Exergy Analysis of the Solar Blind System integrated with a Commercial Solar Greenhouse

Amir Vadiee*‡, Mahmoud Yaghoubi**

*Department of Thermo fluid mechanical engineering, Faculty of mechanical and aerospace engineering school, Shiraz university of technology, Modares blvd.,Shiraz,Iran

** Department of Thermo fluid mechanical engineering, Faculty of mechanical engineering school, Shiraz university, Molasadra st., Shiraz,Iran

(a.vadiee@sutech.ac.ir,yaghoubi@shirazu.ac.ir)

‡ Corresponding Author; First author, Modares blvd.,Shiraz, Iran, Tel: +98 713 726 4102, a.vadiee@sutech.ac.ir

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Abstract- The commercial greenhouse known as the most energy demanding cultivation methods and the energy conservation solution such as solar blind system is essential to be considered for the commercial greenhouses due to the sustainability. The solar blind system is consisted a series of thermal photovoltaic collectors which can rotate around the horizontal axis in order to make shading effect on the greenhouse and act as the solar curtain. In the conventional greenhouse, the solar curtain is utilized regularly to reduce the greenhouse indoor temperature by blocking the incoming solar radiation and it also prevent the sky night heat losses. Then by considering the solar blind system, not only the greenhouse cooling load can be decreased considerably, but also it can cover a part of electrical and heating demand of the greenhouse. Therefore, more energy can be conserved through the greenhouse by considering the solar blind system that leads to higher system exergy efficiency.

In order to conduct the exergy analysis a solar blind integrated greenhouse is modeled which is validated using measured data a case study greenhouse in Shiraz, a southern city in Iran. The results show that by integrating the solar blind system in the commercial greenhouse the annual exergy efficiency can be increased from 0.2% to 4%. However, the maximum possible hourly exergy efficiency can be increased from 36% to 69%.

Keywords- thermal photovoltaic system; solar greenhouse; energy conservation; exergy analysis.

1. Introduction

According to the sustainable energy policies, as one of the most interested subject in the recent decades [1-3]; the idea of solar blind system is formed [4]. The main application of solar blind system is in the commercial greenhouse industry [5-8]; however it also can be utilized in other types of solar buildings [9, 10]. The commercial greenhouse has a great productivity which is about 10 times more than all open field cultivation methods [11-13]. Alternatively, the commercial greenhouse has the highest energy demand in the horticultural industry. Therefore, there is a considerable potential in energy conservatively in the commercial greenhouse due to supply heating and cooling demand [12-14]. In the commercial greenhouse, the indoor climate condition should keep in a certain range. For example, the indoor temperature has to be kept between 18°C to 30°C and relative humidity needs to maintained between 60% to 80%, although it may varying depends on type of cultivation and product [15-17]. Two cooling methods which are usually utilized in the conventional greenhouse to supply cooling demand are using ventilating windows and shading systems. Beside the high cost effectiveness of these two methods, there is a serious weakness which is a great potential for energy losses by considering these two methods [14]. Typically, the heaters are operating in a commercial greenhouse while the ventilating windows are open in order to keep both of temperature and humidity level in the allowable range [8, 18]. Therefore the ventilating windows can be considered as the main source of heat loss in both forms of sensible and latent heat in the commercial greenhouse. In the second cooling method, which is shading system, a thick curtain with high reflectivity will be installed inside or outside the greenhouse structure to block the insolation and reduce the indoor temperature and cooling demand correspondingly [19]. Thus, by introducing the solar blind system as controllable shading system which is integrated with an active cooling system, not only the cooling demand will be reduced considerably but also it can improve system cost effectiveness since a portion of electricity and heating demand of greenhouse will be supplied in this concept [4].

Solar blind system is consisting a series of photovoltaic thermal (PVT) modules that operates based on greenhouse indoor temperature, insolation level and greenhouse indoor light intensity. The schematic of solar blind system in both operative and non-operative condition is demonstrated in Fig. 1.

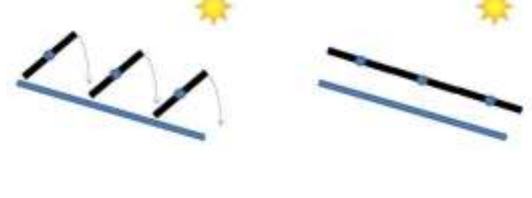

Fig. 1. The schematic of solar blind system in both non-operative mode (a) and operative mode (b).

As it shown in **Hata! Başvuru kaynağı bulunamadı.**, by operating the solar blind system (shading mode (b)) the PVT modules covers the greenhouse roof and block the solar radiation and correspondingly, the indoor temperature of greenhouse will be reduce. Simultaneously, the absorbed solar energy converted into electrical energy as well as heat energy which can be stored for further utilization. The solar blind system promises a considerable improvement in commercial greenhouse energy performance which is studied earlier by vadiee. et al [4, 20].The former studies show that by integrating solar blind system in a commercial greenhouse, cooling demand is reduced between 40% to 65%. Moreover, the total greenhouse energy performance is improved between 17% (for the highest allowable set point temperature) up to 34% (for the lowest allowable set point temperature) [4].It has to be noted that the minimum allowable set point temperature in the solar blind system integrated with a commercial greenhouse is 18°C while the maximum allowable set point temperature is considered as 30°C [16-18]. The solar blind system operates (in the shading mode) by exceeding the indoor greenhouse temperature above cold set point temperature and it rotate to un-shading mode when the greenhouse indoor temperature drops below the hot set point temperature.

Beside thermal energy analysis, an exergy analysis can lead us to understand better the energy conservation potential of this innovative concept. In the solar blind system, the solar energy utilization will be maximized since considerable portion of solar radiation is utilized in this concept while it was reflected to the atmosphere and unutilized earlier in the conventional shading systems [4]. Therefore, the exergy efficiency is expected to be improved considerably due to maximized utilization of solar energy as the main source of energy through the PV/T system.

In this study, the exergy analysis of solar blind system integrated with a commercial greenhouse is assessed using an interconnection between TRNSYS and MATLAB software's. The solar blind systems as well as commercial greenhouse and all integrated thermal systems are modeled using TRNSYS while the exergy analysis for this system is performed by MATLAB. In the next section, the considered assumptions are defined. Then the TRNSYS model is described which is followed by a summarized governing equations that are used in both MATLAB and TRNSYS model. Eventually, this paper is ended up with result and concluding remarks.

2. Exergy Analysis

Exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment [21]. Here the exergetic efficiency has been evaluated according to the second law analysis of thermodynamics. The reference condition defined above is chosen to be the ambient condition at each time step.

In this study, an exergy analysis has been assessed on the greenhouse without any PV/T collectors as solar blind system and then the same analysis is performed on the greenhouse with controlled PV/T solar blind system. Results obtained from both analyses have been compared with each other. It is useful to note that electricity power which is utilized for ventilation system (i.e fans) in the greenhouse is supplied from the grid and is considered as exergy input and the electricity produced by the PV is considered as electrical exergy output. The exergy balance for a commercial greenhouse without and with solar blind system is demonstrated by equation (1) and (2) correspondingly [22].

$$\dot{Ex}_{sun} + \dot{Ex}_{aux} + \dot{Ex}_{el} = \dot{Ex}_{exc} + \dot{Ex}_{des} \quad (1)$$

$$\dot{Ex}_{sun} + \dot{Ex}_{aux} + \dot{Ex}_{el} = \dot{Ex}_{exc} + \dot{Ex}_{PV,el} + \dot{Ex}_{PV,th} + \dot{Ex}_{des} \quad (2)$$

In both studied cases (commercial greenhouse without and with considering solar blind system), the exergy input consists of solar radiation exergy($\dot{Ex}_{sun}$), auxiliary heating system exergy ($\dot{Ex}_{aux}$) and electrical exergy regarding to the force ventilation system (i.e. fan) and artificial lighting system($\dot{Ex}_{el}$). However, by considering solar blind system, photovoltaic exergy in forms of electrical ($\dot{Ex}_{PV,el}$) and thermal ($\dot{Ex}_{PV,th}$) beside the greenhouse heat gain exergy ($\dot{Ex}_{exc}$) are consisting the exergy output terms while there is only one exergy output term in the conventional greenhouse (without solar blind system) that is greenhouse heat gain exergy. Greenhouse heat gain energy is the excess heat in the greenhouse (cooling load) which has to be harvested and stored in the thermal energy storage system in order to utilize later for heating purpose.

Photovoltaic electrical exergy output,$\dot{Ex}_{PV,el}$, is exactly equal to the electricity produced by PV cells and photovoltaic thermal exergy output, $\dot{Ex}_t$, which is calculated as follows [22]:

$$\dot{Ex}_{PV,th} = \dot{Q}_{PV,th}\left(1 - \frac{T_a}{T_o}\right) \quad (3)$$

The various calculation methods can be used for evaluating the incoming exergy of sun such as following correlations that suggested by Petela [4], Spanner [5] and Jeter [6] respectively:

$$\dot{Ex}_{sun} = \left[1 + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4 - \frac{4T_a}{3T_{sun}}\right] G \quad (4)$$

$$\dot{Ex}_{sun}=\left[1 - \frac{4T_a}{3T_{sun}}\right] G \quad (5)$$

$$\dot{Ex}_{sun}=\left[1 - \frac{T_a}{T_{sun}}\right] G \quad (6)$$

where T_a is the ambient temperature and T_{sun} is the equivalent sun temperature, 6000K. Results from the above equations show only 2% difference and then equation (6) is used in this analysis.

Exergetic efficiency (ε) is defined as the ratio of total exergy output to total exergy input. Therefore, the exergetic efficiency for a commercial greenhouse with without solar blind system can be defined as equation 7 and 8 correspondingly [22]:

$$\varepsilon_{SBGH} = \frac{A_{pv}\int_{t1}^{t2}(\dot{Ex}_{PV,th}+\dot{Ex}_{PV,el})dt + A_{gh}\int_{t1}^{t2}(\dot{Ex}_{exc})dt}{(A_c\int_{t1}^{t2}\dot{Ex}_{sun}dt)+(A_{gh}\int_{t1}^{t2}\{\dot{Ex}_{el}+\dot{Ex}_{aux}\}dt)} \quad (7)$$

$$\varepsilon_{GH} = \frac{A_{gh}\int_{t1}^{t2}(\dot{Ex}_{exc})dt}{(A_c\int_{t1}^{t2}\dot{Ex}_{sun}dt)+(A_{gh}\int_{t1}^{t2}\{\dot{Ex}_{el}+\dot{Ex}_{aux}\}dt)} \quad (8)$$

By applying the solar blind concept as it shown in the equation 7 and 8, it is expected that the exergy efficiency will be improved due to the additional exergy output terms in comparison with conventional greenhouse. However, the electrical power demand due to artificial lighting system will be increased by considering solar blind system based on energy analysis assessed in the former studies by vadiee et.al [4]. Therefore, a sensitivity analysis is performed in this study in order to evaluate the effect of each exergy input and output parameters in the solar blind greenhouse concept on the system exergy efficiency.

3. Model Describing

In order to conduct an exergy analysis, the solar blind system integrated with a commercial greenhouse is modeled in TRNSYS. In order to verify the solar blind system model it cross validated with an analytical data using a MATLAB model. However, the commercial greenhouse model is validated the using a commercial greenhouse located in Shiraz is chosen.

The main TRNSYS input data used in the reference model is listed in Table 1:

Table 1 considered conditions and input parameters for commercial greenhouse TRNSYS model

Type	Conventional even span greenhouse
Location	Shiraz
Orientation	East_West
Weather data	Meteonorm library (Type 109 in TRNSYS)
Area	100 m^2
Glazing	Single polycarbonate U=5.68 $Wm^{-2}K^{-1}$; R=0.18 m^2KW^{-1}; τ=0.87
Walls	U-value = 0.7 $Wm^{-2}K^{-1}$; Solar Absorptance = 0.6; thickness =8 cm
Ground	U-value = 0.3 $Wm^{-2}K^{-1}$; Solar Absorptance = 0.8; thickness =42 cm
Roof tilt angle	30^0
Maximum Roof ventilation angel	20^0
Occupancy	Max 2 persons (in working hour between 8:00 – 18:00)
Infiltration ratio	0.5 h^{-1} to 1.5 h^{-1}(ACH) (based on working hour)
Lighting system	High pressure sodium ;Total input = 440 W; Effective flux = 38400 lumen ; µmol.m^{-2} $s^{-1}$of PAR (400-700 nm) = 0.13
Minimum allowable temperature	18^0C
Maximum allowable temperature	30^0C

Four sample days are selected to compare the hourly greenhouse indoor temperature variation obtained by the TRNSYS model and measured values in the case study greenhouse. The following figures show the suitable agreement between the simulated values and measured ones.

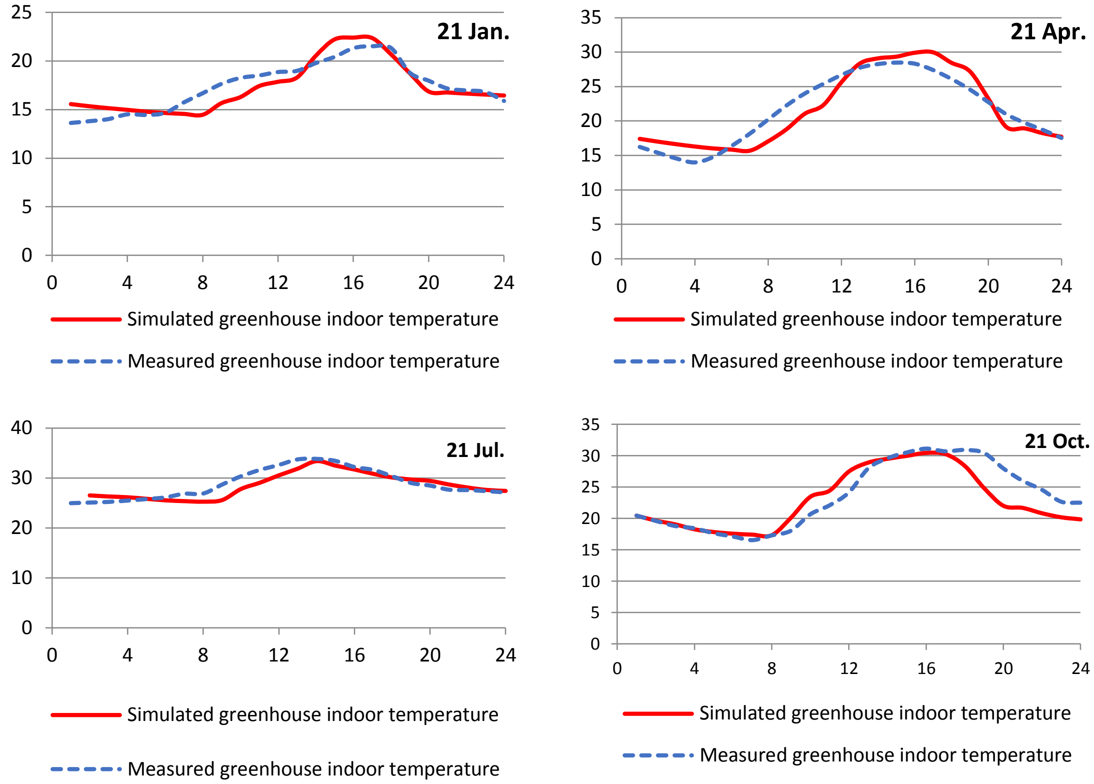

Fig. 1 Comparison of greenhouse indoor temperature variation for simulated and measure value

An energy analysis for using TRNSYS model of the commercial greenhouse with and without considering the solar blind system is assessed earlier in the former studies and more detail information is available in the corresponding references [4,14,15, 23, 24].

The exergy analysis is assessed for two following conditions:

1- A greenhouse without solar blind system
2- A greenhouse integrated with the solar blind system

The simulation program time step is defined as one hour, then the temperature of the greenhouse should measure hourly and if it will be above the user defined set point temperature, the controller will send a signal to the solar blind motors to rotate it and set it in the shading mode.

Technical operating parameters of the selected PV which are considered in the MATLAB and TRNSYS modelling are shown in Table 2.

Table 2 Operation parameters of selected PV

Parameters	Description	Value
$V_{mpp,ref}$	Rated voltage	31.3V
$I_{mpp,ref}$	Rated current	8.3A
P_{mmp}	Rated power	260 Wp
V_{oc}	Open circuit voltage	38.2V
I_{sc}	Short circuit current	8.76A
NOCT	Nominal operating cell temperature	48°C
η	Nominal Photovoltaic electrical efficiency	15.8%
γ	Temperature coefficient (P_{mpp})	-0.44%/°C
α	Temperature coefficient (I_{sc})	+0.04%/°C
β	Temperature coefficient (V_{oc})	-0.31 %/°C
Tilt angle(β)	Slope angle of solar blind photovoltaic system	30°

The solar parameters are read from a separate excel file generated by Meteonorm, and solar irradiation on the tilted surface of the collector is calculated using the following equation:

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d \left(\frac{1+cos\beta}{2}\right) + \rho_g (I_b - I_d)(\tau\alpha)_g \left(\frac{1-cos\beta}{2}\right) \quad (9)$$

$$R_b = \frac{cos\theta}{cos\theta_z} \quad (10)$$

Where the subscripts b, d and g refer to beam, diffused and ground respectively and τα is the transmittance-absorptance product of collector. The angle of θ and θz refer to beam incident angle to tilted surface and beam zenith angle respectively. Then the photovoltaic cell temperature is calculated using equation (11) [25] and with the nominal efficiency of PV that is defined by the manufacture and given in the datasheet.

$$T_{cell} = T_a + \frac{S}{U_L}\left(1 - \frac{\eta_{pv}}{\tau\alpha}\right) \quad (11)$$

Then according to the calculated cell temperature, modified efficiency of PV can be calculated using the equation (12) [25]:

$$\eta_{pv} = \eta_{ref} + \gamma(T_{cell} - 25) \quad (12)$$

Then the modified efficiency is again used in equation (11) to in turn modify the cell temperature. This procedure is repeated until the efficiency of PV module converges to a limit.
The solar irradiation which was calculated using equation (9) is now considered as input to the absorber plate, thus using equation (13) the relevant heat gain from the collector can be obtained [25]:

$$Q_u = A_c * F_R(S - U_L(T_i - T_a)) \quad (13)$$

By considering the obtained heat gain, outlet temperature of fluid from the collector can be calculated using equation (14) [25]:

$$T_o = T_i + \frac{Q_u}{\dot{m}_w * C_p} \quad (14)$$

For both MATLAB and TRNSYS model, 48 collectors, each having 1.2 m2 area and packing factor of 0.93 is considered connected in parallel and mass flow rate of fluid in each collector is designed as 0.028 kg/s that is recommended by the manufacturer. The following additional assumptions are made for MATLAB simulation:

- The steady state condition.
- The edge and back heat loss of the PV/T collector is negligible as it not exceeds 10% of the overall loss [25].
- All thermal resistance regarding to the welding bond material and adhesive layer is assumed to be negligible.
- Inlet water temperature to the thermal storage tank is assumed to be similar as the ambient temperature.

According to the obtained results (shown in fig. (3) for useful heat), for estimating the annual solar thermal energy gained per unit of collector area, thermal efficiency of collector, produced annual electricity and PV efficiency, the model has 4.76% , 6.78% , 5.32% and 7.08% error respectively.

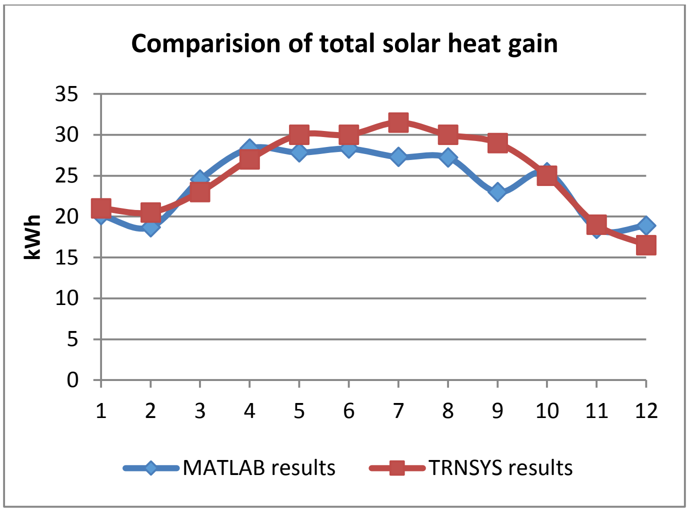

Fig. 2 Comparison of solar useful heat gains

By comparing the total solar useful heat gains by the solar blind system models developed in MATLAB and TRNSYS it observed that the models have a great agreement with less than 5% changes in the annual total solar heat gain then it can be concluded that the results which obtained using TRNSYS can be used in MATLAB due to the exergy analysis without generating a significant error.

4. Results and Discussions

In order to discuss about the exergy performance of the system, an energy performance analysis is required. Therefore, an energy performance analysis for the greenhouse model with and without considering solar blind system is evaluated based on the case study condition which was described earlier. The thermal and electrical efficiency of solar blind system for various set point temperatures are assessed and the results are presented in the Fig. **3**. As it shown in the Fig. **3**, the solar blind system performance is decreasing by increasing the set point temperature. The decreasing of number of solar blind system working hour due to higher set point temperature leads into lower thermal and electrical energy gain and annual energy performance by the system although the total annual solar radiation is constant for all studied cases.

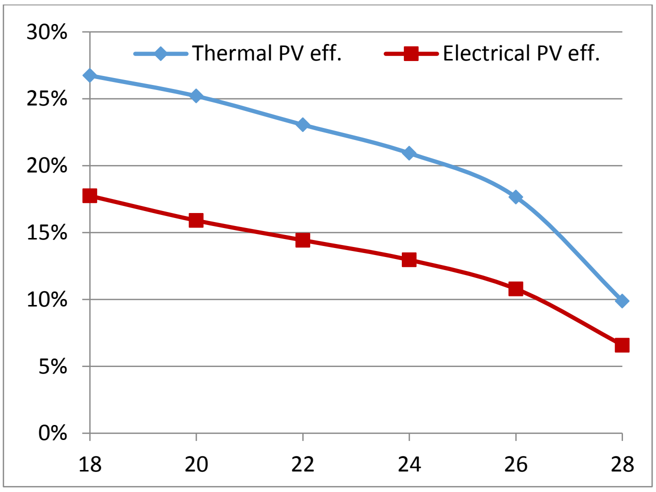

Fig. 3 Thermal and electrical efficiencies of solar blind system for various set point temperatures

Beside the energy performance evaluation for solar blind system, the energy performance for the integration of greenhouse and solar blind as a unit system is also interested to be evaluated. Then, in order to assess the total system energy performance, two parameters as "thermal performance ratio" and "electrical performance ratio" are defined. Thermal performance ratio is the ratio between all thermal energy gains including heat gain by solar blind system in addition to all available excess heat in the greenhouse which can be stored for further utilization to the total system heating demand. The electrical performance ratio is also defined as the ratio between the electrical energy gain by the solar blind system and the annual electrical energy demand for the whole system. These two parameters are evaluated for various set point temperatures and the results are presented in the Fig. **4**.

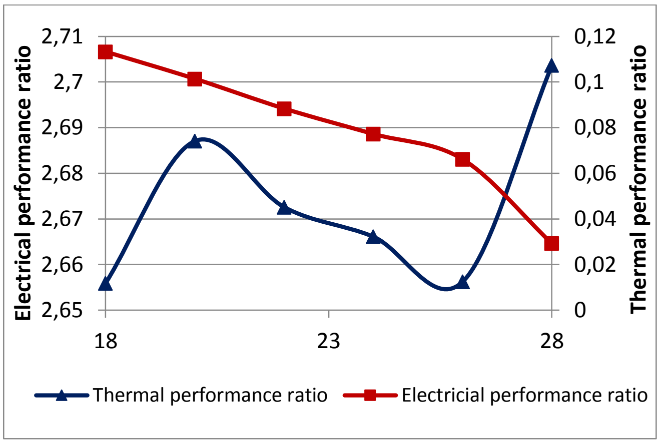

Fig. 4 Thermal and electrical performance ratio for the commercial greenhouse integrated with solar blind system

It can be concluded from the Fig. **4**, that the highest system thermal performance ratio is obtained for 20°C and 28°C as the set point temperature, however, the electrical performance ratio has the lowest value in set point 28°C. Therefore, 20°C may consider as the set point temperature in order to obtain the highest system energy performance.

As the main aim of this study, the exergy performance evaluation is performed based on an analytical method which is described earlier in this paper. The annual assessment for all input and output exergy parameters for 100 m2 commercial greenhouse integrated with solar blind system are summarized in Table 3. Then the exergy efficiency for all defined set point temperatures as well as exergy efficiency for conventional greenhouse without solar blind system is calculated based on equation (7) and the results are given in Fig. **5**. The maximum possible exergy efficiency for all set point temperatures during the whole year is also calculated and presented in Fig. **6** and compared with conventional greenhouse without solar blind.

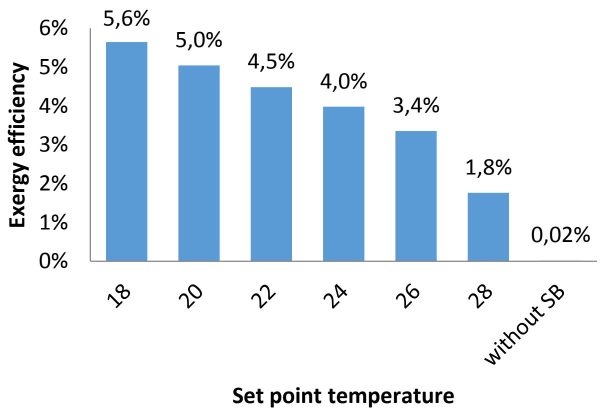

Fig. 5 Annual exergy efficiency of the case study commercial greenhouse integrated with solar blind system for various set point temperatures

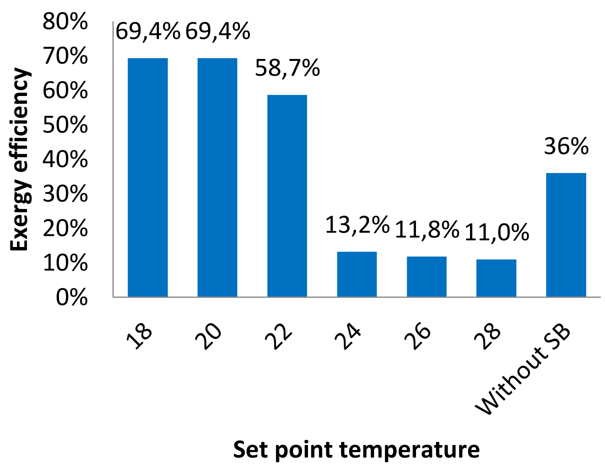

Fig. 6 maximum possible exergy efficiency (in hourly based calculation) which can be obtained during one whole year for various set point temperatures

Table 3 Input and output exergy parameters in commercial greenhouse integrated with solar blind system

Set point temperature	$\dot{E}x_{sun}$ ×10³(kW)	$\dot{E}x_{aux}$ (kW)	$\dot{E}x_{el}$ ×10³(kW)	$\dot{E}x_{exc}$ (kW)	$\dot{E}x_{PV,th}$ (kW)	$\dot{E}x_{PV,el}$ ×10³ (kW)	$\dot{E}x_{in}$ ×10³(kW)	$\dot{E}x_{out}$ ×10³ (kW)
18	178.7	138.6	140.0	165.6	1982.6	15.9	318.8	18.0
20	178.7	131.6	140.1	166.5	1709.0	14.2	318.9	16.1
22	178.7	127.0	146.0	171.6	1498.2	12.9	324.7	14.6
24	178.7	123.3	150.0	181.0	1310.4	11.6	328.7	13.1
26	178.7	119.4	145.8	201.0	1049.3	9.6	324.5	10.9
28	178.7	116.6	201.6	286.1	517.4	5.9	380.4	6.7

The annual exergy efficiency regarding to the conventional greenhouse without solar blind is about 0.02%, then by integrating the solar blind system the exergy efficiency is increased up to 1.8% for the worst case which is corresponding to the highest set point temperature (28°C). As it shown in Fig. **5**, the highest annual exergy efficiency for the commercial greenhouse integrating with solar blind system is about 5% which can be achieved for low set point temperatures such as 18°C and 20°C.

Moreover, as it shown in Fig. **6**, the maximum possible exergy efficiency which can occur during the whole year is about 69% and in case of choosing 18°C or 20°C as the set point temperatures. It has to be noted that this efficiency is based on hourly analysis while the exergy efficiency which assessed in Fig. **5** is calculated based on the annual variables. It can be concluded that, the set point temperature has a considerable effect on the exergy efficiency and by choosing lower set point temperature higher exergy efficiency can be achieved. However, by considering the set point temperatures more than 22°C, the maximum possible hourly based exergy efficiency may reduce by 25% although the annual exergy efficiency will be improved considerably. Then in order to do a more specific assessment of set point temperature influence on the exergy efficiency, the annual frequencies of exergy efficiency is assessed based on five categories as it demonstrate in the Fig. **7**: low exergy efficiency (less than 1%), medium exergy efficiency (1-5%), fairly high exergy efficiency (5-10%), high exergy efficiency (10-15%) and very high exergy efficiency (more than 15%). However, more detail analysis is given in the Table **4**.

As it seen in the Fig. **7**, the most frequent exergy efficiency for all set point temperatures is between 5%-10% and more precisely is about 8% (based on Table **4**). It can also be concluded that the highest exergy efficiencies can only be obtained in set point temperature 18°C and 20°C. However, the minimum frequent low exergy efficiency (less than 1%) is obtained in 20°C, 22°C and 24°C set point temperatures.

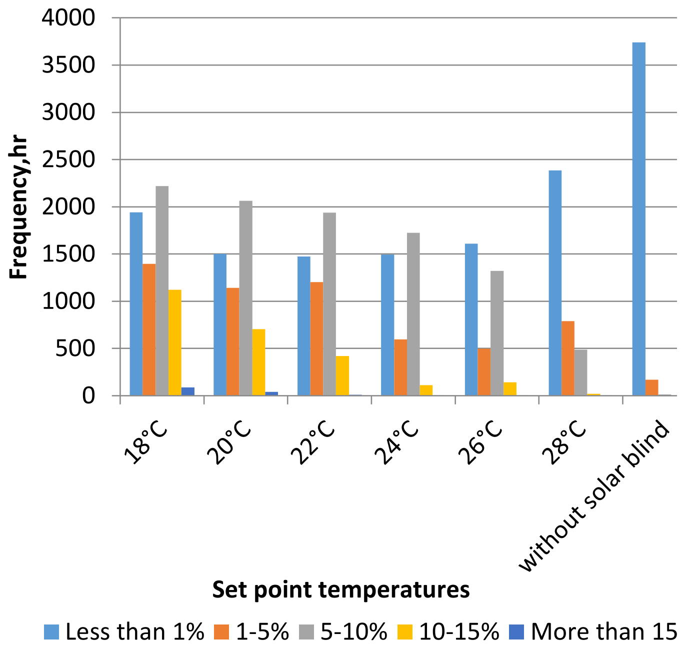

Fig. 7 Frequency of exergy efficiency for various set point temperatures with comparison with conventional greenhouse without solar blind system

It can be concluded from Table **4**, that the summation of number of hours in the commercial greenhouse with solar blind system with the exergy efficiency higher than 1% and 20°C as the set point temperature is 3951 hr, although the number of hours in conventional greenhouse with exergy efficiency less than 1% is 3739 hr which shows a great potential for exergy efficiency improvement by considering solar blind system in the commercial greenhouses.

Table 4 Frequency of exergy efficiency for various set point temperatures with comparison with conventional greenhouse without solar blind system

exergy efficiency	*Frequency of exergy efficiency, hr*						
	Set point temperature in case of using solar blind						*Conventional greenhouse without solar blind*
	18°C	*20°C*	*22°C*	*24°C*	*26°C*	*28°C*	
Less than 1%	1940	1501	1474	1495	1608	2385	3739
1-2%	411	294	263	106	82	172	117
2-3%	451	365	92	105	98	137	27
3-4%	266	235	316	184	145	271	16
4-5%	267	247	192	201	172	208	10
5-6%	447	411	339	256	194	169	5
6-7%	287	273	455	363	245	140	4
7-8%	340	347	312	417	264	69	3
8-9%	714	665	542	376	298	51	1
9-10%	432	366	289	314	322	58	1
10-11%	556	345	342	104	139	18	0
11-12%	430	312	45	9	2	1	1
12-13%	47	19	13	0	0	1	1
13-14%	32	14	10	0	0	0	2

14-15%	55	16	10	0	0	0	0
More than 15%	88	42	12	2	4	4	3

A sensitivity analysis is also performed in this study in order to evaluate the effect of most relevant parameters on the exergy efficiency. Therefore, the ambient temperature, the required electrical power for ventilation system including fans and the electrical power for supplementary artificial lighting system are considered as the variable parameters in the sensitivity analysis. Then a multiplication factor is defined for each parameter which varied between 0.25 to 1.75 means up to 75% reduction and increment correspondingly. This sensitivity analysis is performed for 20°C set point temperature.

The results show, as it presented in Fig. **8**, that the electrical demand for ventilation system has the highest impact on the exergy efficiency for the chosen set point temperature (20°C). It is also concluded that the lighting system cannot be considered as an important parameter which can effect on the exergy efficiency since even in case of reducing or increasing the electrical demand of lighting system by 75%, the exergy efficiency changes less than 1%.

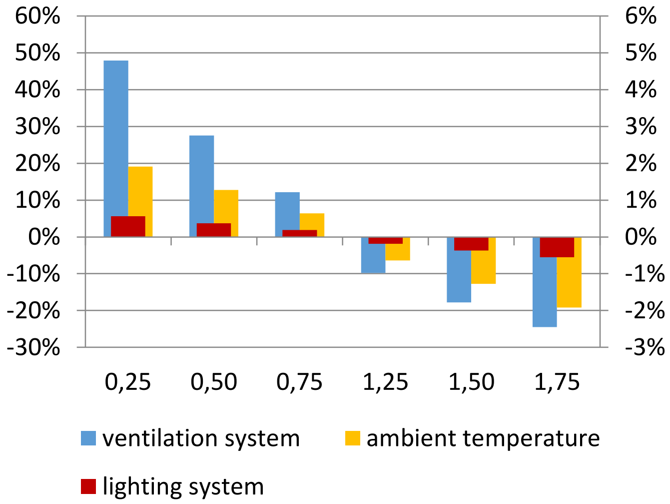

Fig. 8 sensitivity analysis of some relevant parameters on system exergy efficiency

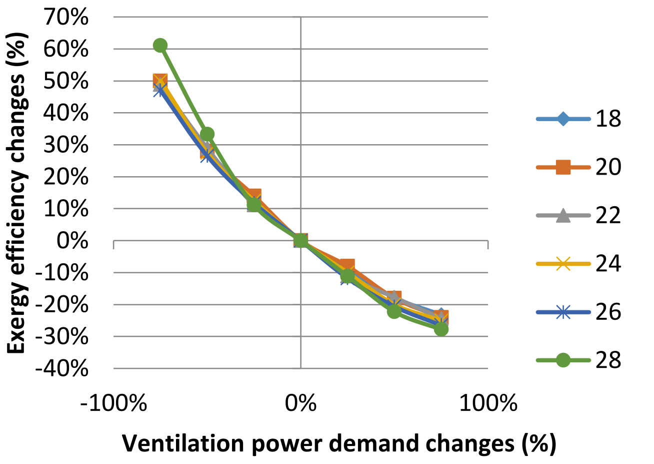

Fig. 9 rate of exergy efficiency changes with ventilation power demand changes for various set point temperatures

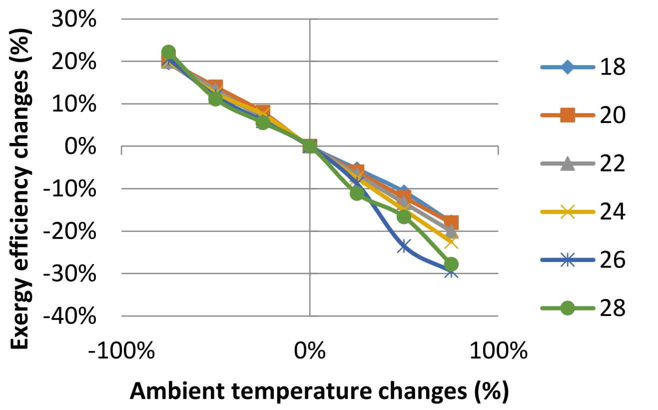

Fig. 10 rate of exergy efficiency changes with ambient temperature changes for various set point temperatures

Then the sensitivity rates of electricity demand of ventilation system (as dominate parameter) as well as ambient temperature on exergy for various set point temperatures are assessed and the results are presented in Fig. **9** and 11.

The Fig. **9** and 11 shows that the sensitivity rate is almost independent of set point temperatures and for all chosen set point temperature values, variation of electricity power demand for ventilation system and ambient temperature has similar effect on exergy efficiency.

5. Conclusion

An exergy analysis is studied for the solar blind system as an innovative solution to maximize solar energy utilization in commercial greenhouses. Based on the obtained results, it can be concluded that the solar blind system has a great potential to improve annual exergy efficiency of the whole system from “0.02%” in the conventional greenhouse (without solar blind) to “1.8-5.6%” with considering the solar blind system ; depends on the chosen set point temperature of solar blind system.

Set point temperature is a key parameter in the both of energy and exergy performance of solar blind system. The result shows that by increasing the set point temperature of solar blind system, the thermal and electrical performance of system will be reduced. The maximum thermal and electrical efficiency of the solar blind system is 27% and 18% correspondingly and the minimum thermal and electrical efficiency for the studied system is about 10% and 7% correspondingly. The frequency of exergy efficiency over the whole year is studied in order to evaluate the exergy performance of solar blind system. It concluded that the most frequent exergy efficiency for all described situation is about 5%-10% after exergy efficiencies less than 1%. By considering the solar blind system, the number of hours with exergy efficiency between 1% to 5% is 8 times more than conventional greenhouse however; this ratio for exergy efficiencies higher than 5% is about 160 which show the great exergy performance improvement in the system.

By performing a sensitivity analysis it is concluded that the ventilation system has a significant effect on the annual exergy efficiency beside ambient temperature. The required power for force ventilation system in the commercial greenhouses will be increased by increasing the solar blind set point temperature. Therefore, the open ventilation system (natural ventilation) is highly recommended in case of choosing higher set point temperatures in order to improve the annual exergy efficiency. The sensitivity analysis also implies that the annual exergy efficiency of a commercial greenhouse integrated with solar blind system has higher exergetic performance in the regions with lower annual average ambient temperature.

Eventually, based on the both of energy and exergy analysis, the solar blind system can be introduced as an innovative solution in order to maximize solar energy utilization, although it the economic feasibility is not studied so far. Therefore, an economical assessment is highly recommended by the authors in order to evaluate the economic feasibility of commercial greenhouse integrated with solar blind system.

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NOMENCLATURE

A	Area (m^2)
Aux	Auxiliary
Exc	Excess thermal energy
$\dot{Ex}_{sun}$	Exergy received by sun radiation (W)
$\dot{Ex}_{th}$	Thermal exergy (W)
$\dot{Ex}_{pv}$	Photovoltaic exergy (W)
F_R	Heat removal factor
Gh	Greenhouse
I_b	Solar beam radiation (W/m^2)
I_d	Solar diffuse radiation (W/m^2)
$I_{mpp,ref}$	Reference PV current at max. power point (A)
I_{sc}	Short-circuit current (A)
$\dot{m}_w$	Collector fluid mass flow rate (kg/s)
NOCT	Nominal Operating Cell Temperature (°C)
Q_u	Useful solar heat gain (W)
Ref	Reference condition in PV characteristic
S	Solar irradiation on tilted surface received by absorber plate (W/m^2)
SB	Solar Blind
T_a	Ambient temperature
T_i	Inlet temperature of fluid
T_o	Outlet temperature of fluid
T_{cell}	PV cell temperature (°C)
U_L	Collector total loss coefficient (W/m^2°C)
$V_{mpp,ref}$	Reference PV voltage at max. power point (V)
V_{oc}	Open-circuit voltage (V)
β	Collector tilt angle
γ	PV efficiency coefficient
ε_p	Emittance of absorber plate
ε_g	Emittance of glass cover
η	PV efficiency
θ	Solar ray incident angle to the collector
θ_z	Solar ray zenith angle
ρ_g	Ground reflectance
$(\tau\alpha)$	Transmittance-absorptance product