New method for applying solar energy in greenhouses to reduce fuel consumption

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Abstract: Renewable energies (especially solar energy) are globally suitable alternatives for fossil fuels. On the other hand, greenhouses, as a main part of agriculture industry, use a significant amount of fossil fuels annually to provide the required heat for the under-cultivation crops in the greenhouse. Currently this heat demand is provided by a heater which burns gas oil as its main fuel. The main problem with these heaters is fuel hyper-consumption. That is why feasibility of utilizing a solar energy storage system in greenhouses is studied here. As the low temperature heat is required for preheating the air in the greenhouse, a solar collector array is proposed to be utilized in order to displace heating demand of the heater and to reduce amount of fuel consumption. To evaluate the proposed system effectiveness, an economic survey has been done on the proposed system based on Net Present Value (NPV) method. The optimum capital cost for the project is found based on economic methods. The economic analysis showed that 85 flat plate collector modules and an 8.5 cubic meters of storage tank are optimum selection of the project. The results showed that, by employing the proposed system, 7 735 USD benefit as well as 11 050 litres of fuel providence is obtainable annually. Economic evaluation based on NPV method resulted in the payback period of ten years.

Keywords: solar energy, greenhouse, storage tank, stratification, NPV

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1 Introduction

Solar energy, radiant light and heat from the sun, has been utilized by humans since ancient times applying various technologies. Solar energy technologies include solar heating, cooling, photovoltaics and agriculture which can play an important role to solve some of the basic problems of the world[1]. Solar technologies are generally known as passive or active solar techniques depending on the matter they harness and convey solar energy. Active solar techniques consist of using photovoltaic panels and solar thermal collectors to profit the energy and passive solar techniques such as orienting

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a building to the Sun, etc. The application of cheap, endless and clean solar energy technologies is increasing so fast. It will cause to enhance sustainability, reduce pollution, lower the costs of mitigating climate change, and keep fossil fuel prices lower than others. Solar thermal technologies can be used for water heating, space heating, space cooling, and heat generation processing. Many studies have been done in this field to offer new methods for applying solar energy in industry and agriculture[2-8].

Sunlight has affected building design since the start of architectural history[9]. Fundamental solar architecture and urban planning manners were firstly applied by the Greeks and Chinese, who oriented their buildings toward the south to profit from light and heat of the Sun[10]. Greenhouse is a place to use sunlight to grow vegetables, fruits and flowers; it is year-round and even in a bohemian climate, and also is more efficient than traditional cultivation methods. Agriculture and horticulture seek to optimize the application of solar energy, aiming to improve the productivity of crops. Techniques such as timed planting cycles, tailored row orientation, staggered heights between rows and the mixing of plant varieties can increase crop yields[11,12]. While sunlight is an abundant resource, the exceptions highlight the importance of solar energy to agriculture. Many years ago, fruit walls were employed to maximize the collection of solar energy by some farmers for the first time. These walls operated as thermal masses and speeded up ripening by keeping plants heat. The first fruit walls were vertical on the ground and facing south, but later, sloping walls were built to have more usage from sunlight. Nicolas Fatio de Duillier[13] proposed applying a tracking system which could follow the Sun by turning. Utilization of solar energy in agriculture in addition to growing crops consists of pumping water, drying crops, brooding chicks and drying chicken manure[14,15]. The energy use intensity of greenhouses production has been analysed by various authors both in general[16,17] and with reference to specific productions (tomato[18,19], grape[20], and strawberry[21]) and has been proved to be extremely high. Although a significant amount of solar energy could be utilized for greenhouses by a passive solar system, a remarkable volume of fossil fuel is needed yet to be burned and provide favorable temperature for the under-cultivation plant in the greenhouse during cold months of the year and even nights in warm months. This is usually carried out by a heater which burns gas oil as its main fuel in Iran. The heater has a fan which sucks ambient air and warms it up. This heated air then is distributed through the greenhouse space by some secondary HVAC systems such as ducts and wicket gates and so on.

Basically, a benefit for a greenhouse can be defined as the increase in the light input, the reduction of heat losses during cold weather and the increase in heat removal during hot weather[22]. Considering the studies on the thermal behaviour of the greenhouse, besides the effect of covering materials[23] and thermal screen stoics[24], many recent papers concentrated on the use of alternative energy sources for the greenhouse air conditioning, especially as regards the geothermal energy[25-27]. For greenhouse heating with solar energy, various methods can be applied, such as separate solar collectors, solar collectors integrated in the greenhouse, and the use of the greenhouse itself as a solar collector. These methods were explained and results are presented for climatic conditions in Germany and Mediterranean countries in the previous study by Zabeltitz[28]. This paper presents the development and validation of a computer model used to describe a greenhouse with a thermally coupled energy store. The physical system modeled consisted of a 6.7 m × 12.2 m greenhouse with a 3 m × 10 m × 1.8 m rock bed attached via insulated ducts. Provisions were made to circulate air from the greenhouse through the rock bed and back whenever heating or cooling were required[29]. Many other works have been done in this issue as well[30-34].

This study aims to introduce a new method of solar energy application in greenhouses by which the heater fuel consumption in greenhouses could be considerably decreased. A solar collector array is suggested to be employed for substituting heating duty of the heater. The proposition includes a modified design of an in-use greenhouse to take advantage of freely available solar heat. The optimization has been carried out in line to minimize the greenhouse design variation and availability of the greenhouse to continue its tasks with or without additional solar system.

2 Materials and methods

2.1 Case study (Dashte Minoo greenhouse)

The proposed model has been applied to study the thermal behaviour of Dashte Minoo greenhouse. The typical case has been chosen to evaluate the proposed system effectiveness. The Dashte Minoo greenhouse is located in Azadshahr city, in the northeast of Iran. Since this area has a moderate climate and is more cloudy and rainy rather than the other areas of Iran, it can bring reliability for sunnier regions if the suggested system would result in a good enough performance for this climate. The average solar flux in Azadshahr is about 4 kWh/m^2 while this figure could rise up to 5.5 kWh/m^2 for the central cities of Iran[35].

The amount of useful energy gained by the collectors directly depends on the climate data such as environment temperature and wind speed. The climatic data for Azadshahr city (Latitude 37° and Longitude 55°) has been obtained from the Iran Weather Institute data centre and the other important information relevant to the greenhouse is provided by the greenhouse manager. This consists of cultivation crop, required temperature, the field area, the cover material and the greenhouse dimensions. Table 1 details the essential information about this greenhouse.

Table 1 Dashte Minoo greenhouse information

Crop	Cucumber
Required temperature	20°C
Field area	40 m × 50 m
Cover material	Dual polycarbonate
Cover thickness	8 mm

As it is obvious from the table above, the greenhouse cover is a dual polycarbonate with 8 mm thickness which could play a remarkable role in keeping heat in the greenhouse space. Figure 1 also shows the greenhouse dimensions.

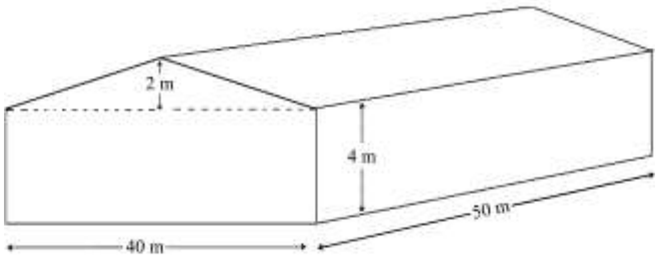

Figure 1 Dashte Minoo greenhouse dimensions

2.2 Greenhouse energy demand

Knowing climate information, especially ambient temperature, the energy balance for the greenhouse could be found as below:

$$\dot{Q}_{GR} = \dot{Q}_{lost} + \dot{Q}_{vent} - \dot{Q}_{solar} \quad (1)$$

where, $\dot{Q}_{GR}$, $\dot{Q}_{lost}$, $\dot{Q}_{vent}$, $\dot{Q}_{solar}$ are required heat for the greenhouse to stay at the favorable temperature, heat lost from the greenhouse walls, heat lost from the greenhouse due to ventilations and added energy to the greenhouse because of sunshine, respectively.

The greenhouse wall heat loss can be obtained from the equation below:

$$\dot{Q}_{lost} = \sum_{i=1}^{n} U_i A_i (T_{in} - T_a) \quad (2)$$

In which U_i is the overall heat transfer coefficient, A_i is the wall area, T_a is ambient temperature and T_{in} is the internal greenhouse temperature which has been reported 20°C for cucumber[36]. Table 2 presents U and A values for all the walls and the field.

Table 2 *U* and *A* values for the greenhouse

	A (m^2)	U (W/(m^2 °C))
Ceiling	2010	3.35
Southern and northern walls	200	3.35
Eastern and western walls	200	3.35
Field	2000	0.5

Knowing ambient temperature and the information in Table 2, it could be easy to calculate the greenhouse walls heat loss to the environment.

Ventilation heat loss for the greenhouse also could be calculated by the following equation:

$$\dot{Q}_{vent} = N \cdot V \cdot \rho \cdot C_p \cdot (T_{in} - T_a) / 3600 \quad (3)$$

where, C_p is the thermal capacity at constant pressure for air with value of 1.005 kJ/(kg ^{o}C); ρ is air density which its value for this range of air temperature is 0.995 kg/m^3; V refers to the internal greenhouse air volume which could be easily computed and its value is 1 000 m^3 and N refers to air change times during an hour for the greenhouse which should be two times per hour[37]. The obtained value from the above equation has to be divided to 3 600 in order to give the energy lost per second.

The last term in Equation (1) is the inlet energy rate to the greenhouse by the input solar rays. The absorbable solar energy by a 1 m^2 area surface could be calculated as below:

$$S = I_b R_b (\tau\alpha)_b + I_d (\tau\alpha)_d (\frac{1+Cos\beta}{2}) + I \cdot \rho_g (\tau\alpha)_g (\frac{1-Cos\beta}{2}) \quad (4)$$

where I, I_d, I_b and S are the total available solar radiation, diffuse component of solar radiation, solar radiation beam component and absorbed solar radiation by the slopped surface, respectively. This equation also includes some Greek symbols such as β and $(\tau\alpha)$: β refers to the surface slope angle rather than the horizon and average absorption-transmission coefficient of the greenhouse cover which is a function of the cover material; $(\tau\alpha)$ refers to physical properties of the internal elements of the greenhouse and radiation angle. Regarding the greenhouse content absorption coefficient for the internal elements of the greenhouse is considered 0.7 for normal radiations[38]. Further explanation is avoided due to abundance of references about this subject[39-46].

Equation (4) has to be solved for all the walls except the northern wall, because this wall is completely deviated from the south and is not able to absorb solar rays. Thus, the absorbed solar flux by the northern wall of the greenhouse is assumed zero. Table 3 presents the β values for all the walls and the ceiling.

Table 3 Slop and azimuth angle values for different walls of the greenhouse

Wall	β
Southern	90
Ceiling	0
Eastern	90
Western	90

Applying Equation (4) for each walls or ceiling the absorbed radiation could be calculated. For computing the overall absorbed solar flux for the whole greenhouse, the following equation could be utilized:

$$\dot{Q}_{solar} = (S_{south} \times A_{south}) + (S_{east} \times A_{east}) + (S_{north} \times A_{north}) + (S_{west} \times A_{west}) + (S_{ceiling} \times A_{ceiling}) \quad (5)$$

Obtaining right hand parameters in Equation (3) $\dot{Q}_{GR}$ can be realized. Thus the fuel consumption mass flow rate for providing this amount of energy can be given by Equation (6).

$$\dot{m}_f = \frac{\dot{Q}_{GR}}{LHV.\eta_h} \quad (6)$$

In the equation above, η_h, LHV, $\dot{m}_f$ are the heater thermal efficiency, the fuel low heating value and the fuel mass flow rate. It should be noted that the current thermal efficiency heaters is low amount and is assumed to be 50%[47].

2.3 Proposed system

Solar energy is being applied broadly for generating heat for many domestic or industrial usages[48]. Solar Water Heating is an effective manner of application solar energy to do many advantageous tasks. The energy from the sun can make hot water for many applications, substituting the need to burn fossil fuels[40-46]. A flat-plate solar collector is one of three main types of solar collectors, which are the most important parts of a solar system[5]. The other types of solar collectors are evacuated tubes and batch solar heaters. Flat-plate collectors are the most prevalent solar collectors for application in sola water-heating systems. Flat-plate

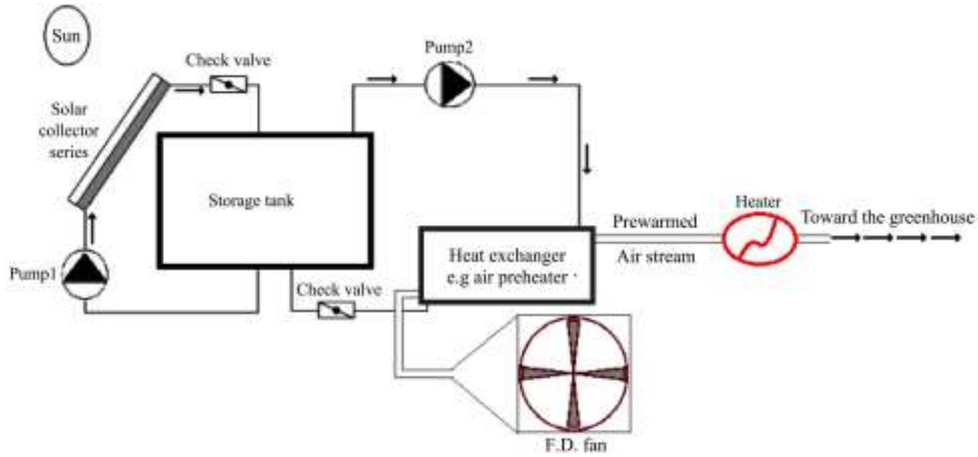

Figure 2 Schematic diagram of the proposed system to utilize solar energy in greenhouses

collectors warm the circulating fluid to a temperature significantly less than that of the boiling point of water. They are the best choice when the demand temperature is 30-80°C and/or for applications that require heat in the winter[5]. Regarding the above recommendations, an array of flat-plate-solar-collectors has been applied in this work. The system has been equipped with a storage tank and a shell and tube heat exchanger. A schematic diagram of the proposed system is shown in Figure 2. The storage tank receives energy from the solar collectors and stores it during daylight hours. During nights the stored heat is transferred from the storage tank to the added heat exchanger in order to preheat the sucked air by the air sucker fan (F.D.Fan) and consequently reduces heating duty of the heater.

2.4 Available solar heat

The useful energy rate for a flat plate solar collector could be calculated from the following relation.

$$\dot{Q}_u = A_c \cdot F_R \cdot (S - U_l(T_{fi} - T_a)) \tag{7}$$

where, F_R, T_{fi}, T_a, A_c and U_l are the collector removal factor, inlet working fluid temperature, ambient temperature, absorption surface area and the total heat transfer coefficient for the collector, respectively. Also S is absorbed solar flux by flat plate collector per 1.0 m^2 area and can be obtained from equation below[40-46]:

$$S = (\tau\alpha)_{av} \cdot I_T \tag{8}$$

where, $(\tau\alpha)_{av}$ and I_T are average absorption-transmission coefficient of collector and radiated solar flux on slopped collector, respectively. The collectors employed in this research are commercial ones which are available for sale in Iran[49]. As noted in the Table 4, the collector has a surface area of 1.9 m^2. The functional dependence of the collector efficiency on the meteorological and system operation values can be represented by the following equation[49]:

$$\eta_i = 0.78 - 1.4\frac{(T_{pm} - T_{am})}{I_T} - 0.09\frac{(T_{pm} - T_{am})^2}{I_T} \tag{9}$$

Which I_T is radiated solar flux on slopped collector and T_{pm} is the absorber surface average temperature. The collector efficiency has been calculated by the manufacturer based on En-12975-2 Standard[49].

Table 4 Properties of employed solar collectors

Information	Characteristic
200 cm	Collector length
95 cm	Collector wide
9.5 cm	Collector thickness
Glass	Cover matter
4 mm	Cover thickness
0.5 mm	Absorber plate thickness
10 mm	Tubes inner diameter
12 mm	Tubes outer diameter
150 mm	Tubes space
1.51 m^2	Plate area
Copper	Plate matter

2.5 Energy analysis

In order to perform thermal analysis on the proposed system, two control volumes should be adopted and the first law of thermodynamics should be written for each one. The first control volume is the storage tank and the second one is the greenhouse.

There are two ways to analyze the storage tank as a control volume, solution with assumption of a lumped mass or a stratified tank. Although the first method could lead to an acceptable result, the second method could result to more accurate conclusions. Obviously, water with higher temperature has a lower density and this rule causes the hot water to lie in upper levels of the storage tank. In contrast with that, colder water lies in lower levels of the tank due to its higher density. Stratified tank models are divided into two categories: 1) The plug flow method in which divisions of liquid at different temperatures are presumed to move across the tank in plug flow, and 2) The multi-node method, in which a tank is divided into N different divisions (node) with different temperatures and densities. Writing the first law of thermodynamics law for each division leads to an N differential equations set which has to be solved simultaneously for the temperature of the N divisions as function of time. Obviously, more node numbers makes a set with more differential equations which make the computations more difficult, though it could result to more accurate conclusions. The best choice for the node numbers is suggested by the experts[50]. Consequently, a three-node tank has been chosen in the proposed system as schematically illustrated in Figure 3.

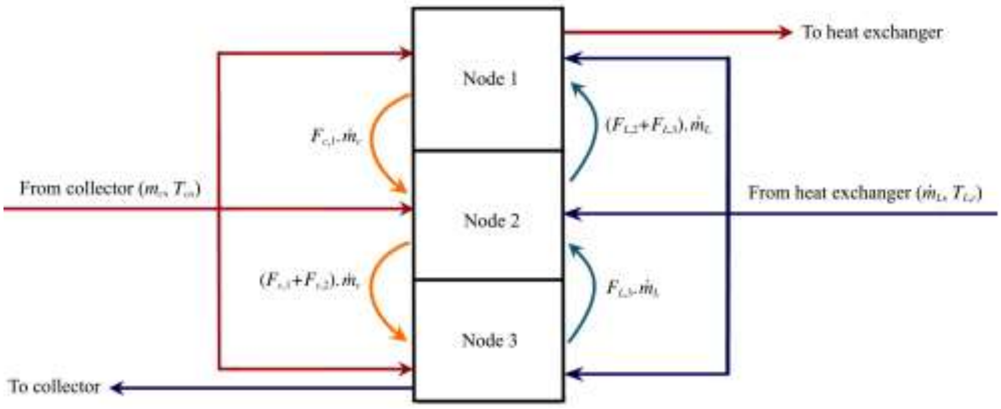

Figure 3   Schematic diagram of three- node storage tank

The collector outlet water enters the tank at a temperature T_{co}. The entrance water lies at a node which has the closest temperature to T_{co}. The collector entrance water comes from the lowest node of the tank (here node 3), and the outlet flow from the tank to the load (the heat exchanger) always leaves from the top node (here node 1). The returning water from the heat exchanger to the storage tank also lies in the node with closer temperature to itself. A coefficient F_i^c can specify which node receives water from the collector. This coefficient could be defined as follows:

$$F_i^c = \begin{cases} 1 \quad if \quad i = 1 \;\; and \;\; T_{co} > T_{s,i} \\ 1 \quad if \quad T_{s,i-1} \geq T_{co} > T_{s,i} \\ 0 \quad if \quad i = 0 \;\; or \;\; if \quad i = N + 1 \\ 0 \quad otherwise \end{cases} \tag{10}$$

where, $T_{s,i}$ refers to the temperature of node i. A fictitious temperature $T_{s,0}$ of the nonexistent node zero is presumed to be large number. Also, F_i^L, which can determine which node receives water from the heat exchanger could be described as follows:

$$F_i^L = \begin{cases} 1 \quad if \quad i = 1 \;\; and \;\; T_{L,r} > T_{s,i} \\ 1 \quad if \quad T_{s,i-1} \geq T_{L,r} > T_{s,i} \\ 0 \quad if \quad i = 0 \;\; or \;\; if \quad i = N + 1 \\ 0 \quad otherwise \end{cases} \tag{11}$$

The mass flow rate between different nodes can be either positive or negative depending on the collector size, mass flow rate value to the exchanger and the two above defined control coefficients at any specific moment. The net mass flow rate from node *i-1* to node *i* could be defined as a function as follows:

$$\begin{cases} \dot{m}_{m,1} = 0 \\ \dot{m}_{m,1} = \dot{m}_c \sum_{j=1}^{i-1} F_j^c - \dot{m}_L \sum_{j=i+1}^{N} F_j^L \\ \dot{m}_{m,N+1} = 0 \end{cases} \tag{12}$$

Considering the three described control functions, the energy balance for node i could be written as follows:

$$m_i \frac{dT_{s,i}}{dt} = (\frac{UA}{C_p})_i (T_a - T_{s,i}) + F_i^c \dot{m}_c (T_{co} - T_{s,i}) + \dot{Q}_{h-ex} + \begin{cases} \dot{m}_{m,i}(T_{s,i-1} - T_{s,i}) & if \quad \dot{m}_{m,i} > 0 \\ \dot{m}_{m,i+1}(T_{s,i} - T_{s,i+1}) & if \quad \dot{m}_{m,i+1} < 0 \end{cases} \quad (13)$$

where, $\dot{Q}_{h-ex}$ is the taken energy from the storage tank by the heat exchanger at any particular instant and could be obtained from the following equation.

$$\dot{Q}_{h-ex} = F_i^L \dot{m}_L (T_{L,r} - T_{s,i}) \quad (14)$$

In which, T_a, $\dot{m}_c$, $\dot{m}_L$, $T_{L,r}$ represent ambient temperature, the mass flow rate from the collector to the storage tank, water mass flow rate to the heat exchanger and the temperature of returning water from the heat exchanger to the tank, respectively[40-46]. For solving Equation (13), numerical methods have to be employed. There are many numerical solutions such as the explicit Euler, the implicit Crank-Nicolson and Runge-Kutta methods which could be used to this affair. The Runge-Kutta method has been applied in this work[50].

The second control volume is the greenhouse. Taking into consideration of the available solar heat, the required heat to reach the favorable temperature in the greenhouse could be obtained by the equation below:

$$\dot{Q}_{GR} = \dot{Q}_{lost} + \dot{Q}_{vent} - \dot{Q}_{solar} - \dot{Q}_{load} \quad (15)$$

All the parameters on the right hand of the equation above have been comprehensively discussed before. Thus, the consuming fuel mass flow rate for providing the greenhouse energy demand in presence of the proposed solar heating system can be given by the following equation:

$$\dot{m}_f = \frac{\dot{Q}_{lost} + \dot{Q}_{vent} - \dot{Q}_{solar} - \dot{Q}_{load}}{LHV \cdot \eta_h} \quad (16)$$

2.6 Economic analysis

There is an important inquiry about this project yet. How do we want to determine about the proposed system capacity? How many collectors and what capacity for the storage tank is the optimum values?

The answer of these main questions is latent behind an economical survey method. As it is described through this evaluation method, the different costs of capital values graph for each optimization system have to be drawn by the corresponding benefits graph at the same chart. The intersection point of the two graphs could lead us to the best choice as the initial investment[50]. It is also noteworthy that the previous studies show that the best storage tank capacity per each collector is 100 L[48].

Every system which is proposed to be employed in industry has to be evaluated whether or not is able to add benefits to the investors. There are several techniques that could be employed for evaluating the effectiveness of the proposed systems such as simple pay back ratio method, Internal Rate of Return (IRR) and Net Present Value (NPV). The NPV method is a comprehensive manner which includes all secondary costs such as inflation and R&M costs. The following equation could be applied to calculate NPV:

$$NPV = \sum_{t=1}^{N} \frac{R_t}{(1+i)^t} \quad (17)$$

where, i, t represent interest/inflation rate and the time of cash flow respectively, while R_t is the net cash flow, i.e., cash inflow subtracts cash outflow[51]. The equation above could specify that after how many years the capital cost could be returned by the proposed system.

3 Results

3.1 Climate data

One of the most important required data through performing the thermo-economic analysis on the proposed system is climate data for the location where the greenhouse is placed. Figure 4 shows Azadshahr city temperature in monthly-hourly average form for 2011. As expected, the warmest month of the year is August in which monthly average ambient temperature reaches to

33°C and the coldest month is January in which the monthly average temperature comes down to 3°C. One of the main parts of the calculation procedure also depends on the absorbable solar flux by different walls and also the greenhouse ceiling which could be calculated by employing Equation (4) and Table 3.

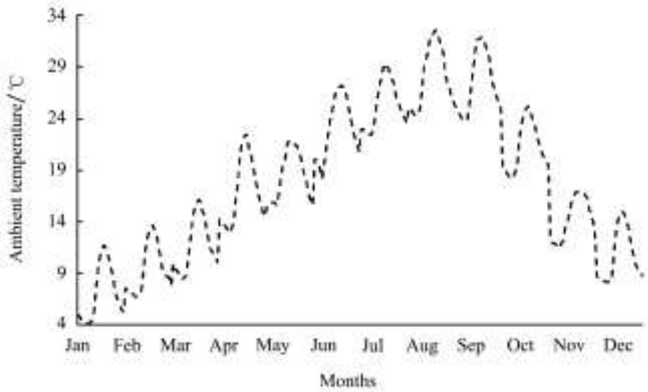

Figure 4 Ambient temperature for Azadshahr city in 2011

3.2 Greenhouse structure heat

Figure 5 presents the total solar heat gained by the greenhouse and both ventilation and walls heat lost values from the greenhouse. Both heat losts to the environment have almost the same order while the total solar heat gained is drammatically more. Especially in the warm months of the year (i.e. from April to September). The total solar heat gain varies from 150 kW in January and December as well to about 340 kW in June and July. On the other hand, the maximum heat loss from walls and ventilation losses take place in January which are around 145 kW and 80 kW respectively. It is also noteworthy that there is no energy loss from early June up to late September.

3.3 Proposed system

The optimum slope angle of the collectors should be selected based on maximizing solar energy absorption. Figure 6 shows the effects collector slop angle on annual solar energy absorption by one collector. It could be realized that optimum slop ange for Azadshahr is 45°.

Figure 7 shows the hourly averaged solar absorbed energy and solar gained energy by water by one collector (monthly averaged too) during sunshine till sunset of each day for the whole 2011. As expected, the absorbed flux is highest at noon.

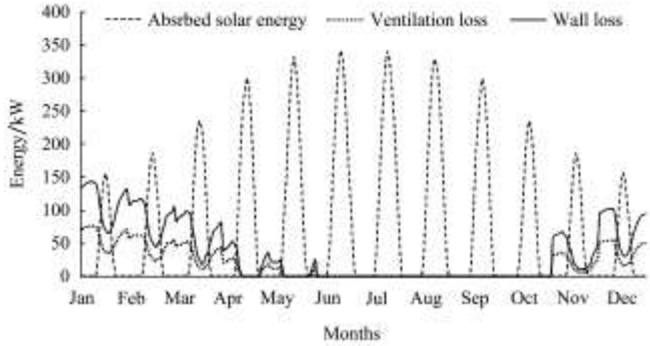

Figure 5 Total solar heat gain and heat loss for the greenhouse in 2011

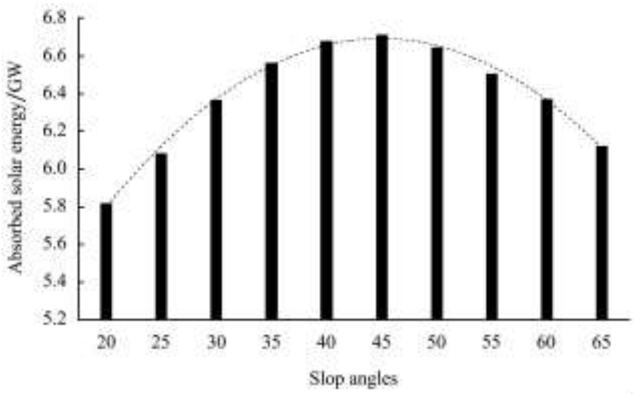

Figure 6 Maximum annual absorbed solar flux variation versus slop angle

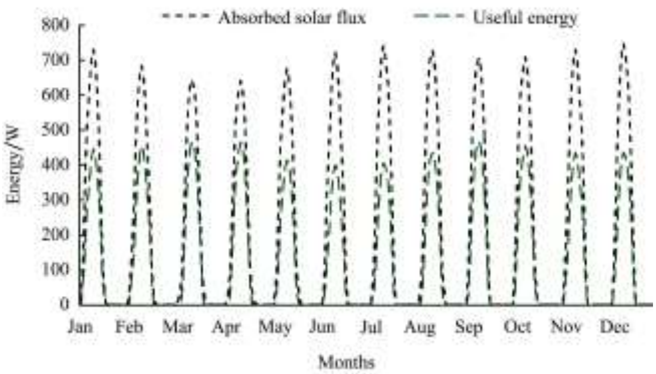

Figure 7 Absorbed solar flux and useful energy gain for each collector

Figure 8 shows instantaneous efficiency as a function of DT/I and ($\frac{T_{pm}-T_{am}}{I_T}$) for the utilized collector.

Obviously from the figure, the efficiency drops as *DT* increases.

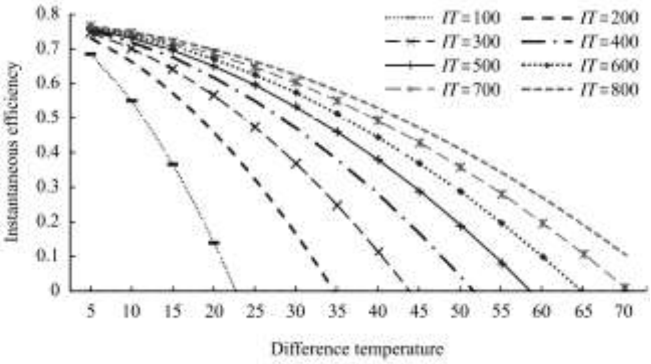

Figure 8 Instantaneous efficiency for the utilized collector as a function of *DT*/*I*

Figure 9 shows the average hourly temperature of different nodes of the storage tank different months of 2011. The maximum reachable temperature is around 75°C, which occurs in September and the least reached temperature is around 50°C in January.

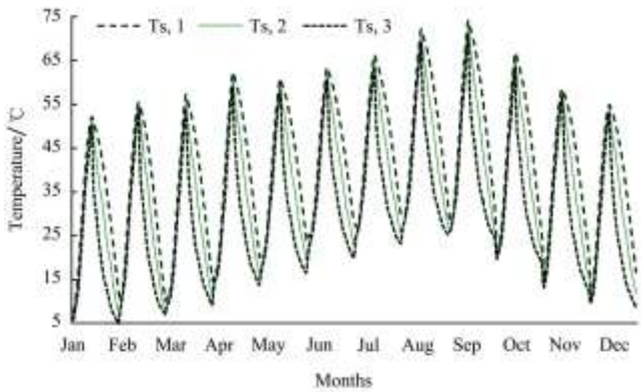

Figure 9 Different nodes temperature in the storage tank in 2011

Figure 10 shows the hourly water mass flow rate between the storage tank and the heat exchanger in different months of 2011. As it is expected from sunset to sunrise the mass flow rate is zero and then it increase. It is also obvious that the maximum and minimum mass flow rates take place in Feburary and June respectively.

After analyzing the storage tank, heating duty of the heater in presence of the proposed solar heating system could be specified. Figure 11 presents a comparison of the heater heating duty before/after employing the proposed sytem in the greenhouse. As the figure shows, in the warm months of the year (from July to November), no providence is occurred because the greenhouse could provide its required heat from the environment. On the other hand, lower environment temperatures could lead to better performances for the proposed system in fuel saving. Therefore, the proposed system leads to more benefits in Winter and Fall. The computation of the heating duty of the heater reveals that the total burned fuel by the heater before the application of the proposed system has been 41 105 L per year while this value could decrease by 27% and fall to 30 055 L per year by employing the proposed system.

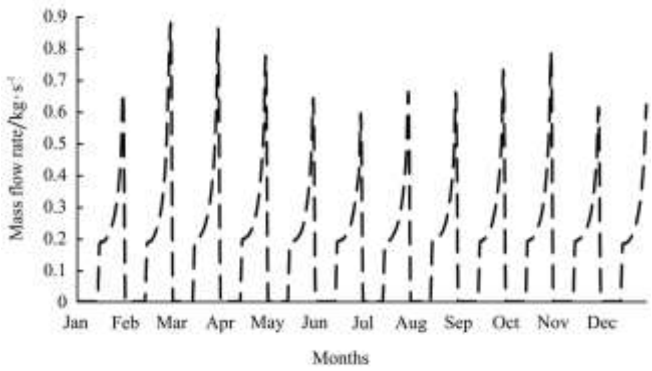

Figure 10 Water mass flow rate from the storage tank to the heat exchanger

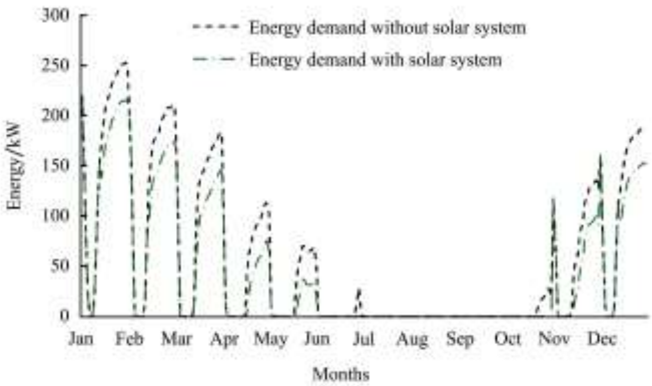

Figure 11 Greenhouse energy demand with/without the proposed solar system in 2011

3.4 Economic analysis

Figure 11 has been plotted based on 85 collector numbers and a storage tank with volume of 8.5 m^3. As described already, the collector numbers and consequently the storage tank capacity must be optted based on an economical survey. Figure 12 demonstrates how the conclusions have led to these values.

As the figure shows, the total capital cost of 38 250 USD is needed to run the proposed system. Figure 13 reveals the total monthly obtainable benefit by employing such system in the typical greenhouse. As the figure proves, the first three and the last two months of the year, as the coldest months of the year, have the highest values of fuel saving just in contrast with the middle months of the year (as warm months), in which no fuel providence occurred.

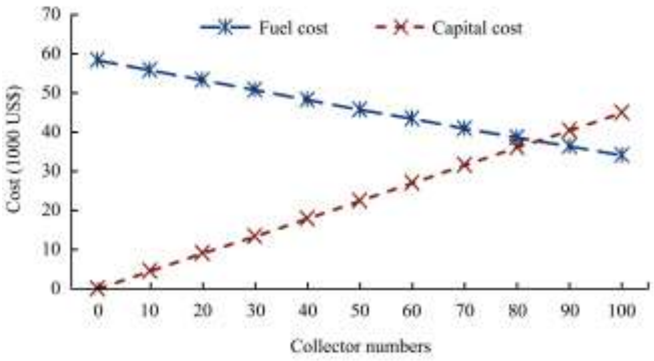

Figure 12 Optimum cost of capital for the proposed investigation

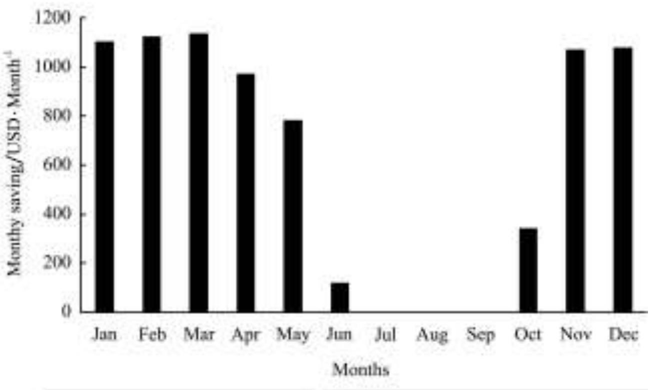

Figure 13 Total monthly benefit (USD/month)

Regarding this figure, the proposed system could result in an annual saving of 7 735 USD. It is noteworthy here that, no separate figure for the total monthly fuel saving has been presented because it has exactly the same trend as the above figure. For calculation of the total saved fuel in each month, the total providenced money should be devided to 0.7 (Fuel price per litter). It should be noted that the extracted climate data reveal that Azadshahr city is sunny in about 60% of the year and in other time of the year is rainy or cloudy which makes it impossible to access solar radiation. The percentage of 60% should be considered in calculation processes.

Employing *NPV* method indicates that the payback ratio for the proposed system is about 10 years with taking into consideration the interest rate of 6% and R&M costs based on the solar system seller company advice which is 5% of the cost of capital. Figure 14 illustrates the details of NPV analysis of the proposed system.

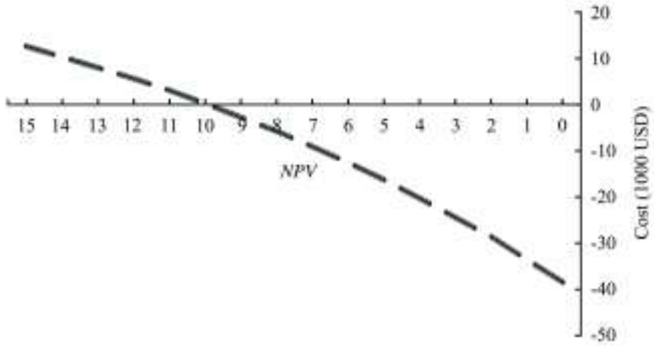

Figure 14 NPV analysis of the proposed system

4 Conclusions

There are many places in industry which have high potential to be equipped with renewable and sustainable energies in order to optimize fossil fuel consumption. Greenhouses are one of these places in agricultral industry. This research reveals that employing the proposed system including 85 flat plate collectors and a 8.5 m^3 storage tank, and considering global gas oil price (0.7 USD pe litter) could result in 7 735 USD annual benefit (11 050 L gas oil) and payback period of 10 years for the studied greenhouse. Considering this fact that, the annual fuel consumption of the greenhouse before the utilization of the proposed system has been 41 105 L. Therefore, this system could reduce the fuel consumption by 27% to 30 055 L per year. As solar facilities usually could present a useful performance in about 25 years, therefore the proposed system is strongly recommended to be employed. Considering this fact that the typical greenhouse, which has been studied through this work, is located in the north of Iran which has a moderate weather (the solar system could be utilized in only 60% of days), the proposed system even could lead to better results in more sunny weather.

Nomenclature

C_{pw} Water heat capacity

F_R Removal factor

m_{st} Mass of exist water in the storage tank, kg

$\dot{m}_f$ Mass flow rate of fuel consumed by the heater, kg/s

$\dot{Q}_{GR}$ Greenhouse energy demand, kW

$\dot{Q}_{lost}$ Total heat lost from the greenhouse walls, kW

$\dot{Q}_{vent}$ Total ventilation heat lost from the greenhouse, kW

$\dot{Q}_{solar}$ Total solar heat gain by the greenhouse, kW

T_a Ambient temperature, ^oC or K

T_{st} Temperature of water in the storage tank, ^oC or K

T_w Temperature of water in the tank, ^oC or K

T_{fi} Inlet working fluid temperature, ^oC or K

T_{pm} Average temperature of absorber plate, ^oC or K

U Total heat transfer coefficient, W/(m^2 ·K)

I Available solar radiation, W/m^2

N Air change number per hour

V The greenhouse volume, m^3

S Absorbed solar flux, W/m^2

U_l Overall heat loss coefficient, W/(m^2 ·^oC)

I Available solar radiation, W/m^2

Greek symbols

η_h Heater efficiency

η_i Collector efficiency

$(\tau\alpha)_{av}$ Average absorption-transmission coefficient of collector

β Collector slop angle

γ Collector azimuth angle

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