed the drives. Excess power during peak sunshine hours is used to generate hydrogen in a electrolyzer bank, and the stored hydrogen is consumed by a fuel cell stack during night hours to support minimum lighting loads. The performance analysis reveals that by using a proper combination of evaporative cooling, shading and ventilation arrangements the inside micro-climatic can be maintained within permissible limits throughout the year. Coupling of hydrogen generating device and fuel cell with solar photovoltaic system ensures availability of power day and night, making the greenhouse system suitable for use in areas away from electrical grid.

Keywords: Greenhouse, Solar photovoltaic, Hydrogen, Fuel cell.

1. INTRODUCTION

Greenhouse technology is one of the methods of controlled environmental cultivation to increase the agricultural output by creating a barrier between the environment and the plant microclimate. The extent of control required varies depending upon the nature of crop, geographical location of the place and its prevailing climatic condition. The plant growth is influenced by several factors such as availability of light, carbon dioxide, water, the prevailing temperature and the humidity. The growth is retarded or even stopped when one of the factors become restrictive [1,2]. In India plenty of solar radiation is available and the climate in most of the plain and highland regions is dry and hot, with coastal regions witnessing a hot and humid climate for most part of the year. The excessive hot and humid climate is detrimental to the growth of crops, especially flowers. Floriculture has got a tremendous potential in India and also in other countries in the subcontinent. A number of floral plants are cultivated in the subcontinent but the yields and qualities are restricted by the inherent limitations of the traditional open field cultivation usually practiced by the growers who are mostly from low-income groups. Implementing greenhouse technology that makes use of local and low-cost materials can effectively boost the floriculture industry, giving increased quantity of quality products for sale in regional, national and even in international markets.

This paper presents a typical design of a floriculture greenhouse employing evaporative cooling, mechanical as well as natural ventilation and shading systems to maintain the desired microclimate inside the greenhouse round the year. The study is based on ambient data for Kolkata, a location that represents a mixed climate for hot-dry and hot-humid areas. Roof–top solar photovoltaic panels enable the greenhouse to generate power independently for the drives of the fans and pumps. Excess power generated during peak sunshine hours is used to generate hydrogen in a bank of electrolyzers and the stored hydrogen is consumed by a proton exchange membrane (PEM) fuel cell during night hours to support lighting loads. The concept is highly relevant to the rural development in regions where extreme climates restrict floricultural outputs and where considerable portion of farming land is still far away from the power grid.

A lot of research and development works have been carried out on greenhouse and related technologies for decades together and quite a good number of publications are available in the literature. Tiwari [2] and Tiwari et.al [3] presented a detailed analytical approach for thermal design of a greenhouse taking into consideration a number of factors and using different configurations of greenhouse. Pieters et.al [4] investigated the relative importance of the parameters that influence the solar energy collecting efficiency of greenhouses under western European conditions. Kittas et.al [5] studied the temperature and humidity gradients in a commercial greenhouse producing cut roses equipped with ventilated cooling pad systems and a half shaded plastic roof. Ghosal *et.al* [6] presented a detailed thermal modeling of a floriculture greenhouse considering Indian climatic condition.

2. MODELING AND ANALYSIS

The general arrangement of the greenhouse is shown in Fig1. The East-West oriented greenhouse has the dimensions of 25m(L) x 8m(W) x 3m(H). The canopy of the greenhouse is ridge type, with the part inclined due south housing the photovoltaic panels on top of the same. Cooling pads and horizontal fans are located on the opposing end walls. Windows on the longer walls and ridge vents are provided to augment natural ventilation when fans are not in use. The following sections present the modeling and analysis strategies for the thermal aspect and the power management aspect separately.

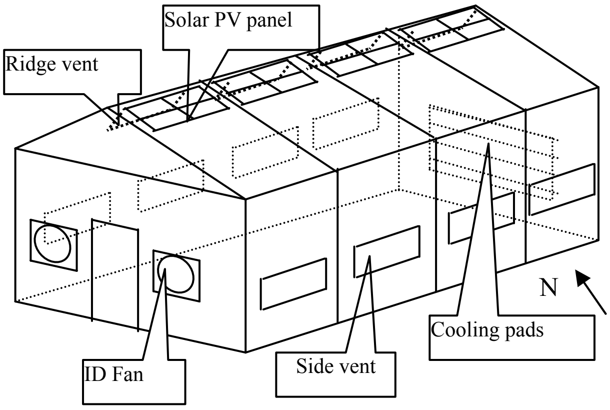

Fig 1. General arrangement of the greenhouse

2.1 Thermal Modeling

While developing the thermal model for the greenhouse system, the following assumptions were made:

Location: 22.39^0N, 88.27' E (Kolkata, India)
Configuration: Even span, ridge type
Covering material: Fibre Reinforced Plastic (FRP)
Transmissivity of the coverings: 0.8
Saturation efficiency of cooling pad: 0.85 to 0.88
Efficiency of solar photovoltaic cell: 25 %
Efficiency of PEM Fuel Cell: 55 %
Electrolyser Efficiency: 80 %
Lighting Load: 0.3 W/m^2
Effect of structural elements other than coverings and shadings on heat transfer is neglected.

The total incident solar radiation on different surfaces of greenhouse is calculated using recorded radiation data for the assumed location and considering the solar radiation geometry for the relevant surfaces.

The rate of incident solar radiation for any surface is given as

$$I_t=I_b \times R_b + I_d \times R_d + (I_b + I_d) \times R_r \qquad (1)$$

Where I_b and I_d are intensities of beam and diffuse radiation and R_b, R_d and R_r are radiation tilt factors for beam, diffuse and reflected radiation respectively for a surface. The tilt factors are determined from the radiation geometry data of the concerned surfaces and can be calculated from parameters such as declination angle (□), hour angle (□), surface tilt angle (□) etc.[7]. The total incoming radiation into the greenhouse is thus given by

$$Q= \sum A_i .I_{ti}. \square_i \qquad (2)$$

where A_i is the area of the surface 'i'. I_{ti} and $\square_i$ are total incident radiation flux and transmissivity respectively of the 'i'th surface. Effective heat flux through the greenhouse coverings for an elemental length dl of the greenhouse is given by [8]

$$dQ = \{\tau_c S_c.(I_{t\cdot N}+I_{t\cdot S}).p + \tau_w S_w I_d 2H \}dl \qquad (3)$$

where, p is the half-perimeter of the canopy, S is the shading factor and the subscripts 'c' and 's' stand for canopy and side wall respectively. A part of this heat flux is absorbed by the plants, a part is transferred to the outside environment through the coverings. The rest may be considered as the effective cooling load, and heat energy equivalent to this load is to be carried away by the air ventilated across the greenhouse.

The temperature (T_x) inside the greenhouse at a distance x from the cooling pad end can be determined by considering a thermal equilibrium condition of the elemental length dl at the said distance and may be described by the relation [5, 8]

$$V\rho c_p.(T_x-T_p) = \int\{\tau_c S_c.(I_{t\cdot N}+I_{t\cdot S}).p + \tau_w S_w I_d 2H \}(1-\alpha.C)dl - \int K.2(p+H)dl(T_x-T_a) \qquad (4)$$

where, α is plant absorptivity, C is the factor for ground coverage for plants, ρ is the density of air and V is the ventilation rate given by

$$V= (ACM.\ L.W.H)/60 \qquad (5)$$

where, ACM is the air change per minute for the greenhouse. The contribution of beam radiation through the vertical walls is very small compared to the total radiation, particularly at the peak radiation hours and therefore can be neglected for design point analysis.

Assuming the same transmissivity and shading for all surfaces, the maximum temperature inside the greenhouse may also be estimated from the relation

$$V\rho c_p(T_{g.max} -T_p) = \tau S.(A_{c.N} I_{t.N} + A_{c.S}.I_{t.S} + A_s.I_d).(1-\alpha.C) - K(A_c+A_s).(T_{g\cdot max}- T_a) \qquad (6)$$

where A_c and A_s are the areas of canopy and side walls respectively.

The average greenhouse temperature (T_g) is obtained from the temperature of the cooling pad and the maximum greenhouse temperature as

$$T_g=(T_{gmax} - T_p)/2 \qquad (7)$$

For natural ventilation, temperature of the cooling pad is irrelevant and ambient temperature is to be considered instead. Further, for natural ventilation no fan is in operation and the rate of ventilation may be estimated based on measured air velocity data for the vent openings or using a CFD modeling. In the present analysis the natural ventilation rate is assumed based on an analysis reported by Campen and Bot [9].

2.2 Modeling of Power System

The power consumption for the fans and the circulating water pump is estimated from the volume flow rate and pressure drop of the fluids in the respective equipment, allowing for losses in the drives.
Power generated by the solar PV panels is estimated as

$$P_{PV} = A_{PV}.I.\eta_{PV} \qquad (8)$$

where, A_{PV} is the total PV panel area and η_{PV} is the conversion efficiency of the PV panels.

During sunshine hours, The power generated by the PV panels (P_{PV}) is directly consumed by the fan and pump drives and any excess power is fed to the electrolyzer bank that produces hydrogen through electrolysis. The rate of energy (Es) thus stored in the product gas is given by

$$Es = P_{PV}.\ \eta_e \qquad (9)$$

where, η_e in the conversion efficiency of the electrolyzer. During off-sunshine hours, the stored gas is consumed by the PEM fuel cell stack. Power produced (P_{FC}) by the fuel cell is given by

$$P_{FC} = Es.\ \eta_{FC} \qquad (10)$$

where, η_{FC} is the overall efficiency of the fuel cell.

3. PERFORMANCE ANALYSIS AND DISCUSSION

Computer codes were developed based on the thermal model presented above to simulate the performance of the greenhouse. In this analysis, attention is particularly focused on the feasibility of integration of PV modules and fuel cell with the thermal greenhouse and on the overall performance of the integrated system. Considering this aspect, an overall performance analysis of the integrated system in a representative summer day in the month of April is presented here.

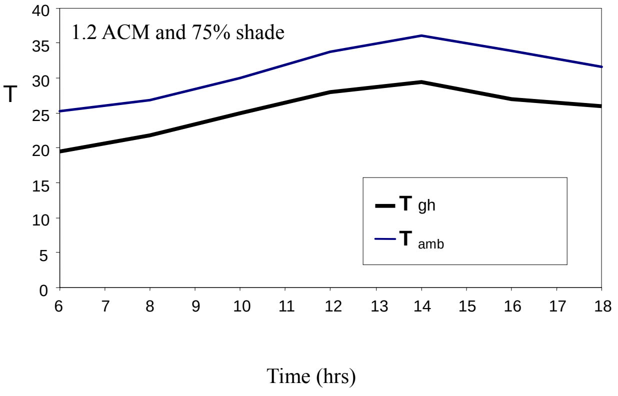

Fig 2. Hourly variation of the ambient and greenhouse temperatures in a representative summer day in April.

The hourly variation of greenhouse inside temperature in a representative summer day in April is shown in Fig.2. From the graph it is seen that the maximum temperature inside the greenhouse can be limited to 30^{o}C when the ambient temperature is 36^{o}C (RH being 50%) using fan pad evaporative cooling and 75% shading.

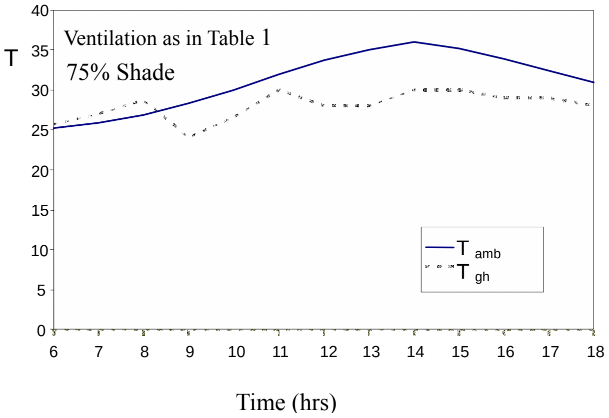

Fig 3. Hourly variation of the ambient inside temperature in April employing different modes of operation as per Table 1**.**

Calculations reveal that during peak hours when both ID fans are in operation along with the circulating water pump for the cooling pads, total power consumption exceeds 700W. In order to reduce total energy consumption for a whole day, different modes of operation may be implemented at different hours of the day, depending upon the prevailing ambient temperature and solar radiation intensity. Table 1 shows an operation philosophy employed in a summer day when natural ventilation or part ventilation (fan) is used at non-peak hours.

Table 1: Hourly temperature and modes of operation for the greenhouse for a summer (April) day

Time of day (hrs)	Ambient temp. (^{o}C)	Max. GH temp. (^{o}C)	Ventilation type
6	25.2	25.7	Natural
7	25.8	27.0	Natural
8	26.8	28.7	Natural
9	28.3	24.0	1 Fan & CWP
10	30.0	26.6	1 Fan & CWP
11	31.9	30.0	1 Fan & CWP
12	33.7	28.0	2 Fans & CWP
13	35.1	28.0	2 Fans & CWP
14	36.0	30.0	2 Fans & CWP
15	35.2	30.0	1 Fan & CWP
16	33.9	29.0	1 Fan & CWP
17	32.5	29.0	1 Fan & CWP
18	31.0	28.0	1 Fan & CWP

The variation of greenhouse inside temperature with respect to ambient temperature during the representative summer day is redrawn in Fig.3 where above-mentioned operational philosophy is implemented. It is seen that the greenhouse inside temperature is maintained within the range 24°C – 30°C, although at some times the inside temperature is more than the ambient.

Figure 4 shows the hourly variation of panel insolation I_t (W/m2) for a typical summer day in the month of April. From the figure it is seen that for a considerable part of the day the insolation level is in excess of 600 W/m^2 and a total of 7.33 kWh energy is available per sq.m. of panel.

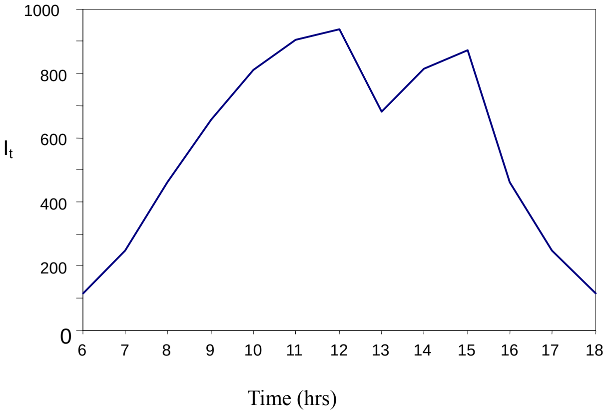

Fig 4. Hourly variation of panel insolation I_t (W/m^2) for a typical summer day in the month of April.

This amount of solar energy would generate about 7 kWh of electrical energy from a total panel area of 3.75 m^2 during the sunshine hours, well exceeding the total consumption for drives and lighting for the day and the night. However, the available energy gets reduced during off-sunshine hours owing to the losses associated with the electrolyzer and the fuel cell. This necessitates a study of the hourly energy balance for the greenhouse.

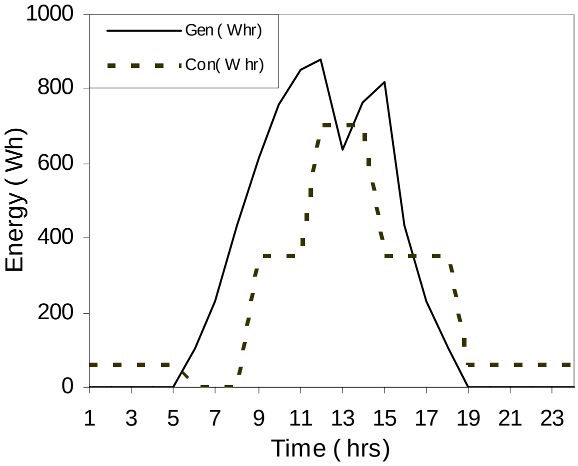

Fig 5. Hourly power generation (Wh) and consumption (Wh) pattern for a summer day in the month of April.

Hourly power generation and power consumption are shown in Fig.5 for a summer day in the month of April. From the figure it is seen that power needs to be supplied by the fuel cell from around 17 hours onwards till 5 hrs in the morning. Table 2 gives a comprehensive hourly energy balance for the greenhouse for an April day.

Table 2: Energy storage and consumption pattern during the 24-hour cycle for a summer day in April.

Time of day (hrs)	PV power Generation (Whr)	Consumption (Whr)	H_2 stored energy (Whr)	H_2 energy consumed (Whr)
6	106.6	0	85.3	0
7	233	0	186.4	0
8	432.9	0	345.8	0
9	616.6	352	211.7	0
10	760.7	352	326.9	0
11	850.1	352	398.5	0
12	880.7	704	141.4	0
13	640.1	704	0	116.2
14	764.6	704	48.5	0
15	817.8	352	372.6	0
16	432.3	352	64.2	0
17	233	352	0	216.4
18	106.5	352	0	446.4
19-5	0	600	0	1090.9
Total	6874.9	5176	2181.3	1169.9

The present analysis considers a photovoltaic system comprising of 4 PV Panels, each consisting of 60 single crystalline Silicon solar cells, each having a dimension of 125 mm by 125mm [10]. The estimated conversion efficiency of the solar cells is 25%. It may be noted here that advanced Si or GaAs solar cells have shown conversion efficiency exceeding 30% [10].

From the power system analysis it is found that the greenhouse is able to support its power requirement from its own power generation and storage mechanism, provided it receives clear solar radiation throughout the day hours. This arrangement would make possible the implementation of grid-independent greenhouse.

The PV panels considered in the analysis would occupy a canopy area equivalent to about 1.5% of the total canopy area. Panel area would be substantially less if higher conversion efficiency, as stated above, is considered.

4. CONCLUSIONS

The study reveals that in summer when the thermal load on the greenhouse is severe, the microclimate inside the greenhouse can be controlled effectively using evaporative cooling and mechanical ventilation. During peak sunshine hours a temperature about 6 – 7°C below the outside temperature is maintainable inside the greenhouse. It is seen that employing a combination of the different modes of operation, viz., natural ventilation, partial mechanical ventilation and cooling during off-peak sunshine hours effectively reduces the total energy consumption of the greenhouse for a whole day. The integration of the solar photovoltaic power generator, electrolyzer and fuel cell systems ensures in-house power generation and storage to support its electrical loads day and night. Such integrated power system makes the greenhouse independent of grid power and thus offers the flexibility of locating the greenhouse at remote places away from the utility grid.

Advanced high-efficiency solar cells, coupled to high-efficiency electrolyzers, can produce hydrogen at a solar-to-hydrogen conversion efficiency level of around 20%, while the hydrogen thus produced can be utilized in PEM fuel cell at 50-60% efficiency. With the advancement of solar and with the development of reversible fuel cells, photovoltaic-hydrogen-fuel cell systems are expected to become more and more attractive over the coming years.

5. REFERENCES

1. Nelson, P. V., 2003, *Greenhouse Operation and Management*, Prentice Hall (New Delhi).
2. Tiwari, G. N., 2003, *Greenhouse Technology for Controlled Environment,* Narosa Publishing House (New Delhi).
3. Tiwari, G. N. and Gupta, A., 2002, "Performance evaluation of greenhouse for different climatic zones of India", J of Solar Energy Society of India (SESI), 22:15-20.
4. Pieters, J. G. and Deltour, J. M., 1999, "Modelling Solar Energy Input in Greenhouses", Solar Energy, 67:119-130.
5. Kittas, C., Bartzanas, T., Jaffrin, A., 2003, "Temperature gradients in a partially shaded large greenhouse equipped with evaporative cooling pads*",* Biosystems Engineering, 85(1):87-94.
6. Ghosal, M. K., Tiwari, G. N. and Srivastava, N. S. L., 2003, "Thermal modeling of a controlled environment greenhouse cum solar distillation for composite and warm humid climate of India", Desclination, 151:293-308.
7. Sukhatme, S. P., 1991, *Solar Energy - Principles of Thermal Collection and Storage*, Tata McGraw-Hill Publishing Company Limited (New Delhi).
8. Ghosh, S., DattaGupta, K.K. and Ganguly, A., 2005, "Designing a photovoltaic power supported greenhouse suitable for hot and humid climates", *Proc. of PRITHVI 2005, Global Eco-meet,* Thiuivanantapuram, Kerala, India, Feb.19-28.
9. Campen, J. B. and Bot, G. P. A., 2003, "Determination of Greenhouse Specific Aspects of Ventilation using Three Dimensional Computational Fluid Dynamics", Biosystems Engineering, 84(1):69-77.
10. Green, M. A, Emery, K., King, D. L, Igari, S and Warta, W., 2003, "Solar cell efficiency tables (version 21)", Progress in Photovoltaics Research and Applications, 11:39-46.

6. NOMENCLATURE

Symbol	Meaning	Unit
A	Area	(m^2)
ACM	Air change per minute	(min^{-1})
C	Factor for ground coverage for the plants	-
C_p	Specific heat of air,	$(J/kg\text{-}^{O}C)$
Es	Rate of energy storage	(W)
H	Height of greenhouse	(m)
I	Solar insolation	(W/m^2)
K	Overall heat loss coefficient	$(W/m^2\text{-}^{o}C)$
L	Length of greenhouse	(m)
p	Half-perimeter of canopy	(m)
P	Power	(W)
Q	Heat flux	(W)
R	Radiation tilt factor	-
S	Shading factor	-
T	Temperature	(^{o}C)
V	Ventilation rate	(m^3/sec)
W	Width of greenhouse	(m)
α	Absorbtivity	-
τ	Transmissivity	-
ρ	Density of air	(m^3/kg)
η	Efficiency	-
Subscript		
a	Ambient	
b	Beam (radiation)	
c	Canopy	
d	Diffuse (radiation)	
e	Electrolyzer	
FC	Fuel cell (PEM)	
g	greenhouse	
N	North (canopy)	
p	Cooling pad	
PV	Photovoltaic panel	
r	Reflected (radiation)	
S	South (canopy)	
t	Total (radiation)	
w	Side wall	