JOURNAL OF ENERGY SYSTEMS

2021, *5*(4)

2602-2052

DOI: 10.30521/jes.950754

Review Article

Energetic and economic analysis for improving greenhouse energy efficiency

Laila Ouazzani Chahidi
SIGER, Intelligent Systems, Georesources and Renewable Energies Laboratory, Faculty of Sciences and Technologies, Sidi Mohamed Ben Abdellah University, Fez, Morocco. laila.ouazzanichahidi@usmba.ac.ma
Abdellah Mechaqrane
SIGER, Intelligent Systems, Georesources and Renewable Energies Laboratory, Faculty of Sciences and Technologies, Sidi Mohamed Ben Abdellah University, Fez, Morocco. abdellah.mechaqrane@usmba.ac.ma

Submitted: *16.06.2021*
Accepted: *01.11.2021*
Published: *31.12.2021*

Abstract: Protected agriculture is one of the prominent agricultural techniques. It allows for creating an adapted microclimate to the plant growth, which leads to high quality and off-season production. Instead, a significant amount of energy is required. This study aims to provide the potential of energy saving based on the optimal selection of the greenhouse design under Fez City’s climatic conditions (Morocco). For this purpose, a dynamic model of a gothic-arch-shaped greenhouse is created in EnergyPlus environment. The impact of four different orientations (0°, 90°, 45° and - 45°) on greenhouse energy needs is first investigated. The selected design is further improved by using a thermal insulation blankets system operating during the coldest months and deploying from the sunset to sunrise. To define the prospect of the energy saving, two variables were primarily evaluated: the greenhouse inside air temperature variation and thermal loads prompted by creating the optimum microclimate for tomato plant. Finally, an economic analysis is performed. The results show that 0° relative north (longer axis) is the optimal orientation for a gothic-arch greenhouse and that the thermal insulation blankets allow for reducing 17 % of the greenhouse heating needs under the climate conditions of Fez

Keywords: *Agricultural greenhouse, Energy modeling, EnergyPlus, Insulation, Orientation*

Cite this paper as: Chahidi, LD., Mechaqrane, A., Energetic and economic analysis for improving greenhouse energy efficiency. Journal of Energy Systems 2021; 5(4): 296-305, DOI: 10.30521/jes.950754

Nomenclature		**Greek**		**Subscripts**	
EER	Energy efficiency ratio	α_f	Fractional vegetation coverage	$cond$	Conduction
HDPE	High density polyethylene	ε_1	$\varepsilon_g + \varepsilon_f - \varepsilon_f \varepsilon_g$	$conv$	Convection
$\dot{Q}''_{conv}$	Convective heat flux rate (W/m^2) ;	ε_f	Emissivity of the foliage layer	f	Foliage layer
$\dot{Q}''_f$, $\dot{Q}''_g$	Net heat flux rate to foliage layer and ground surface respectively (W/m^2)	ε_g	Emissivity of the ground surface	ir	Long-wave
$\dot{Q}''_{ir}$	Short-wave radiation flux rate (W/m^2)	η	Boiler efficiency	glz	Glazing surfaces
$\dot{Q}''_{lat,f}$, $\dot{Q}''_{lat,g}$	Foliage and ground latent heat flux respectively (W/m^2)	ρ_g	Ground reflectance	opq	Opaque surfaces
$\dot{Q}''_{sens,f}$, $\dot{Q}''_{sens,g}$	Foliage and ground sensible heat flux respectively (W/m^2)	σ	The Stefan-Boltzmann constant $6.699.10^8 (W/m^2.K^4)$	sw	Short-wave
$\dot{Q}''_{sw}$	Long-wave radiation flux rate (W/m^2)	σ_f , σ_g	Albedo (short wave reflectivity) of the foliage layer and the ground surface respectively		
T_f	Foliage layer temperature (K)				
T_g	Ground surface temperature (K)				

1. INTRODUCTION

Currently, climate change, disappearance of fossil fuels, population growth, constant increase of energy needs and other numerous constraints are facing the world. Therefore, opting for energy efficient systems has become an unavoidable necessity [1, 2]. Protected agriculture is one of the highly productive techniques. Moreover, its yield per cultivated area is 10 times more important than that of free field cultivation [3]. Being one of the energy-intensive systems, agricultural greenhouse ought to be a part of the energy transition strategies. Therefore, energy optimization must be considered at the earliest stages of the greenhouses construction. The greenhouse heating and cooling energy needs undoubtedly depend on its design and geographic localization. Thus, in specific climatic conditions and for a particular type of cultivation, the greenhouses design should be chosen to maintain, as much as possible, adequate microclimate parameters.

To select the greenhouse suitable design and to assess the resulting energy-saving potential, dynamic modeling and simulations are essential. Several researchers have been, for a long, interested in modeling greenhouse microclimate using several tools. Sharma et al. [4] modeled the microclimate of a greenhouse located in Delhi, India, based on energy balance equations. Their object was to study the distribution of air temperature inside the greenhouse by dividing the latter into four horizontally zones. The impacts of heat capacities of the plants and the greenhouse, air infiltration and relative humidity on the plant and inside air temperatures were also investigated. Their main result showed that the difference of temperatures between the studied zones is minor. Based on the Computational Fluid Dynamic (CFD) method, Lokeswaran and Eswaramoorthy [5] presented a numerical and experimental analysis of a solar greenhouse drier. The numerical model prediction was in agreement with the experimental measurement with an error rate below 20%. Fatnassi et al. [6] simulated, also using CFD method, solar radiation distribution and inside air temperature distribution and circulation into two greenhouse shapes; glass Asymmetric and Venlo greenhouses. The aim of their study was to analyze the effect of roof PV panels' arrangements on the greenhouses microclimate. According to them, checkerboard arrangement was found to be better than straight line. Kıyan et al [7] developed a dynamic simulation method using Matlab/Simulink environment to study the thermal behavior of a greenhouse heated by an hybrid system (solar collectors with a fossil fuel auxiliary heater). Based on this model, they estimated the auxiliary fuel-heater consumption, the inside air and water stored temperatures. Using TRNSYS tool, Vadiee and Martin [8] evaluated several single and combined energy-saving measures in a commercial greenhouse under Nordic climatic conditions. Double thermal screens, double glazing and closed greenhouse concepts were found to be the most beneficial measures. In a recent work, Liu et al. [9] proposed a one-dimensional transient model, to predict the inside air temperature and humidity in a Chinese greenhouse. The predictions were done using only weather parameters, and the model was validated using data collected from two different greenhouses (Chinese greenhouses with different dimensions and cover). According to them, the model could be adapted and used in different Chinese solar greenhouses. In another recent study [10], different passive techniques (shading glaze surface, operable windows for natural ventilation) and renewable energy based strategies (roof semitransparent PV panels, and HVAC system with a ground-coupled heat pump) was studied. For that a dynamic model of the high-efficiency greenhouse "SamLab" (located in Albenga, Italy) is created in EnergyPlus Environment and validated using experimental measurement from the greenhouse [11]. A significant potential of energy saving was ensured by adopting the proposed strategies.

The greenhouse design significantly influences the solar heat gains and thus the microclimate of the greenhouse. Its optimal selection could help reducing the amount of energy consumption in a passively way, which promoted the interest of the scientific community. Many researchers were interested in optimizing the greenhouse shape [12], cover [13] and orientation. To evaluate energy comportment of greenhouse with different orientations, research is conducted. Gupta et al. [14] studied the effect of the greenhouse orientation (0° / 30° / 45° / 60° / 90°) and area (4 m×6 m / 4 m×12 m / 12 m×18 m) on the total solar fraction transmitted based on a 3D shadow analysis in Auto-CAD software. The comparison was done based on a typical clear day of winter and summer, under the climatic condition of New Delhi, India, considering only the beam solar radiation. Their results show that the greenhouse oriented 45° clockwise (Relative East–West orientation) resulted on the lowest radiation loss during winter and maximum one during summer. In another work, Dragićević [15] analyzed the total solar radiation availability in an uneven-span greenhouse located in Belgrade, Serbia in East-West and North-South orientation (longer axis). Based on the measured global solar radiation on a horizontal surface, the total incident solar radiation was calculated. The model adopted in their study was experimentally validated by comparing the predicted and measured daily average of incident solar radiation on a horizontal surface and on the south wall. According to them, an EW oriented uneven-span greenhouse is the best one. Exhaustive reviews on this field have been presented. Odesola and Ezekwem [16] reviewed the effect of greenhouse's shapes and orientation studies. Choab et al. [17] presented a comprehensive review on the developments and research conducted on greenhouses from different standpoints; greenhouse design, thermal modeling and simulation, and climate controlling technologies.

The literature review showed that the optimal greenhouse design depends strongly on the site localization and climatic conditions. Also, the selection of the optimal one could help maintaining an adequate microclimate and leading to decrease the heating and cooling loads, thereby the operating cost. The aim of this study is first to evaluate different greenhouse orientations (0°, 90°, 45° and -45°), in order to select the most suitable one in terms of energy optimization. Then, to further improve the greenhouse energy efficiency by using a thermal insulation blankets system operating in night, during the coldest months. For this purpose, a dynamic energy model is created in EnergyPlus environment of a gothic-arch greenhouse by considering as location the Moroccan city of Fez (33.93° N, 4.98° W, 579 m). To assess the potential of energy saving, two variables were first evaluated: the inside air temperature variation and thermal loads in tomato greenhouse. Finally, an economic analysis is performed.

2. METHODOLOGY

The aim of this study is to assess the energy-saving potential generated from the optimal selection of a tomato greenhouse design under the climatic condition of Fez, Morocco. On a previous authors' investigation [18] 36 different combinations were compared; nine shapes (standard span, uneven span, single slope, mansard, modified-IARI, quonset, modified-quonset, gothic-arch, modified-gothic-arch) and four covering materials (glass, LDPE, BPE, EVA). Based on the previous study, the combination of Gothic arch and bubbled polyethylene (BPE) plastic has been selected as the optimal shape and covering material, respectively, under the climatic conditions of Fez, Morocco. The studied greenhouse is of an area of 220 m² (20 m×11 m) with a height of 6 m. Fig. 1 represents the greenhouse 3D model created in SketchUp graphical interface. In this study, four greenhouse orientations are first considered; 0°, 90°, 45° and - 45° relatively to the north direction (longer axis). Then, a further improvement of the selected design is studied, namely the use of thermal insulation blankets, which is, in this study, the high-density polyethylene (HDPE), opaque material with a relatively low thermal conductivity operating from sunset to sunrise.

The modeling and simulations are carried out in EnergyPlus software. The greenhouse is modeled as a single zone interacting with its outside environment as well as with its interior components (plants and soil). The loads calculation is based on the air energy balance of the zone and the different greenhouse components, where the transparent surfaces are considered as windows (Eq. 1) and opaque ones as walls (Eq. 2). The energy balance equation is solved in the time domain based on a third order backward approximation of the zone temperature derivative with a time step calculation of 6 times per hour. Moreover, the soil and plants are defined in EnergyPlus as the floor material layers, respectively. Their effect is considered based on the FASST model [19], developed for the US Army Corps of Engineers by Frankenstein and Koenig, as presented in Eqs. (3, 4).

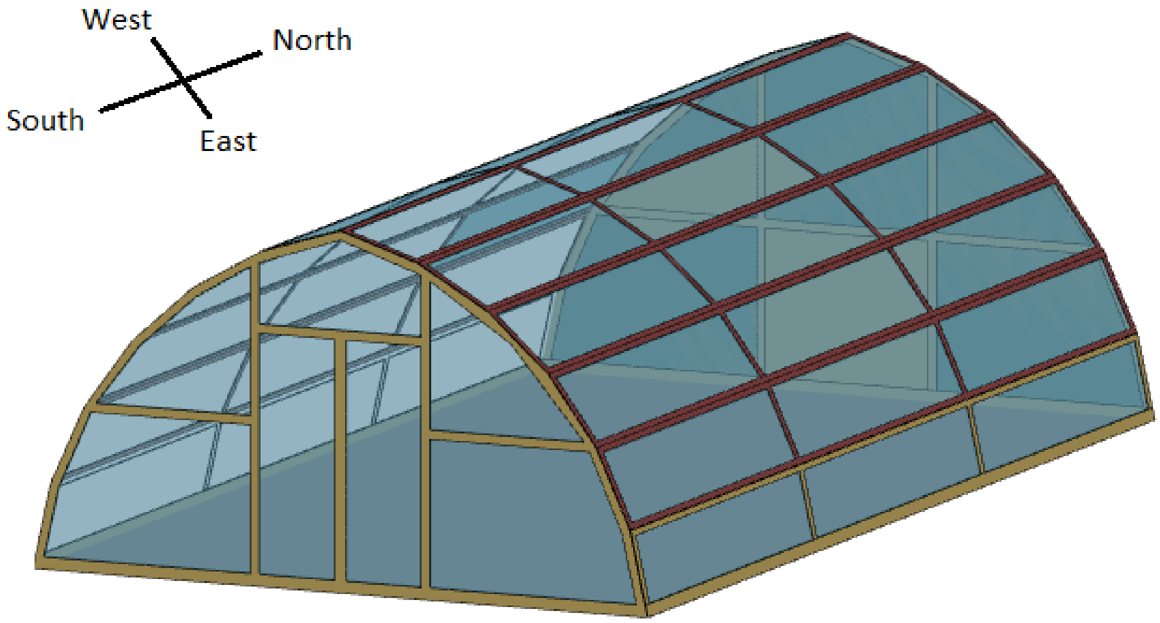


Figure 1. Greenhouse 3D model (orientation 0°).

Transparent surfaces energy balance:

$$\dot{Q}''_{ir,glz} + \dot{Q}''_{sw,glz} + \dot{Q}''_{conv,glz} + \dot{Q}''_{cond,glz} = 0 \tag{1}$$

Opaque surfaces energy balance:

$$\dot{Q}''_{ir,opq} + \dot{Q}''_{sw,opq} + \dot{Q}''_{conv,opq} + \dot{Q}''_{cond,opq} = 0 \tag{2}$$

Plant layer energy balance:

$$\dot{Q}''_{f} = \sigma_f \left[G_{sw}(1-\alpha_f) + \varepsilon_f G_{ir} - \varepsilon_f \sigma T_f^4 \right] + \frac{\alpha_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1}(T_g^4 - T_f^4) + \dot{Q}''_{sens,f} + \dot{Q}''_{lat,f} \tag{3}$$

Soil layer energy balance:

$$\dot{Q}''_{g} = (1-\sigma_f)[G_{sw}(1-\alpha_g) + \varepsilon_g G_{ir} - \varepsilon_g \sigma T_g^4] - \frac{\alpha_f \varepsilon_g \varepsilon_f \sigma}{\varepsilon_1}(T_g^4 - T_f^4) + \dot{Q}''_{sens,g} + \dot{Q}''_{lat,g} + k_g \frac{\partial T_g}{\partial z} \tag{4}$$

In this study, the climate data of the city of Fez, Morocco is obtained from Meteonorm software and the simulation is conducted over a year. Table 1 represents the greenhouse parameters used for modeling.

Table 1. Greenhouse parameters.

Site localization	
City	Fez
Longitude	4.98° W
Latitude	33.93° N
Altitude	579 m
Covering material	
Material	BPE
τ_{PAR}	63 %
ρ_{PAR}	14 %
α_{PAR}	23 %
τ_{NIR}	68 %
ρ_{NIR}	14 %
α_{NIR}	18 %
Q	63 %
Thermal insulation blankets	
Material	HDPE
Thickness	5 mm
Conductivity	0.5 W/m K
Density	960 kg/m^3
Plant	
Name	Tomato
Height	1 m
Leaf area index	4
Minimum stomatal resistance	120 s/m
Soil	
Conductivity of dry soil	0.35 W/m K
Density of dry soil	1100 kg/m^3
Specific heat of dry soil	600 J/kg K
Solar absorptance	0.7

3. RESULTS AND DISCUSSIONS

Simulations are first performed separately for the four greenhouse orientations. Thereafter, the analysis of the greenhouse thermal behavior is conducted to investigate the impact of its orientation; first on the inside air temperature without an air conditioning system, then on the thermal loads for heating and cooling by considering the adapted microclimate for tomato plant (mean daily value of 21 °C and relative humidity of 75 % [20, 21]). Finally, the annual energy cost of the air conditioning system is estimated and the operational cost reduction generated from the right selection of the greenhouse orientation is evaluated. After selecting the optimal orientation, the greenhouse energy efficiency is further improved by using a thermal insulation blankets system, operating during night in the coldest months. To assess the potential of energy saving generated through the use of this nightly insulation system, the thermal loads of the greenhouse with and without the system are compared, and the economic benefit is presented.

3.1 External Temperature

The climate data of Fez City, Morocco are downloaded from Meteonorm software. Fig. 2 presents the monthly variation of the minimal, mean and maximal temperatures. The monthly mean temperature varies between 9.37 °C in the month of January and 27.19 °C in the month of July. During the whole year, the minimal and maximal monthly temperatures are around 3.82 °C and 35.12 °C observed in

January and July, respectively. Having the extreme temperatures, it can be considered that the month of January is the coldest month and July is the hottest one in Fez, Morocco.

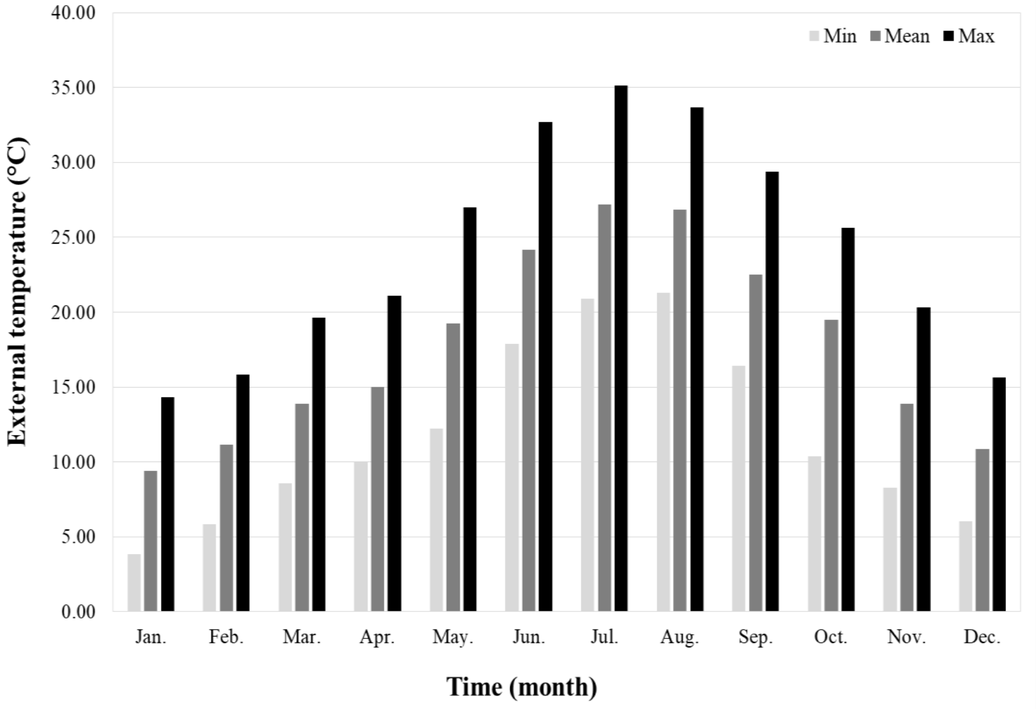
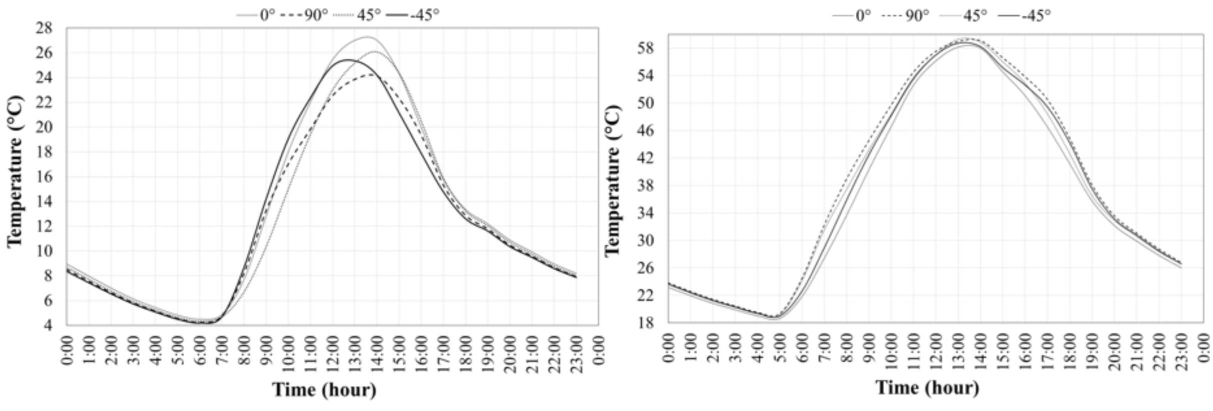


Figure 2. Monthly minimal, mean, and maximal outside air temperature.

3.2. Orientation

3.2.1. Inside air temperature

Based on the previous consideration (sub-section 3.1) and in order to clearly assess the greenhouse inside air temperature variability depending on the greenhouse orientation, January 15th (winter) and July 15th (summer) are considered, as presented in Fig. 3. As a general observation of the graphs, the effect of the orientation on the greenhouse inside air temperature is clear during winter compared to summer, especially in the hours when the sun is high in the sky. Since the sun is the major source of thermal loads in agricultural greenhouses and since the system is transparent from the four sides, it is obvious that the temperature effect seems more noticeable during winter when solar altitude is lower than that of summer.



(a) *(b)*

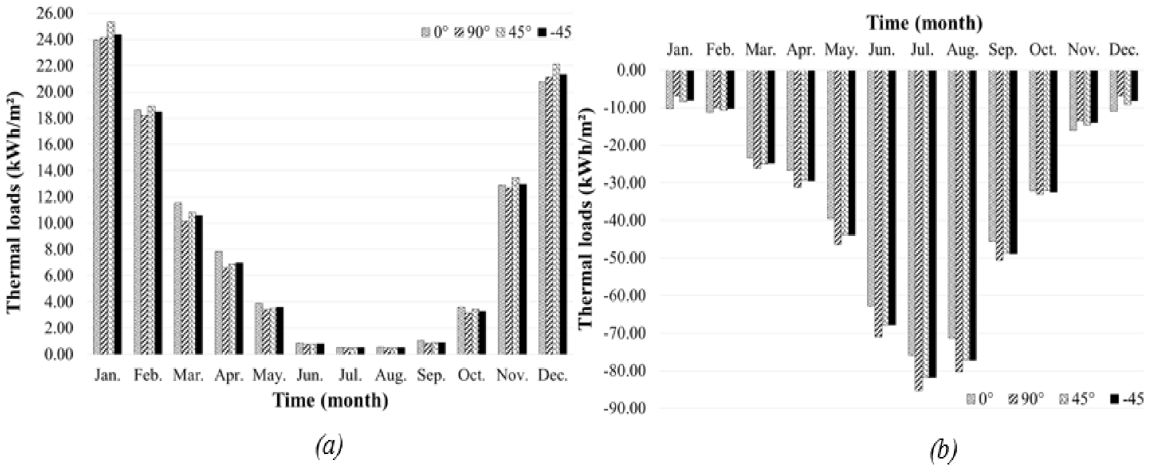
Figure 3. Inside air temperature for different orientations: (a) Winter, January 15th (b) summer, July 15th.

During winter, the temperature does not exceed 28 °C. The maximal temperature is obtained when the orientation is 0° relative north while orientations 90°, 45° and - 45° provide smaller air inside temperature with a maximal difference of about 3 °C at 13h00, 10h00 and 15h00 respectively. In summer, the higher temperature during the day reaches 59°C. The orientation 0° provides the minimal temperature during the whole day. The maximal difference is about 5 °C, 4 °C and 3°C for 90°, 45° and - 45° orientations respectively.

3.2.2. Heating and cooling requirements with different orientations

This section presents the effects of orientation on reducing heating and cooling requirements. The comparison is based on the monthly thermal loads of the greenhouse. 21 °C is assigned as a mean daily set point temperature.

Fig. 4 shows the greenhouse monthly heating and cooling loads. Based on the graphs, the maximal heating and cooling requirements occurs during the month of January and July respectively. In January, the heating loads of the greenhouse oriented 0°, 90°, 45° and -45° are about 23.96, 24.13, 25.36 and 24.36 kWh/m^2, respectively. For the cooling loads, amounts of about 75.84, 85.36, 81.85 and 81.84 kWh/m^2 are observed during the month of July.



(a) (b)

Figure 4. Monthly heating (a) and cooling (b) loads of the greenhouse with different orientations.

Finally, on an annual basis, the minimal heating loads (around 102.05 kWh/m^2) are observed in greenhouse oriented 90°, relatively to the north direction. For the other orientations, the heating loads are of about 104.28 kWh/m^2, 106.13 kWh/m^2 and 107.26 kWh/m^2 (+ 2 %, + 4 % and + 5 % compared to 90°) for - 45°, 0° and 45°, respectively. Although, the minimal cooling loads occur when the greenhouse is oriented 0° with a value around 427.20 kWh/m^2. For the other orientations, cooling loads of about 448.86 kWh/m^2, 450.42 kWh/m^2 and 463.24 kWh/m^2 (+ 5 %, + 5.5 % and + 8.4 % compared to 0°) are obtained in - 45°, 45°, and 90°, respectively.

3.2.3 Economic analysis of the impact of orientation

To evaluate the financial gain obtained from the optimal selection of the greenhouse orientation, a comparison on the annual basis is conducted. The annual energy operating cost is calculated for each orientation and considered as the main indicator to select the optimal one. In this study, a standard conventional system for the greenhouse air conditioning is selected. This system is composed by a boiler with a top efficiency $\eta = 0.96$ and a chiller for cooling purpose with $EER = 3.5$. In Morocco, electricity consumers associated to the agricultural sector benefits from a special pricing “green tariff”. In this pricing mode, the electrical kWh price depends on several parameters; season, time of the day, and others. The electrical kWh price considered in this study is 0.9 MAD/kWh.

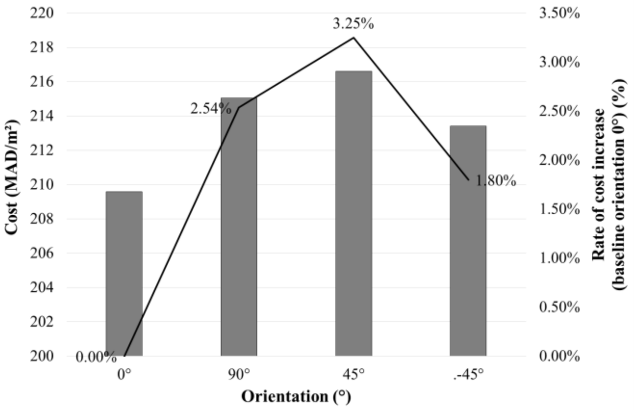


Figure 5. Annual energy cost for the greenhouse air conditioning according to the orientations.

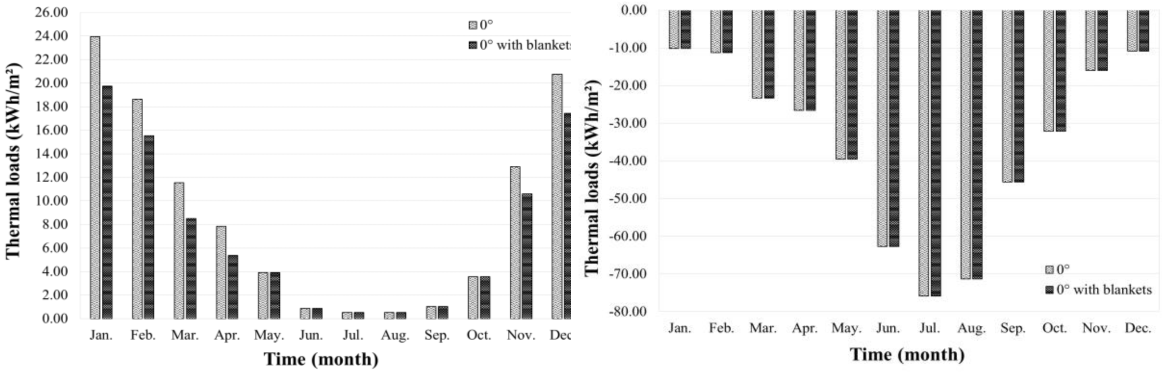
Fig. 5 represents the annual energy cost (MAD/m²) variation depending on the greenhouse orientation. It can be observed from the graph that the orientation of 0° relatively to the north direction is the optimal one with an annual energy cost of about 209.60 MAD/m². For the other orientations; - 45°, 90° and 45°, the annual energy cost is around 213.42 MAD/m², 215.03 MAD/m² and 216.62 MAD/m², respectively. The annual energy cost is more important in the case of greenhouses oriented - 45°, 90° and 45° compared to the greenhouse oriented 0°, with a rate of 1.80%, 2.54% and 3.25%, respectively.

3.3. Thermal blankets insulation

After analyzing the impact of the orientation on greenhouse energy requirements, the orientation of 0° relative to the north (longer axis) is selected. To minimize the greenhouse heating loads a thermal insulation blankets system operating from the sunset to sunrise is investigated. The system is active only on the months where the heating loads are important: from November to April. The thermal insulation blankets, used in this study, is the high-density polyethylene (HDPE), opaque material with a relatively low thermal conductivity that is used to protect the greenhouse from the potential heat losses during night in the coldest period.

3.3.1. Heating and cooling requirements using the thermal insulation blankets

Fig. 6 presents the heating and cooling requirements of the selected greenhouse with and without thermal insulation blankets system. It can be remarked from the graphs that this system has any effect on cooling loads since it is operating only in the coldest months (November to April) and during nights where only the heating is required. An annual heating requirement of about 106.13 kWh/m² is observed in the non-isolated greenhouse while an amount of only 87.68 kWh/m² is obtained when it is isolated. Thus, the heating requirements decreases with around 17%.



(a) (b)

Figure 6. Monthly heating (a) and cooling (b) loads of the greenhouse with and without the thermal insulation blankets.

3.3.2. Economic analysis of insulation by thermal blankets

In this study, the price of the selected thermal insulation blankets material is found to be 20 MAD/m² in the Moroccan markets, with a lifetime up to eight years. The financial gain obtained from the use of the insulation is calculated using the same approach as in the previous economic analysis (Section 3.2.3). Table 2 presents the total investment, financial gain and the payback time.

Table 2. Economic analysis of the greenhouse with thermal insulation blankets.

HDPE price/m²	Investment Area	Financial gain	Payback time
20 MAD/m²	6960 m²	3809.5 MAD/year	1 year 10 months

The financial gain obtained when insulating the greenhouse is of about 3809.5 MAD/year, equivalent to 17 % of heating needs reduction. Moreover, a payback time of one year and 10 months seems to be attractive compared to a lifetime period up to eight years.

4. CONCLUSIONS

In this study, different greenhouse orientations (0°, 90°, 45° and - 45° relatively to the north direction (longer axis)) are evaluated accordingly to the potential of energy saving. For this aim, a dynamic model of a gothic arch-shaped greenhouse is created in EnergyPlus environment. To determine the potential of energy saving resulting from the optimal selection of the greenhouse orientation, two variables were first examined: the greenhouse inside air temperature variation during winter day (15th January) and summer day (15th July), and thermal loads resulted from ensuring the adapted microclimate for tomato plant. Then, an economic analysis is performed by calculating the annual energy cost of the greenhouse with the different studied orientations. The annual energy cost is considered as the main indicator to select the optimal orientation. Finally, to evaluate the energy-saving thanks to thermal insulation blankets, the greenhouse energy requirements and the economic analysis are performed.

The results show that a gothic arch-shaped greenhouse with Bubbled polyethylene (BPE) plastic covering and oriented 0° relatively to the north direction (longer axis) are recommended for an optimal design of protected agriculture. This conclusion is obtained by considering the yearly energy cost of the air conditioning system for tomato plant's greenhouse in the climatic conditions of Fez, Morocco. The annual energy cost for the selected design is estimated 209.60 MAD/m², lower than the one of - 45°, 90° and 45° orientations by about 1.80 %, 2.54 % and 3.25 %, respectively. Furthermore, the energy efficiency of the greenhouse is improved by using thermal blankets as a nighttime insulation system during coldest months. An energy saving of about 17 % can be obtained by adopting such a system, with a payback period of one year and 10 months.

REFERENCES

[1] Avezova, NR, Toshev, JB, Dalmuradova, NN, Farmonov, AA, Mardonova, MSh. Renewable Energy: Scenario and Model of Development. *Appl. Sol. Energy* 2019; *55(6)*: 438–445, DOI: 10.3103/S0003701X19060021.

[2] Yavor, KM, Bach, V, Finkbeiner, M. Resource Assessment of Renewable Energy Systems—A Review. *Sustainability* 2021; *13*(11): 6107, DOI: 10.3390/su13116107.

[3] Taki, M, Ajabshirchi, Y, Ranjbar, SF, Rohani, A, Matloobi, M. Modeling and experimental validation of heat transfer and energy consumption in an innovative greenhouse structure. *Information Processing in Agriculture* 2016; *3*(3): 157–174, DOI: 10.1016/j.inpa.2016.06.002.

[4] Sharma, PK, Tiwari, GN, Sorayan, VPS. Temperature distribution in different zones of the micro-climate of a greenhouse: a dynamic model. *Energy Conversion and Management* 1999; *40*(3): 335–348, DOI: 10.1016/S0196-8904(98)00100-9.

[5] Lokeswaran, S, Eswaramoorthy, M. An Experimental Analysis of a Solar Greenhouse Drier: Computational Fluid Dynamics (CFD) Validation. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 2013; *35*(21): 2062–2071, DOI: 10.1080/15567036.2010.532195.

[6] Fatnassi, H, Poncet, C, Bazzano, M. M, Brun, R, and Bertin, N. A numerical simulation of the photovoltaic greenhouse microclimate. *Solar Energy* 2015; *120*: 575–584, DOI: 10.1016/j.solener.2015.07.019.

[7] Kıyan, M, Bingöl, E, Melikoğlu, M, Albostan A. Modelling and simulation of a hybrid solar heating system for greenhouse applications using Matlab/Simulink. *Energy Conversion and Management* 2013; *72*: 147–155, DOI: 10.1016/j.enconman.2012.09.036.

[8] Vadiee, A, Martin, V. Energy management strategies for commercial greenhouses. *Applied Energy* 2014; *114*: 880–888, DOI: 10.1016/j.apenergy.2013.08.089.

[9] Liu, R, Li, M, Guzmán, JL, Rodríguez, F. A fast and practical one-dimensional transient model for greenhouse temperature and humidity. *Computers and Electronics in Agriculture* 2021; *186*: 106186, DOI: 10.1016/j.compag.2021.106186.

[10] Ouazzani Chahidi, L, Fossa, M, Priarone, A, Mechaqrane A. Energy saving strategies in sustainable greenhouse cultivation in the mediterranean climate – A case study. *Applied Energy* 2021; *282*: 116156, DOI: 10.1016/j.apenergy.2020.116156.

[11] Ouazzani Chahidi L, Fossa M, Priarone A, Mechaqrane A (2021) Greenhouse cultivation in Mediterranean climate: Dynamic energy analysis and experimental validation. Thermal Science and Engineering Progress 26:101102 . https://doi.org/10.1016/j.tsep.2021.101102

[12] Sahdev, RK, Kumar, M, Dhingra, AK. A comprehensive review of greenhouse shapes and its applications. *Front. Energy* 2019; *13*(3): 427–438, DOI: 10.1007/s11708-017-0464-8.

[13] Rezaei, SD, Shannigrahi, S, Ramakrishna, S. A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment. *Solar Energy Materials and Solar Cells* 2017; *159:* 26–51, DOI: 10.1016/j.solmat.2016.08.026.

[14] Gupta, R, Tiwari, GN, Kumar, A, Gupta, Y. Calculation of total solar fraction for different orientation of greenhouse using 3D-shadow analysis in Auto-CAD. *Energy and Buildings* 2012; *47*: 27–34, DOI: 10.1016/j.enbuild.2011.11.010.

[15] Dragićević, SM. Determining the optimum orientation of a greenhouse on the basis of the total solar radiation availability. *Thermal Science* 2011; *15*(1)*:* 215–221, DOI: 10.2298/TSCI100220057D.

[16] Odesola, IF, et Ezekwem, C. The effect of shape and orientation on a greenhouse: a review. *AFRREV STECH: An International Journal of Science and Technology* 2012; 1(1): 122-130, eISSN: 2227-5444, print ISSN: 2225-8612.

[17] Choab, N, Allouhi, A, El Maakoul, A, Kousksou, T, Saadeddine, S, and Jamil, A. *Review on greenhouse microclimate and application:* Design parameters, thermal modeling and simulation, climate controlling technologies. *Solar Energy* 2019; *191:* 109-137, DOI: 10.1016/j.solener.2019.08.042.

[18] Ouazzani Chahidi, L, Mechaqrane, A. Greenhouse Design Selection in Moroccan Climatic Conditions. In: Bennani S., Lakhrissi Y., Khaissidi G., Mansouri A., Khamlichi Y. (eds) *WITS 2020. Lecture Notes in Electrical Engineering* 2022; 745. Springer, Singapore. DOI: 10.1007/978-981-33-6893-4_59.

[19] Frankenstein, S, Koenig, G. FASST Vegetation Models. *Cold Regions Research and Engineering Laboratory* 2004; 56, ERDC/CRREL TR-04-25.

[20] Kittas, C, and Bailie, A. Determination of the spectral properties of several greenhouse cover materials and evaluation of specific parameters related to plant response. *Journal of Agricultural and Engineering Research* 1998;. *71*(2): 193–202, DOI: 10.1006/jaer.1998.0310.

[21] Baudoin W, Nono-Womdim R, Lutaladio N, Hodder A, Castilla N, Leonardi C, et al. Good Aagricultural Practices for greenhouse vegetable crops: principles for Mediterranean climate areas 2013; FAO plant production and protection paper (FAO). DOI: 10.1201/b13737-8.