Energy Design and Optimization of a Greenhouse

A Heating, Cooling and Lighting Study

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Abstract—**This paper presents a new approach to properly optimize the energy consumption in a greenhouse. An improved intermediate modeling to establish the energy balance in a greenhouse within a higher precision was adopted. While the classical model focuses on the efficient cooling and heating demands and neglects the profound impact of lighting parameters, it was shown that these three necessary components are interdependent, and they should be taken into account all together to comfortably reach optimal crop production and energy consumption. This study's contribution is the classical model's improvement and the demonstration of the fact that the heat released by the luminaries and the energy used by this equipment has fundamental consequences on the energy balance as well as the preferred choice of the possible shape of the greenhouse and its adequate cover.**

Keywords-cooling; energy; greenhouse design; heating; lighting

I. INTRODUCTION

Facing a constant increase of world population, an efficient food production system is ought to aim accurately for cost minimization, to allow a sufficient supply and adequately meet the consumers' demand. Being one of the most energy demanding sectors in modern agriculture, the greenhouse industry is in definite need of energy consumption reduction, while maintaining an adequate microclimate for cultivating crops, thus guaranteeing minimal production expenses and an optimal crop quality. Because of the considerable importance of thermal modeling of a greenhouse typically used for energy simulation, to optimize energy-efficient designs and to verify the economic feasibility of greenhouse production, studies have been conducted to develop the greenhouse thermal models and try to correctly describe the specific process of heat and mass transfer in greenhouses [1-3]. Greenhouse thermal models are generally classified into three specific groups: static, dynamic and intermediate. Static models [4-6] determine the productive capacities of heating and cooling equipment and are based on approximate heat gains and losses, depending on periodic collected meteorological data. On the other hand, intermediate models [7-14] consider the factor of sunlight, while complex dynamic models [9, 15-18] are principally based on the integration of numerous greenhouse components. Despite the relative accuracy of these models, the estimation of heating energy requirements over long periods or for a greenhouse with different configurations requires very complex modifications and does not mention the effect of evapotranspiration of plants and control systems of the environment on the greenhouse's energy balance. In order to obtain higher yield and better production quality in the greenhouse, this study will start from the equations used in the energy balance of previous models as references. Our contribution is to develop an updated version of these models.

II. METHODOLOGY

A. *Greenhouses Studied Shapes*

Four forms of greenhouses studied (elliptic, even span, uneven span and rectangular), as shown in Figure 1.

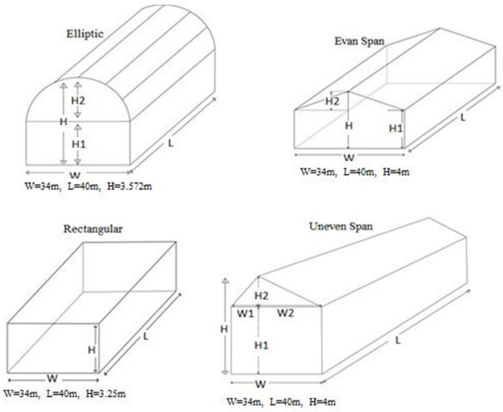

Fig. 1. Analyzed greenhouse forms.

The analysis of these greenhouses is carried out for the same greenhouse volume of $4420m^3$ and the same dimension of the base surface (W=34m, L=40 m).

B. *Covering Materials of Studied Greenhouses*

Five different covering materials of greenhouses were studied. The characteristics of these materials are shown in Table I [9, 16, 20, 21].

C. *Heat Balance Inside the Greenhouse*

To fix the climatic problem inside the greenhouse, several factors must be inevitably retained during the establishment of

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the energy balance. The energy balance of the greenhouse is precisely the heat transfer and the mass exchange between the greenhouse and the external environment. This multidimensional quantity can be expressed according to (1):

$$Q_s = Q_L - Q_G \quad (1)$$

In this energy equation, positive Q_S means that the heat loss is greater than the heat gain, which would imply a need for warming up the greenhouse, whereas in case this value is negative, it would indicate the heat gain is greater than the heat loss so there is necessarily a need, to cool it. We could classify the various parameters intervening in the development of the energy balance equation in two categories:

- First category defines the structure of the greenhouse by its geometric shape, the diverse materials which constitute its shell, mainly in terms of materials selected for its cover, and the temperature, light and moisture to retain inside the greenhouse.
- Second category: it is, essentially, related to the external environmental conditions of the greenhouse like solar radiation level, wind speed, external temperature, humidity degree, altitude, latitude and the orientation of the greenhouse.

TABLE I. COVERING MATERIALS CHARACTERISTICS

	PF	GL	LEG	PC	Acr
Index	**M1**	**M2**	**M3**	**M4**	**M5**
Lc	0.000152	0,003	0,0032	0,01	0,006
Solar transmission	0,87	0,905	0,78	0,9	0,9
Long-wave transmission	50	3	<3	<3	<5
Kc	0,33	0,76	0,76	0,17	0,2
ACH	0,85	1,1	1,1	1,1	1,1

D. Traditional Model Design

Our approach is essentially based on the results of previous intermediate models that took into account the different components that act on the energy balance. These theoretical models have paved the way for our contribution. In the traditional model the heat gain Q_G calculation depends only on the solar radiation as shown in (2):

$$Q_G = \tau \, I_{sr} \, A_f \quad (2)$$

While the precise determination of the heat loss was generally based on the calculation of two fundamental parameters, the heat transfer caused by the phenomenon of conduction and convection $Q_{cd\text{-}cv}$ and the heat transfer due to the infiltration Q_{inf}. The convection and conduction heat transfer is calculated by (3):

$$Q_{cd-cv} = U \, A_G \, (T_{in} - T_{out}) \quad (3)$$

where U is the overall heat transfer coefficient and which was taken as general constant [1]. The heat transfer due to the Infiltration Q_{inf} is estimated by (4):

$$Q_{inf} = A_{CH} \, \rho_a \, C_a \, V_G \, (T_{in} - T_{out}) \quad (4)$$

Figure 2 represents the energy demand of heating and cooling for the elliptic form equipped by polyethylene covering material applied in the climatic and geographical conditions of the Tunisian latitude, and by keeping the desired indoor temperature of the cultivated invariably to 20°C, according to the previous equations.

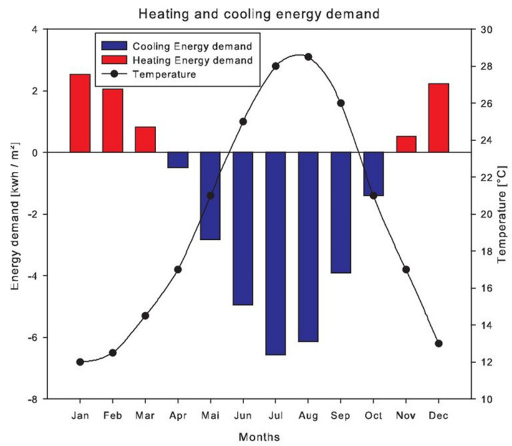

Fig. 2. Energy demand of the heating and cooling using traditional approaches

Note that despite the same temperature of some months (April and November, 17°C), (May and October, 21°C), we do not have the same behavior in terms of heating-cooling and this is expected since a sunny day with a low temperature does not mean we will have a need for heating and vice versa (a hot day with low sun does not mean that we will need ventilation). In order to represent the energy demand of all shapes and all covering materials studied in this paper, we replicated the same process for all the chosen shapes and covering materials, the results are presented in Table II.

TABLE II. TRADITIONAL MODEL AVG DAILY HEATING AND COOLING APPLIED TO TUNISIA [KWHM^{-2}]

	Even span	Uneven span	Elliptic	Rectangular
M1	4,472	4,483	4,799	4,549
M2	3,334	3,339	3,513	3,369
M3	4,940	4,956	5,387	5,055
M4	3,666	3,673	3,658	3,711
M5	4,102	4,112	4,396	4,179

We can deduct through Table II that if using the traditional model without any changes in the energy balance, the most appropriate shape is the even span equipped with M2, while the worst is the elliptic form equipped with M3. According to our analysis of the different computation models of the energy balance, the traditional model remains an ineffective one, despite it took into consideration the majority of the parameters intervening in the equation of the energy balance, since it ignored the impact of other parameters that must be included such as:

- The global heat transfer coefficient U

Has been defined as a constant whereas it should be dynamic since it depends on the internal and external conditions of the greenhouse such as the properties of the covering material, the air velocity outside and inside the greenhouse, and the ambient and desired temperature. Therefore, the variable U cannot be considered as a constant when establishing the energy equilibrium equation of a greenhouse.

- Heat loss due to long-wave radiation Q_{lw}

In general, thermal radiation emitted from inside the greenhouse can be partly absorbed by the cover, reflected in the greenhouse or transmitted to the outside of the greenhouse. Depending on the degree of transparency of the greenhouse cover, the exchange of long-wave radiation by the transparent surface will cause a significant effect on the heat loss so a considerable amount of heat will be transmitted to the outside.

- Soil heat loss Q_f and the heat due to the perimeter Q_p

The heat loss engendered from the greenhouse's floor is principally due to the conduction of the soil and the heat transfer of the perimeter. This quantity exerts an effect on the estimate of the equation of the energy balance that we should not neglect in order to increase the accuracy of the results of the energy balance equation.

- Heat loss due to evaporation Q_{evap}

The evapotranspiration remains a crucially essential component that we should not neglect while establishing the equation of the energy balance because it represents a significant amount of heat loss. This quantity is produced from the plant leaves and the ground surface.

- The absence of the lighting effect Q_{li}

Q_{li} is the sufficient amount of specific heat typically emitted by the lighting system. Previous studies and researches have overlooked the energy weight of lighting in the choice of the shape and cover of the greenhouse and its impact on the energy balance equation, while our model in its analysis considers the predicted effects of lighting on the model.

E. Presentation of BGHM Model

Our developed model, named BGHM, is typically based on the cultivation of tomatoes inside greenhouses in the climatic and geographical conditions of the Tunisian latitude band. We took into account the neglected parameters of the traditional model: Q_{lw}, Q_f, Q_p, Q_{evap}, and the heat gains from lighting Q_{li}. We have also recalculated the overall heat loss coefficient U which was taken static during the study of the traditional model [1], and which is in fact dynamic. We claim by our approach to highlight the direct impact of the specific shape of the greenhouse and its adequate coverage of the energy needed by acting on various components that have been severely neglected in the successful establishment of the energy balance equation: mainly cooling, heating and lighting. To perform this, we will update the traditional model by injecting the neglected parameters Q_{lw}, Q_f, Q_p, Q_{evap} with and without the heat gain from lighting $Q_{li,}$ as this factor has been neglected in the majority of studies who worked on the energy balance equation, in order to emphasize on the importance of the effect of the lighting component to retain an efficient system in terms of energy.

1) BGHM Program Design

In order to develop our model, we have created the program presented in Figure 3.

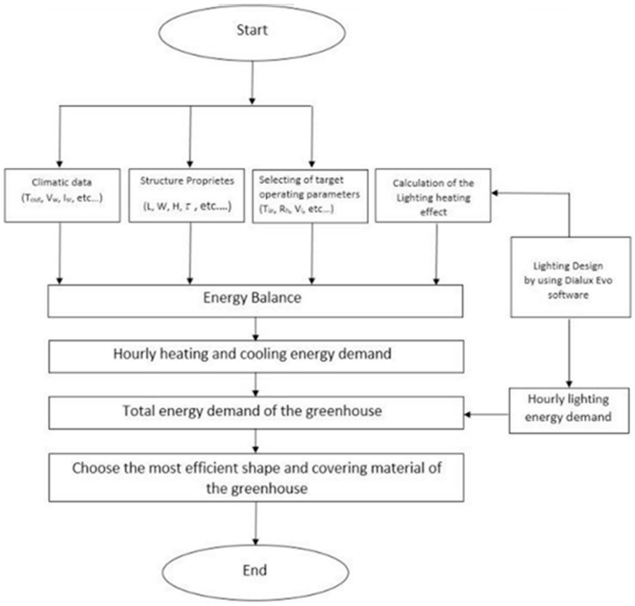

Fig. 3. Flowchart of the program

2) Study of BGHM Model without Lighting Impact

We will therefore resume the traditional model and remodel it while injecting in the energy balance equation the neglected parameters Q_{lw}, Q_f, Q_p, Q_{evap} and the improvement of the $Q_{cd\text{-}cv}$ by adopting a dynamic heat transfer U_d. The equation $Q_{cd\text{-}cv}$ then becomes as follows:

$$Q_{cd-cv} = U_d \, A_G \, (T_{in} - T_{out}) \tag{5}$$

where:

$$U_d = [h_0^{-1} + Lc \, Kc^{-1} + h_i^{-1}]^{-1} \tag{6}$$

and h_0 and hi can be estimated as shown in (7)-(8):

$$h_0 = 2.8 + 1.2 \, W_V \tag{7}$$

$$h_i = 1.52 \, [T_{in} - T_{out}]^{1/3} + 5.2 \, (A_{CH} \, S_G \, L)^{1/2} \tag{8}$$

The heat transfer through the greenhouse floor Q_f is:

$$Q_f = K_s \, d^{-1} \, A_f \, (T_{in} - T_s) \tag{9}$$

The heat transfer through the greenhouse perimeter Q_p, is estimated by (10):

$$Q_p = F_p \, P_G \, (T_{in} - T_{out}) \tag{10}$$

The long wave radiation heat loss Q_{lw} is calculated as:

$$Q_{lw} = h_0 \, A_G \, (1 - \tau) \, (T_{in} - T_{sky}) \tag{11}$$

where, T_{sky}, is calculated by:

$$T_{sky} = 0.552\,(T_{out} + 273.15)^{1.5} - 273,15 \qquad (12)$$

Finally, the heat transfer engendered by the process of evapotranspiration Q_{evap}, is calculated as shown in (13)-(14):

$$Q_{evap} = M_T\; L_V \qquad (13)$$

$$M_T = A_p\;\rho\,(wps - wi)\,(Ra + Rs)^{-1} \qquad (14)$$

where A_p could be determined from the plant's leaf area index, while W_{ps} and W_i could be calculated as:

$$W_{ps} = 0.6219\; p_{ws}\;(101.325 - p_{ws})^{-1} \qquad (15)$$

$$W_i = 0.6219\; p_w\;(101.325 - p_w)^{-1} \qquad (16)$$

By assuming a negligible temperature difference between T_{in} and T_{plant}, we could deduce the actual vapor pressure from the relative humidity and the saturated vapor pressure as shown in (17)-(18):

$$P_{ws} = \left(\exp\left(\begin{matrix} C1.10^{3}.a^{-1} + C2 - C3.10^{-3}\,a + C4.10^{-6}.a^{2} \\ -C5.10^{-9}.a^{3} + C6.\ln(a) \end{matrix} \right) \right) 1000^{-1} \qquad (17)$$

where a=T_{in}+273.15, $C1$=-5.80002, $C2$=1.3915, $C3$=48.64024, $C4$=41.764768, $C5$=14.45209310, and $C6$=6.5459673.

$$P_W \;=\; P_{ws}\; R_h \qquad (18)$$

In order to calculate R_a and Rs we could apply (19) and (20):

$$R_a = 220\; L_f^{\,0.2}\; V_i^{-0.8} \qquad (19)$$

$$Rs = 200\;(1 + (\exp(0.05\,(\tau\; I_{sr} - 50)))^{-1}) \qquad (20)$$

We can apply the above theoretical development on the various shapes and covers of the greenhouse. Figure 4 accurately represents the need for heating and cooling of the elliptic form equipped by polyethylene covering material during the different months of the year. To conclude, we will precisely calculate the energy demand in specific terms of heating and cooling using the BGHM model without lighting potential effect to correctly determine the most efficient form and greenhouse cover (Table III). Based on the results of Table III, it is clear that the most efficient form is the elliptic if the greenhouse is adequately covered by the polyethylene film M3, while if we utilized the traditional models we would have shown that this form was the worst energy-efficient and therefore the most economically expensive.

TABLE III. AVERAGE DAILY HEATING AND COOLING OF OUR MODEL WITHOUT LIGHTING IMPACT [KWH M-²]

	Even Span	Uneven Span	Elliptic	Rectangular
M1	3,677	3,683	3,669	3,723
M2	3,996	4,005	3,983	4,210
M3	3,462	3,469	3,452	3,514
M4	3,651	3,657	3,643	3,696
M5	3,554	3,562	3,543	3,612

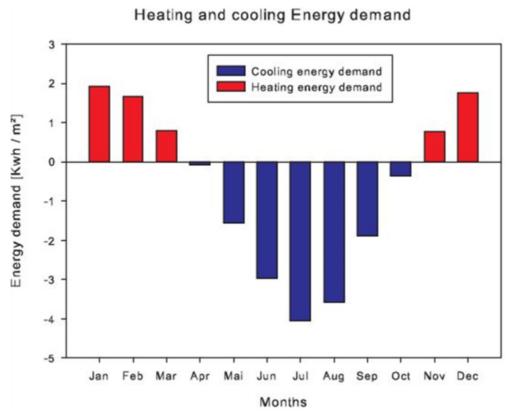

Fig. 4. Estimated heating and cooling load of the elliptic shape

3) *Study of BGHM Model with Lighting Impact*

We will calculate the artificial lighting requirements to determine the hourly lighting energy demand [W] which will allow us to deduce the heating effect of the lighting system. Starting from the fact that any lighting device emits heat as well as light, from our model we will check the impact of these two parameters on the choice of the form and the covering material which must be used. To do this we will, at first, present the need of illumination of a tomato plant (Table IV). Then we will determine the daily light to calculate the additional energy effort that meets the optimal need of the cultivation of our plant.

TABLE IV. TOMATO PLANT NEEDS [23-27].

Parameters	Value
Daily photoperiod	16 Hours
Required Illumination(1)	8475 Lux

1Lux=0.0177µmol×m^{-2} s^{-1}

a) Lighting System Design

- Daylight calculation

To design the daylight system, we started with the 3D modeling of each shape of the selected greenhouse, then, we defined the covering material properties, the type of the reference sky (clear sky, overall sky, and covered sky), the hours and the days considered for the simulation to create the daylight scenes. Daylight from 07:00 am to 10:00 pm was simulated, for the 1st, 8th, 15th and 22th of each month. This process has been applied for all types and covering materials of the greenhouse. An example of the daylight simulation of the elliptic form equipped with M3 has been shown in Figure 5 (a) and (b) for August and December respectively. In order to compare the daylight of a different shape, we calculated the average daylight illumination of each greenhouse's type applied for M3 covering material. The results are shown in Figure 6. By referring to Figure 6 we could deduce that the rectangular shape of the greenhouse is apparently the best in terms of daylight and that the elliptic shape remains the least efficient. In order to study the impact of coating materials on daytime lighting, we have simulated, through DIALUX EVO, all types of coating materials for a reference date and time 15/06/2018 at 1:00 pm), because the lighting depends not only on the transparency but also on light reflection and absorption, and the height, size and shape of the greenhouse. The results are shown in Table V. The gain/loss illumination factor to all greenhouse types with combined effects of covering material and applied greenhouse types, is shown in Figure 7.

(a)

(b)

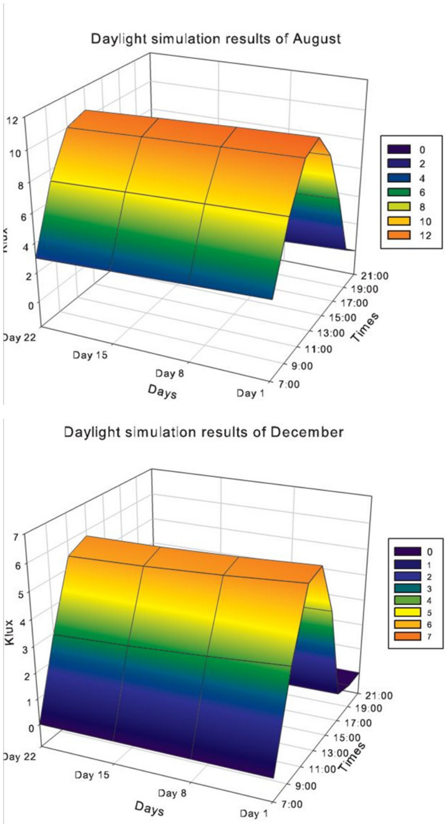

Fig. 5. Daylight simulation results in (a) August, (b) December.

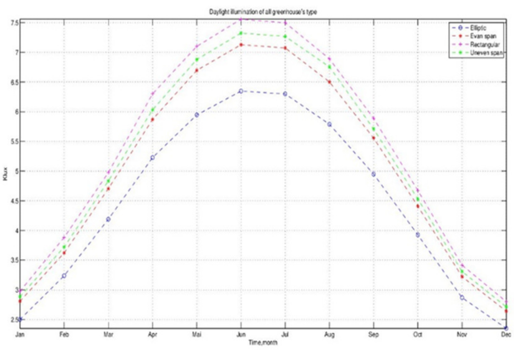

Fig. 6. Daylight illumination of all greenhouse types.

TABLE V. EFFECT OF THE COVERING MATERIALS

Covering material	Illumination simulated on (15-06-2018 at 1 PM) [KLux]	Gain/loss compared to reference M3 [%]
M1	13.185	4.5%
M2	11.705	-7.6%
M3	12.596	Taken as reference
M4	13.182	4.4%
M5	13182	4.4%

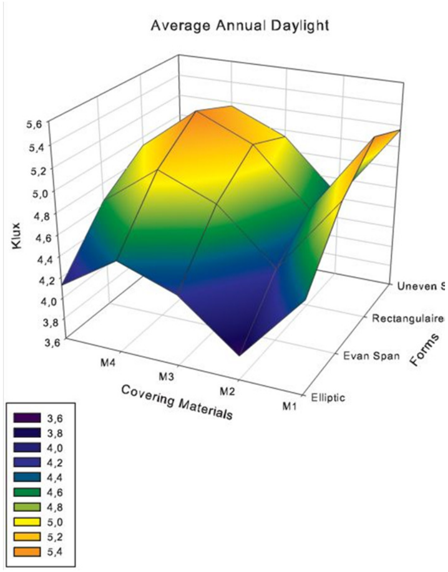

Fig. 7. Average annual daylight illumination of all greenhouse types.

Figure 7 shows the daylight illumination of all greenhouse types. It is clearly noticed that the rectangular greenhouse has the best value in terms of Lux level, while M3 and M4 have the lower lighting values. There is not a big difference in the rest of the material.

- Lighting energy demand

In order to design the required artificial lighting, we have applied the process described in Figure 8 to meet the target Lux level for the tomato plant which is 8475Lux [22].

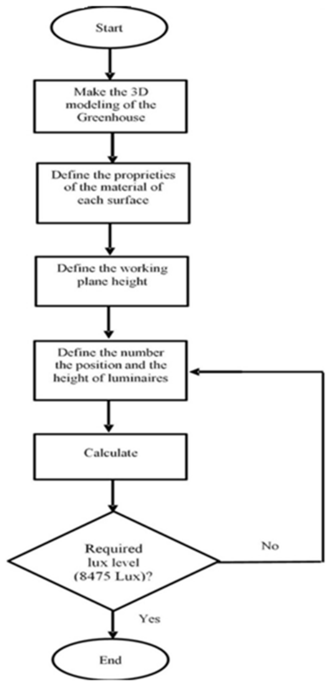

Fig. 8. Lighting design process

After all calculations were done, we used 1400 luminaries of 60w suspended at 1.8m from the working plan (floor) and within an efficiency of 160lm·w^{-1} and a CCT of 4000K. According to the simulation, our target was achieved within an illumination of 8478 vs 8475 (target) and a consumption of about 61w·m^{-2}. An example of false color rendering of the simulation is shown in Figure 9, which proves that illumination is around our target light level and that the light distribution remains uniform throughout the entire greenhouse area.

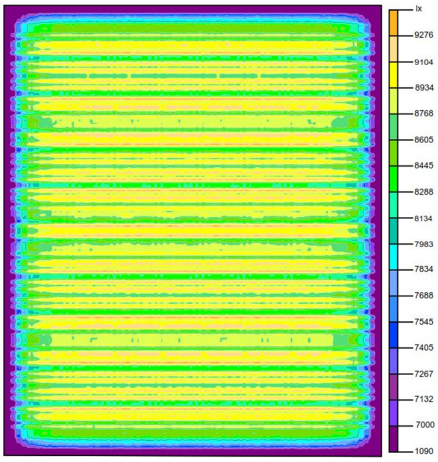

Fig. 9. A sample false color rendering of a lighting configuration, and light distribution map of the greenhouse

To reduce the lighting energy, we have implemented a daylight system control consisting of a light sensor connected to a raspberry pi3 in order to transmit the value of the light in real time to calculate the difference between the target value and the sensor value in the PWM signal, to dim the luminaries in order to obtain a uniform illumination equal to the desired value at any time *t* from 7:00 am to 10:00 pm when the daily PPFD is lower than the target value of the tomato plant. Once the daily PPFD is reached, the lighting system will be automatically switched off. To estimate the average of the compensated illumination of all greenhouse types equipped with M3 we have to subtract the illumination of the total installed luminaries (when all luminaries are ON) from the daylight. Finally, we calculated the compensated need of illumination, to deduct the annual power consumption of lighting for all greenhouse types and covering as shown in Figure 10. We note that in Figure 10 the need for energy compensation in lighting remains high compared to the other greenhouse forms, especially in the case of the rectangular form. Despite the satisfactory results so far, in terms of the choice of shape and coverage and their impact on the efficiency of the lighting system, we will look further into our analysis to see if there is an impact of the heat emitted by the luminaries and, if applicable, its effect on the energy equilibrium equation and on the response of the equation to the variation of heating and cooling components. This amount of energy allowed us not only to estimate the energy requirement of the lighting, but also to estimate heat loss from the lighting equipment as mentioned in (21):

$$Q_{li} = W_l \, k' \, k'' \quad (21)$$

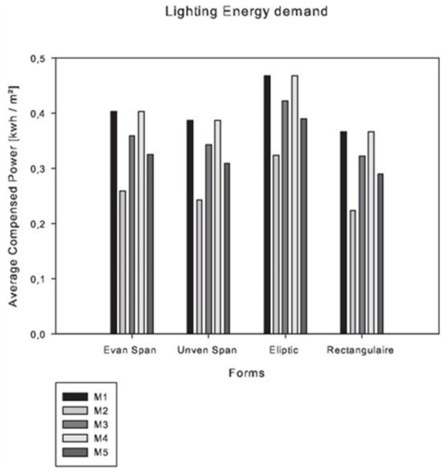

Fig. 10. Lighting energy demand

After all calculations are done, the estimated heat gains and losses are represented in Figures 11-12. Figure 11 shows the monthly evolution of energy captured by solar radiation Q_{sr}, the evolution of the global greenhouse gain system which encompasses Q_{sr}, and the heat effect gained from the lighting system. We also note that the difference between the heat gains due to the solar energy and the global heat gains are approximately identical during the hot period which is expected since the need of additional lighting in these months decreases because they have more daylight.

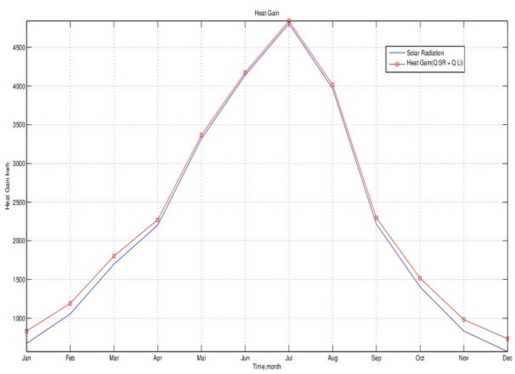

Fig. 11. Monthly evolution of heat gain

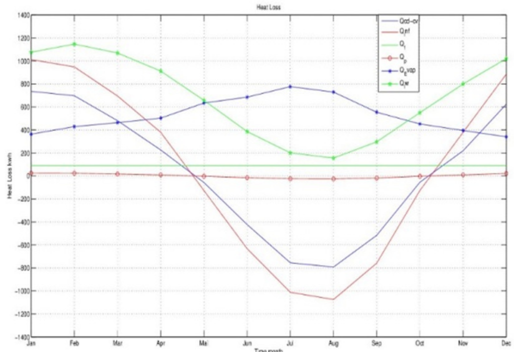

Fig. 12. Monthly evolution of heat loss

Figure 12 represents the evolution of the heat loss caused by conduction convection Q_{cd-cv}, infiltration Q_{inf}, perimeter heat transfer Q_p and soil Q_f, heat transfer due to long wave radiation Q_{lw}, and the evapotranspiration Q_{evap}. It can be seen from Figure 12 that the quantities of heat Q_p, Q_{inf}, Q_{cd-cv} follow a double sign, which is expected since these quantities depend on both internal and external temperatures of the greenhouse. They are positive when the external temperature is lower than the internal temperature and vice versa. In order to compare the state of the different models in terms of energy demand (heating and cooling), the models are presented in Figure 13.

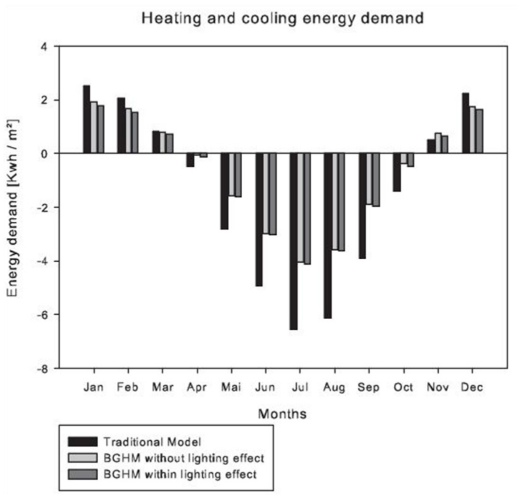

Fig. 13. Monthly evolution of energy demand

According to Figure 13 the energy demand estimate by the traditional model remains inaccurate, whereas with the improvement of this model by the injection of the neglected parameters, there is a clear improvement. We also note that the energy gap in cooling and heating is around 49.87% compared to the traditional model. Our developed model, even if the direct results at this elevated level are satisfactory, shows better results and allows demonstrating the considerable weight of the heat effect of the lighting on sufficient accuracy of the energy demand level in heating and cooling. The potential impact of lighting equipment's electrical consumption for the various possible shapes and coverage materials is shown in Table VI.

TABLE VI. TOTAL ENERGY DEMAND* [KWH M-²]

	Even Span	Uneven Span	Elliptic	Rectangular
M1	4,022	4,010	4,084	4,028
M2	4,205	4,196	4,262	4,237
M3	3,763	3,751	3,824	3,775
M4	3,996	3,984	4,058	4,001
M5	3,829	3,819	3,888	3,848

* Heating, cooling, and lighting

According to Table VI, our developed model points that the uneven span is the most efficient form. Our model adequately supported the model parameters conveniently overlooked by the traditional model and the impact of the lighting system and its effects.

III. CONCLUSION

This research showed that the energy balance can exclusively reveal the optimal values of energy consumption if all the principal determinants that cause a direct effect on the fundamental process of greenhouse cultivation, are taken into account. From this study, the following conclusions are derived:

- The need for energy consumption has been optimized by adopting the uneven span form.
- In our energy equation, it is possible to confirm that the uneven span form could improve the efficiency of our energy balance more significantly by using appropriately polyethylene M3 as greenhouse cover.
- The development of the heat release effect of the lighting system enabled a considerable gain in electric energy, especially during the cold period, since it enabled a residual heat to be amply provided. Therefore, a tangible net cost reduction efficient energy ordinarily required by the greenhouse tomato cultivation was observed.
- The proposed model exhibited a substantial gain, reaching 49.87%, of the energy consumption of cooling and heating compared to the reference "traditional" model.

NOMENCLATURE

A_G	Greenhouse area [m²]
A_f	Greenhouse floor area [m²]
A_p	Plant area [m²]
Acr	Acrylic
A_{CH}	Number of air changes per hour [m^3s^{-1}]
CCT	Correlated color temperature, [K]
C_a	Specific heat of air [J. kg-1 K^{-1}]
D	Depth of constant soil temperature [m]
F_p	Perimeter heat loss factor, [w.m^{-1}. K^{-1}]
G	Glass
H	Height of the greenhouse [m]
h_0	Outside convective heat transfer coefficients
h_i	Ohe inside convective heat transfer coefficients
I_{sr}	Solar radiation on the horizontal surface [w.m^{-2}]
K'	Lighting allowance factor
K''	Heat conversion factor
K_s	Thermal conductivity of soil [w m^{-1} K^{-1}]
Kc	Thermal conductivity [w m^{-1} K^{-1}]
L	Length of the greenhouse [m]
L_f	Characteristic length plant leaves [m]
L_v	Latent heat of water vaporization, [J kg^{-1}]
L_{max}	Maximum illumination inside the greenhouse [lux]
LEG	Low E glass
LC	Covering material thickness [m]
M_T	Moisture transfer rate, [kg s^{-1}]
PF	Polyethylene film
PC	polycarbonate
P_G	Perimeter of the greenhouse [m]
P_w	Partial pressure of the water vapor, [kPa]
P_{ws}	Partial pressure at saturation, [kPa]
Q_{cd-cv}	Conduction and convection heat transfer [w]
Q_{inf}	Infiltration heat transfer [w]
Q_f	Floor heat transfer [w]
Q_p	Perimeter heat transfer [w]
Q_{lw}	Long-wave radiation heat transfer [w]
Q_{evap}	Evapotranspiration heat transfer [w]
Q_s	Total required heating and cooling power [w]
Q_{sr}	Solar radiation heat gain [w]
Q_{Li}	lighting heat gain [w]
Q_G	Total heat gain inside the greenhouse [w]

Q_L	Total heat losses from the greenhouse [w]
R_a	Aerodynamic resistance [s m^{-1}]
R_s	Stomatal resistance, [s m^{-1}]
R_h	Relative humidity
S_G	Section of the greenhouse [m]
T_{in}	Inside air temperature [°C]
T_{out}	Average outdoor air temperature [°C]
T_s	Greenhouse soil temperature [°C]
T_{sky}	Sky temperature [°C]
T_{plant}	Plant temperature [°C]
U	Static overall heat transfer coefficient
U_d	Dynamic overall heat transfer coefficient
V_i	Indoor airspeed airspeed, m s^{-1}
V_G	Volume of the greenhouse [m]
W	Width of the greenhouse [m]
W_l	Lighting energy consumption [w]
W_V	Wind velocity [m s^{-1}]
W_i	Humidity ratio of air at indoor temperature
W_{ps}	Saturated humidity ratio of air at the plant temperature
ρ_a	Density of internal air [kg m^{-3}]
τ	Transmissivity of the greenhouse cover

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