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Energy Demand of Supplementary Lighting in Agricultural Greenhouses: Solar Energy Utilization

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ABSTRACT

Light is a critical parameter for plant growth such that providing enough light for the plant can ensure better quality and higher yield in greenhouses. In many areas, in the cold seasons of the year, not enough natural light reaches the plant. Thus, to compensate for the natural light deficit, artificial light is used. Since the use of artificial light leads to energy consumption, effective parameters in the energy consumption of the lighting system such as available natural light, greenhouse shape, and the on-off plan of the lighting system should be considered. In this paper, available natural light is estimated based on greenhouse structure in five cities of Iran. Then, the natural light deficit was investigated. Finally, to achieve clean cultivation, the utilization of photovoltaic panels is investigated to compensate for the electrical energy needed for supplementary lighting. The results show that although Iran is recognized as a region with high solar energy potential, natural light is not enough for optimum tomato lighting demand. Using supplementary lighting in greenhouses could compensate for the lack of natural light in proportion to the capacity of the lighting system. In 73.22 % to 91.32 % of days in the period of September to April, the natural light is not sufficient for optimum lighting. Therefore, 98 ($kWh\ m^{-2}\ y^{-1}$) to 377 ($kWh\ m^{-2}\ y^{-1}$) electricity is needed to supply power for supplementary lighting system. Accordingly, the photovoltaic area and its associated with costs to compensate electrical energy consumption for the supplementary lighting is estimated to be 0.47 m^2_{PV} to 2.58 m^2_{PV} per m^2 of greenhouse area, which is equal to \$ 171.08 to \$ 939.12 per m^2 of greenhouse area, respectively.

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1. INTRODUCTION

Plants need light for photosynthetic operations to provide the energy needed for their activity by converting light energy into chemical energy [1]. Photosynthesis is only caused by the wavelength including Photosynthetic Active Radiation (PAR), which is generally considered be ranging from 400 nm to 700 nm [2]. Insufficient PAR light leads to impaired delivery of sufficient energy to the plant and ultimately lack of optimal growth and poor-quality yields. For tomatoes, it is generally estimated that every 1 % reduction in light leads to a 0.7-1 % reduction in tomato yield [3]. In many areas, due to the high day length and higher altitude of the sun in the summer, sufficient light is provided by the sun. However, in cold seasons when the altitude is lower and the day length is short, it can lead to insufficient light reaching the plant [4]. Since greenhouses involve out-of-season cultivation, lack of natural light generally occurs in greenhouses [5]. Therefore, using an artificial light system to compensate for the lack of natural light seems necessary. The most crucial challenge of using a lighting system is its electrical energy consumption [4, 6] which can significantly raise the operation cost of growing plants. Therefore, it is necessary to study the plant's needs and requirement for light and control how much the lighting system is on.

Greenhouse shapes affect incoming solar radiation. In general, greenhouses can be categorized into two types: single-span and multi-span greenhouse [7]. Each type of greenhouse includes different shapes. Even-span, uneven-span, vinery, modified-arch, and quonset types are the most commonly used single-span shapes of greenhouses [8]. In addition, Venlo, modified arch (arch-shaped roof), and tunnel greenhouses are the most commonly used multi-span shapes for greenhouses [9]. To analyze the energy demand of supplementary lighting, it is important to study the effect of greenhouse shapes on available natural light. Gupta and Chandra [10] studied three types of greenhouse shapes in northern India. Their result indicates that the Gothic arch greenhouse is more energy-efficient than the gable roof and Quonset shape. Sethi [8] studied available solar radiation in five different greenhouse shapes and found that uneven-span greenhouse received highest solar radiation, while Quonset-shaped greenhouse received the lowest solar radiation. Ghasemi et al. [11] investigated six different greenhouse shapes in Tabriz, Iran. Their results showed that the single-span greenhouse received the highest solar radiation, while vinery greenhouse received the lowest. All the above-

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mentioned researchers studied the effect of greenhouse shapes to find the most energy-efficient greenhouse shapes, while in this study, two types of multi-span greenhouse were studied to explore the effect of greenhouse shapes on available natural light.

After evaluating the available natural light according to the structure and location of the greenhouse, the effect of artificial light will be investigated. According to Dorais [12], the quantity and quality of light affect plant growth. The quantity of light is indicated by daily light integral (DLI), the intensity of the light, and the photoperiod. The quality of light means the spectral distribution of the available light. While examining each of the parameters related to the quantity and quality of light, Dorais states the desired amount of these parameters and the results of not achieving the desired amount for tomatoes, cucumbers, and sweet peppers. When natural light is not enough in the cold seasons of the year, artificial lighting is used to ensure the quantity and quality of light suitable for the plants. In the past, High-Pressure Sodium (HPS) lamps were the most popular technology used in greenhouses to meet the need for plant light [13]. Nowadays, due to longer life, less power consumption, less heat loss, and achieve wavelength specificity, Light Emitting Diode (LED) technology has been noticed [14]. Several researchers around the world studied the effect of artificial lighting system on the plant. Paucek et al. [15] conducted a study on the effect of supplementary LED lamps in the Mediterranean greenhouse. Their results showed that a capacity of 170 $\mu mol\ m^{-2}\ s^{-1}$ for 16 hours had a positive effect on the tomato plant, which led to an increase in fruit size. Gomez and Mitchell [16] investigated the effect of artificial lighting systems on tomatoes in two scenarios, 1) with intracanopy LED Towers and 2) with overhead HPS Lamps. Their results showed that in West Lafayette, USA, the presence of artificial light compared to its absence increases fruit number and yields. They also showed that the LED system could save up to 75 % energy.

As mentioned before, while supplementary lighting has a favorable effect on plant growth and yields, the noticeable cost of the lighting system is a major concern for growers. For this reason, it is essential to schedule the on-off program for the lighting system to minimize cost while maintaining the level of light required by plants. Growers usually follow a fixed scheme to control the lighting system; whenever the sunlight is less than a certain amount, the lighting system turns on [17]. A dynamic lighting plan proposed by Heuvelink and Challa [18], in this lighting plan, suitable on-off scheme for lighting system resulted of economic optimization. Niu et al. [19] used another approach based on the Daily Light Integral (DLI); the lighting system switches off when the DLI threshold is met.

In this paper, first, based on the most prevailing climates type, five different cities of Iran were selected, then the natural light available in these cities was estimated. For this purpose, the effect of Venlo and modified arc greenhouse structure on solar transmission coefficient was investigated. After that, by introducing two indicators, an attempt was made to assess the natural light available relative to the light required by tomatoes. In section 2.3, to investigate the effect of the lighting system, the on-off program was proposed, which determines the lighting system program both by considering the available solar radiation at each hour and the DLI. In the following, according to the proposed program, the effect of two capacities of the lighting system (100 and 200 $\mu mol\ m^{-2}\ s^{-1}$) on the available DLI is investigated. Finally, in section 2.4 the area of the photovoltaic (PV) panel required to meet the electrical energy requirements of the lighting system is calculated. The main novelties of this work is (1) to study the effect of greenhouse structure and climate condition on available natural light and (2) presenting a new lighting plan for a lighting system based on DLI requirements and available solar radiation for HPS and LED lamps in greenhouses.

The main contribution of this paper can be presented as follows:

1- the amount of available natural light for two different greenhouse designs in Iran is determined.
2- the algorithm for estimation of supplementary lighting to compensate light deficit is presented.
3- the minimum capacity for a photovoltaic system is determined to supply the electricity demand for supplementary lighting.
4- The presented algorithm is applied to five cities in Iran with different climates as the case studies.

2. METHOD

2.1. Case study

In this article, five cities were selected to estimate the demand for artificial light and its energy requirements. Criteria for selecting different cities to achieve this goal are the climate and population concentration of the studied areas. To classify the climate of Iran, the Köppen–Geiger climate classification was used. According to Kottek et al. [20] and Rahimi et al. [21], different regions of Iran can be divided into nine different climates. In this paper, five different climates have been selected that cover more than 87 % of the area of Iran. These climates are BWh, BWk, BSk, BSh, and Csa. The first letter means the main climate (B: arid and C: warm temperate), the second letter means precipitation (S: steppe, W: desert, and s: summer dry), and the last letter means temperature (h: hot arid, k: cold arid, and a: hot summer) [20]. After nominating several cities in each climate, the study area was selected based on other criteria (population concentration and distribution of major greenhouse cultivation areas). Selected cities and their location are seen in Table 1 and Figure 1.

2.2. Incoming solar radiation

The intensity of solar radiation varies according to the location, season, day, time of day, and cloud cover of the studied area. In addition, in greenhouses, the covering material of greenhouse structure also affects the radiation reaching the plants. These two affect the solar radiation passing through the greenhouse cover and thus, reaching the plant. In this paper, only radiation reaching the horizontal surface of the greenhouse is considered because this part that reaches the plant leads to meeting the plant's light needs. Solar radiation reaching the greenhouse ground consists of two parts of direct and diffuse radiation extracted from the www.renewables.ninja with the help of latitude and longitude presented in Table 1. The method used in this web site is based on Pfenninger et al. [22] and Staffell et al. [23]. The cultivation period in this paper is considered from September 24, 2018 (day 1) to April 20 (day 210), 2019. Two common types of greenhouse structures are shown in Figure 2. In commercial greenhouses, a significant part of the sunlight enters from the roof of the greenhouse; thus, to investigate the effect of the structure on the radiation entering the greenhouse, only its roof is considered.

Table 1. Geographical and meteorological information of the selected cities

City	Lat. (°N)	Long. (°E)	Climate type*
South of Tehran-Varamin	35.35	51.65	BSh
Ahvaz	31.32	48.67	BWh
Mashhad	36.26	59.62	BSk
Isfahan	32.65	51.66	BWk
Rasht	37.27	49.58	Csa
* Base on Köppen climate classification			

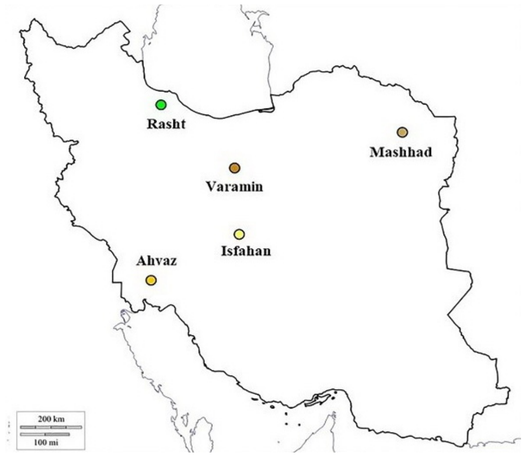

Figure 1. Geographical location of the studied cities

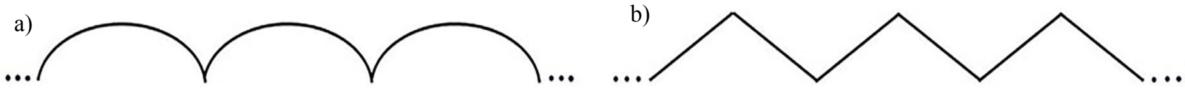

Figure 2. Greenhouse structures: a) modified arc and b) Venlo

Assuming that the incident angle of solar radiation on the greenhouse roof is known, the light transmission coefficient can be calculated with the help of the Fresnel equation. Based on Kalogirou [24], the angle of refraction (θ_2) is first calculated using Eq. (1), where n is the refraction index and for glass, it is equal to 1.526 [24]. Based on Eq. (1), the transmittance of solar radiation is equal to the product of (τ_r) and (τ_a), where subscripts r and a indicate that only reflection losses and absorption losses are considered, respectively. (τ_r) can be calculated from the average transmittance of the two components ($r_{||}$ and $r_{\perp}$) considering Eq. (2) and (τ_a) is calculated based on Eq. (3), where K is the extinction coefficient, which is assumed to be equal to 30 m^{-1} for glass and L is the thickness of the glass cover that is assumed to be 4 mm [24]. Equations (1) to (6) are shown in Table 2.

Table 2. The equations for calculation of transmittance of solar radiation

Transmittance of solar radiation calculation	Equations No.	Reference
$n=\frac{\sin(\theta_1)}{\sin(\theta_2)}$	(4)	[24]
$\tau \cong \tau_a \tau_r$	(5)	
$\tau_r=\frac{1}{2}\left(\frac{1-r_{\parallel}}{1+r_{\parallel}}+\frac{1-r_{\perp}}{1+r_{\perp}}\right)$	(6)	
$r_{\parallel}=\frac{\tan^2(\theta_2-\theta_1)}{\tan^2(\theta_2+\theta_1)}$	(7)	
$r_{\perp}=\frac{\sin^2(\theta_2-\theta_1)}{\sin^2(\theta_2+\theta_1)}$	(8)	
$\tau_a=\exp\left(-\frac{KL}{\cos(\theta_2)}\right)$	(9)	

Factors affecting the incident angle of solar radiation can be generally divided into two categories, the first one related to the position of the sun and the second part related to the structural characteristics of the greenhouse. The width, eaves, and ridge height of each span in the two studied structures are the same and assumed to be 5, 3, and 4 m, respectively. The main difference between these two structures is the tilted angle of the roof.

In Venlo structure, the roof slope angle is always constant; however, in the modified arc structure, the roof slope angle is changed based on the position x from the origin (Figure 3-a). The equation of the modified arc greenhouse roof is shown in Eq. (7). Then, through the derivation, the slope angle of the roof (β) is calculated in terms of x, as shown in Eq. (8). In order to calculate the slope angle using the coordinates of that point, the point of incidence of the sun's rays must be determined. For this purpose, first, with the help of Eq. (9), Eq. (8) is expressed in polar coordinates. (α) is the height of the sun because it is assumed that the point O is located exactly at the center of the span (Figure 3). (r) is also calculated based on Eq. (10) and through the use of the angle of the height of the sun (α), the width of the span (2a), and the height of the roof (b).

Table 3. The equations for estimating titled angle in the modified arc structure

Tilted angle calculation in the modified arc structure	Equations No.
$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$	(10)
$\tan(\beta)=\frac{dy}{dx}=\frac{b}{a^2}\frac{x}{\sqrt{1-\frac{x^2}{a^2}}}$	(11)
$x=r\cos(\alpha)$	(12)
$r=\frac{ab}{\sqrt{b^2\cos^2(\alpha)+a^2\sin^2(\alpha)}}$	(13)

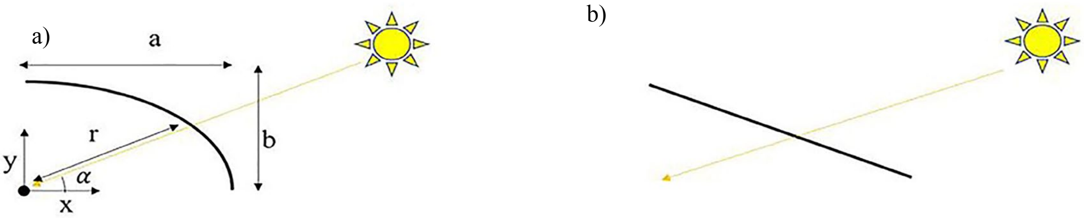

Figure 3. The effect of solar radiation on two structures: a) modified arc and b) Venlo

2.3. Available natural light and supplementary lighting demand

According to the radiation reaching the greenhouse floor, the natural light reaching the plant can be calculated. The portion of the light spectrum utilized for photosynthesis is in the range of 400-700 nm, called Photosynthetically Active Radiation (PAR) [25]. The ratio of PAR to solar radiation has been reported in previous studies. Tsubo and Walker [26] reported this ratio in the range of 0.45 to 0.5. Rao [27] estimated this ratio in the range of 0.44 to 0.46. Udo [28] also reported this ratio in the range of 0.42 to 0.47. Therefore, according to the reported ranges, the constant ratio of 0.45 was used to approximate PAR to solar radiation.

In the present paper, two indicators are considered to examine the available natural light. The first indicator based on the Eq. (11) indicates the Percentage of Days with a Natural Light Deficit (PDNLD) or, in other words, the percentage of days when the amount of natural light is less than the ideal amount required for tomatoes (30 $\mathrm{mol\,m^{-2}\,day^{-1}}$) in the whole cultivation period (210 day in our case study). Also, the second indicator that is presented in Eq. (12) indicates the Amount of Light Deficit (ALD) which must be provided to achieve ideal conditions.

The demand for artificial light can be estimated based on the natural light received by the plant and Daily Light Integral (DLI) required for the plant. First, it is necessary to determine the photoperiod according to the plant type, which is Tomato in our research. Dorais and Gosselin [29] reported that tomato plants needed at least 6 hours of dark period. Dorais [12] also reported that in several cases, leaf chlorosis was observed for tomato plants in photoperiod more than 17 hours. In this paper, progressive photoperiod was used so that the photoperiod was determined based on the natural light available during the day. In this work, the photoperiod can be increased up to 16 hours.

It is assumed that supplementary lighting starts at 4 am and continues until 7 pm at maximum. At each hour, if solar radiation is less than a certain amount (300 $\mathrm{W\,m^{-2}}$) and the daily light integral is less than what the plants need (30 $\mathrm{mol\,m^{-2}}$), the supplementary lighting system will turn on. This process continues until the required DLI or maximum photoperiod interval is met. Then, according to the capacity of artificial light, the amount of moles of light reaching the plant can be calculated, and knowing the efficacy of lighting system, the electrical energy related to the lighting system can be estimated. In this paper, two types of lighting system technology including Light Emitting Diode (LED) and High-Pressure Sodium (HPS) have been used. Their efficacy is the average of the values reported by Runkle [30], which are equal to 4.8 $\mathrm{mol\,kWh^{-1}}$ and 7.2 $\mathrm{mol\,kWh^{-1}}$ for LED and HPS lamps, respectively. Figure 4 show the supplementary lighting plan to calculate the energy consumption of supplementary lighting system.

Table 4. Indicators related to the evaluation of natural light in the studied cities

Two indexes for examine the available natural light	Equations No.
$\mathrm{PDNLD} = \dfrac{\text{The number of days that is less than the required amount of light}}{\text{Total days in caltivation period}}$	(14)
$\mathrm{ALD} = \sum_{i} \text{Light deficit on the ith day}$	(15)

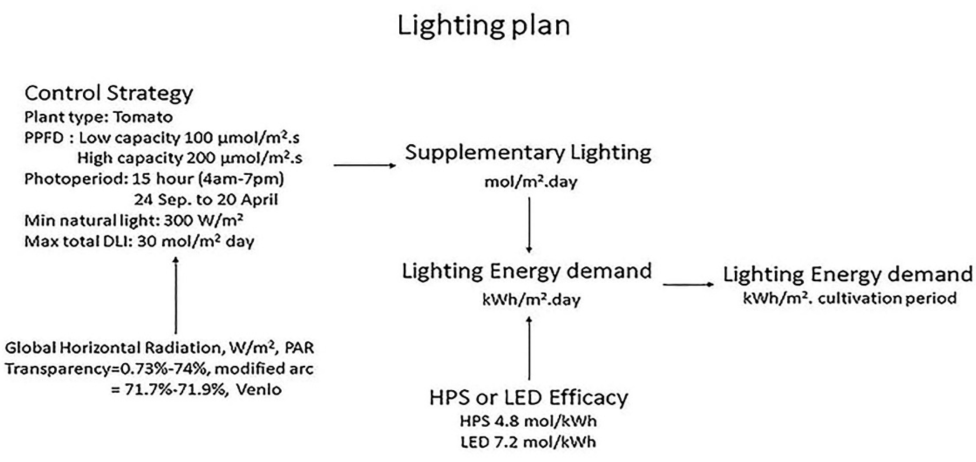

Figure 4. Lighting plan algorithm for supplementary lighting energy consumption [12, 31]

2.4. Meeting supplementary lighting energy demand by photovoltaic panel

After determining the lighting plan with the help of lamp efficacy, electricity demand can be calculated. In order to find the required panel area to meet the electricity demand of the lighting system, the peak-hour approach was used based on Masters [32]. In this approach, since 1-sun is defined as 1 $\mathrm{kW\,m^{-2}}$, the daily insolation in that area can be defined based on the available hours of 1-sun. Average daily insolation in selected cities on the optimal tilted angle of the panel is shown in Table 5. According to Jacobson et al. [33], the optimal tilted angle can be calculated by latitude of location. Jacobson et al. first estimated the optimal tilt angle derived from the National Renewable Energy Laboratory's PVWatts program at 1-4 sites in a number of countries worldwide. The optimal tilt angle at each site was determined by a tilted angle obtained from maximum panel output. Then, the 3rd-order polynomial fits of optimal tilted angel versus latitude were derived. The resulting function is shown in Eq. (13). In this paper, by knowing the latitude of each location, the optimal tilt angle can be calculated.

According to the electricity demand, the number of peak hours, and the number of days, the required ac power can be estimated based on Eq. (14). For converting ac into dc power under Standard Test Condition (STC), it is necessary to estimate the impacts of temperature, inverter efficiency, module mismatch, and dirt, all of which are considered as conversion efficiency. Upon determining the conversion efficiency, the dc power is calculated according to Eq. (15). Then, the collector area can be estimated with dc power and collector efficiency based on Eq. (16).

Table 5. Average daily solar insolation and daily maximum temperature in the cultivation period

Region	Optimal tilted angle (°)	Insolation ($\mathrm{kWh\,m^{-2}\,day^{-1}}$)	Average daily maximum temperature (°C)
Varamin	29.40	5.44	23.87
Ahvaz	27.34	5.18	34.94
Mashhad	29.83	5.49	19.48
Isfahan	28.04	6.07	22.86
Rasht	30.30	4.32	23.84

Table 6. The equations for calculation of required area of the solar panel

Required area of the solar panel calculation	Equations No.
$\beta_{PV.opt} = 1.3793 + \mathrm{Lat}(1.2011 + \mathrm{Lat}(-0.014404 + \mathrm{Lat} \times 0.000080509)$	(16)
$P_{ac} = \dfrac{\mathrm{ALED}}{(\mathrm{h/day}) \times \mathrm{NOD}}$	(17)
$P_{dc,STC} = \dfrac{P_{ac}}{\text{Conversion efficiency}}$	(18)
$A_{PV} = \dfrac{P_{dc,STC}}{\text{1 sun of insolation } \times \eta_{PV}}$	(19)
$T_{cell} = T_{amb} + (\dfrac{\mathrm{NOCT} - 20^{\circ}}{0.8}) \times I$	(20)
$\mathrm{TIE} = 1 - \mathrm{PR} \times (T_{cell} - 25)$	(21)

The panel's efficiency is estimated according to the average efficiency of ten best-selling panels of 2021, reported by www.cleanenergyreviews.info and shown in Table 7. This value is equal to 21.18 %. Based on Masters [32], inverter, module mismatch, and dirt efficiency are assumed to be 90 %, 97 %, and 96 %, respectively, and the effect of temperature on panel performance is calculated using Eq. (17) and Eq. (18). For this purpose, the LG-Neon R panel is first selected from Table 7 and then, the temperature effect is calculated using the parameters reported in the panel characteristics [34]. These parameters include Nominal Operating Cell Temperature (NOCT) and power reduction due to the temperature difference (PR), reported as 44 °C and 0.3 % $°C^{-1}$, respectively.

Table 7. Top 10 solar panels 2021 [35]

Manufacture	Model	Cell type	Max efficiency
LG Energy	Neon R	N-type IBC	22.00 %
Sunpower	Maxeon 3	N-type IBC	22.60 %
REC	Alpha	N-type HJT MBB	21.70 %
Panasonic	EverVolt	N-type HJT MBB	21.20 %
Solaria	Power XT	P-type Half-cut MBB	20.50 %

Qcells	QPeak DUO G9	P-type Half-cut MBB	20.60 %
Trina Solar	Vertex S	P-type Half-cut MBB	21.10 %
Winaico	WST-375MG	P-type Half-cut MBB	20.60 %
JinkoSolar	Tiger Pro N-type	N-type Half-cut MBB	20.70 %
Canadian Solar	HiKu6	N-type Half-cut MBB	20.80 %

3. RESULTS AND DISCUSSION

3.1. Effect of greenhouse structure on incoming solar radiation into the greenhouse

In order to investigate the effect of Venlo and modified arc structures in commercial greenhouses, Section 2.2 was followed and the results are shown in Figure 5 for two specific days, September 24 and January 1. The first point that can be seen from Figure 5 is that the effect of the greenhouse structure on solar transmittance is visible more at sunrise and sunset and is almost constant in the middle of the day. The main reason for this difference at sunrise and sunset is the solar incident angle. According to Equation (2), the solar transmittance is approximately equal to the product of τ_r and τ_a. τ_a depends on the material and thickness of the greenhouse cover and the angle of refraction. Assuming the refraction index equal to 1.526, the refraction angle varies from zero to about 41 degrees for the incident angle of zero to 90 degrees. Since other factors affecting the τ_a are constant, it changes from 0.88 to 0.85, which changes by only about 3.4 percent, while during the regular day, the incident angle does not have such wide changes. Therefore, τ_a does not have a significant effect on justifying changes in the solar transmittance. On the other hand, based on Equation (3), τ_r depends on solar incident angle and angle of refraction. τ_r changes are exponential. Thus, if the incident angle changes from 30 to 50 degrees, the τ_r decreases by only 0.51 percent; however, this change becomes more severe at high angles so that by increasing the incident angle from 80 to 85 degrees, τ_r decreases by almost 7 percent. This leads to the fact that at sunrise and sunset, when the incident angle is high (more than 75 degrees), τ_r has a noticeable effect on the solar transmittance. However, in the middle of the day, when the incident angle is much lower, it has no noticeable effect.

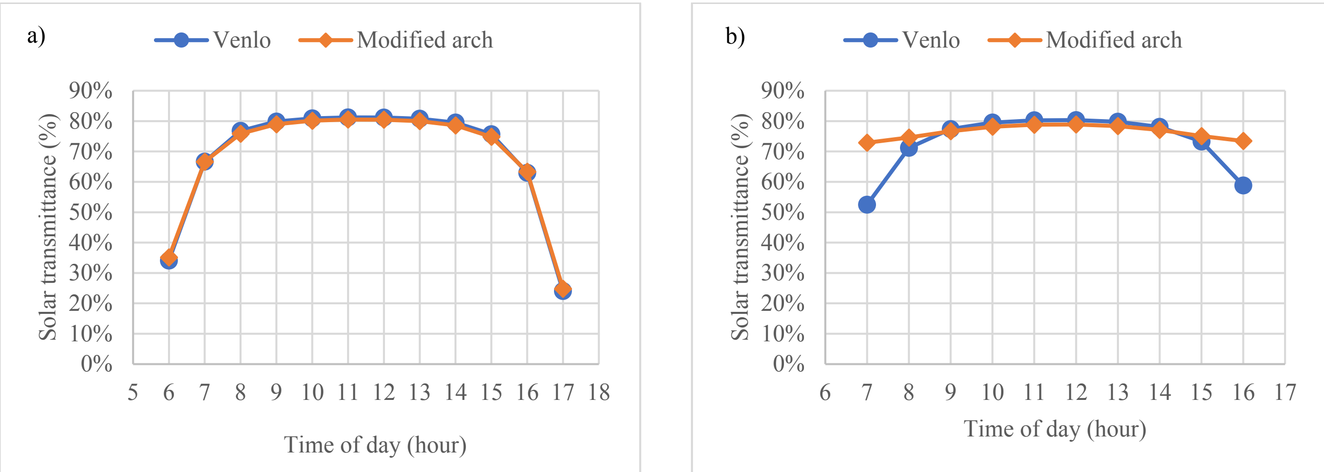

Figure 5. The effect of greenhouse structure on solar transmittance on a) September 24 and b) January 1

Another point that can be deduced from Figure 5 for January 1 and September 24 is that on January 1, especially at sunrise and sunset, there is a difference in the light transmittance of the two structures Venlo and modified arc, while there is no difference at sunrise and sunset on September 24. The reason for this difference is in the roof's shape of modified arc structure. As mentioned earlier, τ_r has an exponential behavior in proportion to changes at the incident angle. On January 1, the incident angle at sunrise is 80.5 degrees for the modified arc structure and 88.4 degrees for the Venlo structure. This fact means that at sunrise and sunset on January 1, the solar transmittance in the Venlo structure is less than that in the modified arc structure. There is no such difference in the incident angle on September 24.

Sunrise light is essential to the initiation of photosynthesis, but it is responsible for only a small part of total incoming light into the greenhouse. Thus, in this paper, the average solar transmittance throughout the cultivation period for two different structures is used, as indicated in Table 8.

Table 8. Average solar transmittance throughout the cultivation period for Venlo and modified arc structures

	Average solar transmittance, Venlo (%)	Average solar transmittance, Modified arc (%)
Varamin	71.64	73.08
Ahvaz	71.98	73.33
Mashhad	71.71	74.04
Isfahan	71.93	73.06
Rasht	71.61	73.14

3.2. Evaluation of available natural light

According to Section 2.3, the natural light available in the five selected regions during the cultivation period is shown in Figure 6 to Figure 10. According to Dorais [12], the optimum PAR Light (DLI) for Tomato is 30 mol m^{-2} day^{-1}. As shown in Figures 6 to 10, during the cultivation period, which starts on September 24 (Day 1) and lasts until April 20 (Day 210), there are many days in all the studied cities where the available natural DLI is less than the desired amount. It can also be seen that there is no significant difference between Venlo and modified arc structures in terms of natural DLI deficit.

As shown in Figure 6 to 10, in all regions, the general trend of available natural DLI is reduced to a minimum between days 80 and 110, equivalent to late December and early January, and then the available natural DLI has increased again. Rasht has been experiencing a natural DLI deficit since the first days of the cultivation period, while in other cities, there is a natural DLI deficit from about the 10th day.

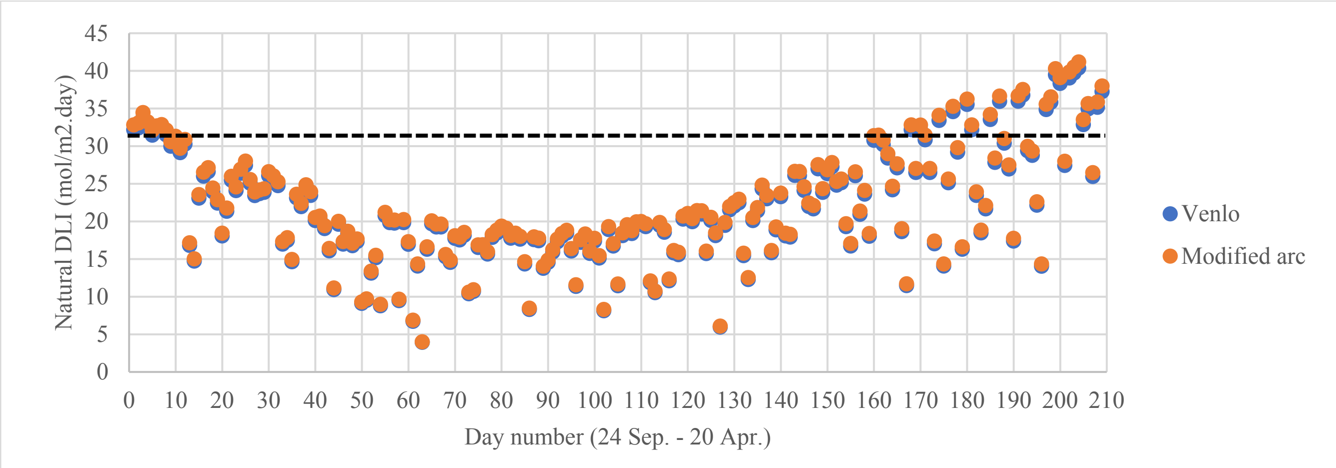

Figure 6. Available daily light integral during the cultivation period in Varamin

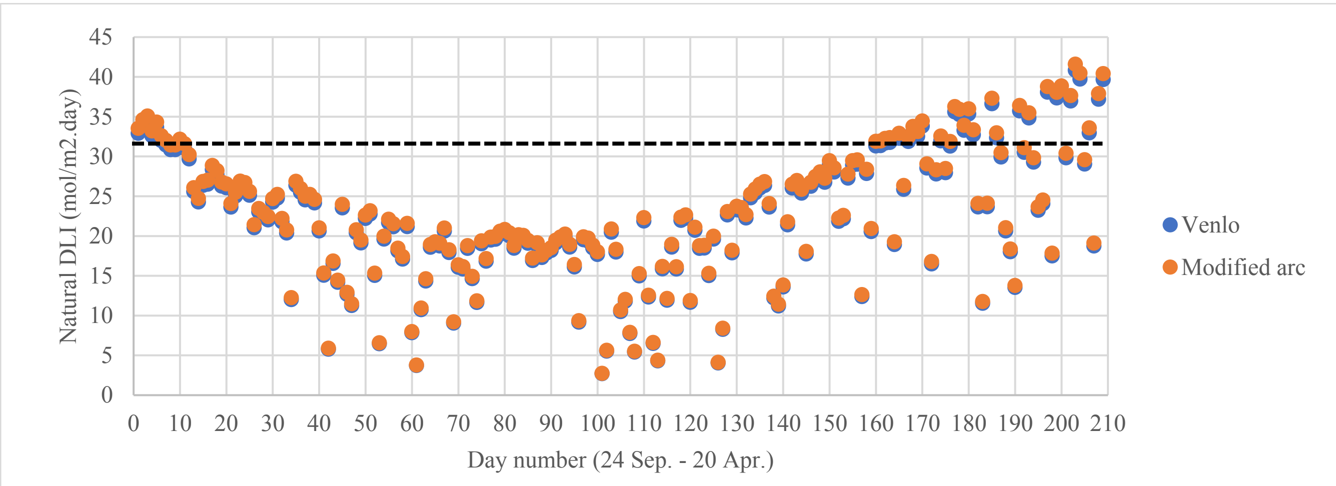

Figure 7. Available daily light integral during the cultivation period in Ahvaz

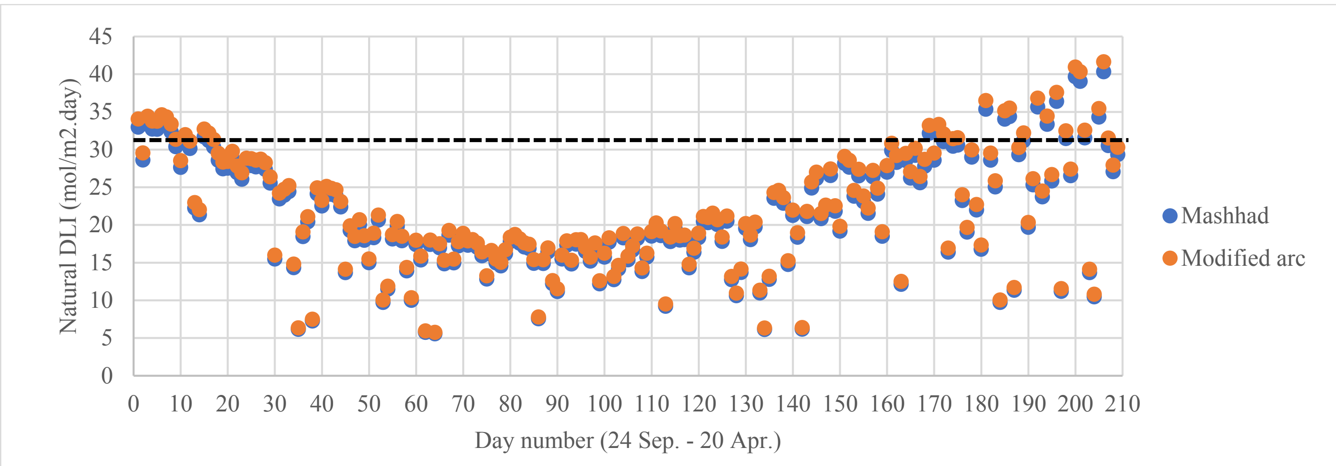

Figure 8. Available daily light integral during the cultivation period in Mashhad

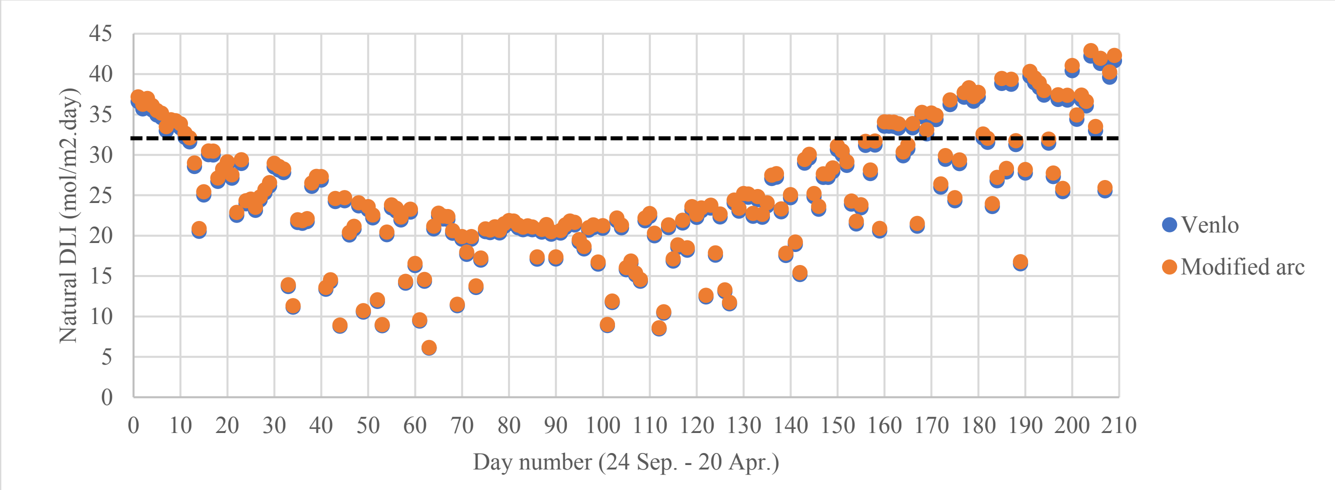

Figure 9. Available daily light integral during the cultivation period in Isfahan

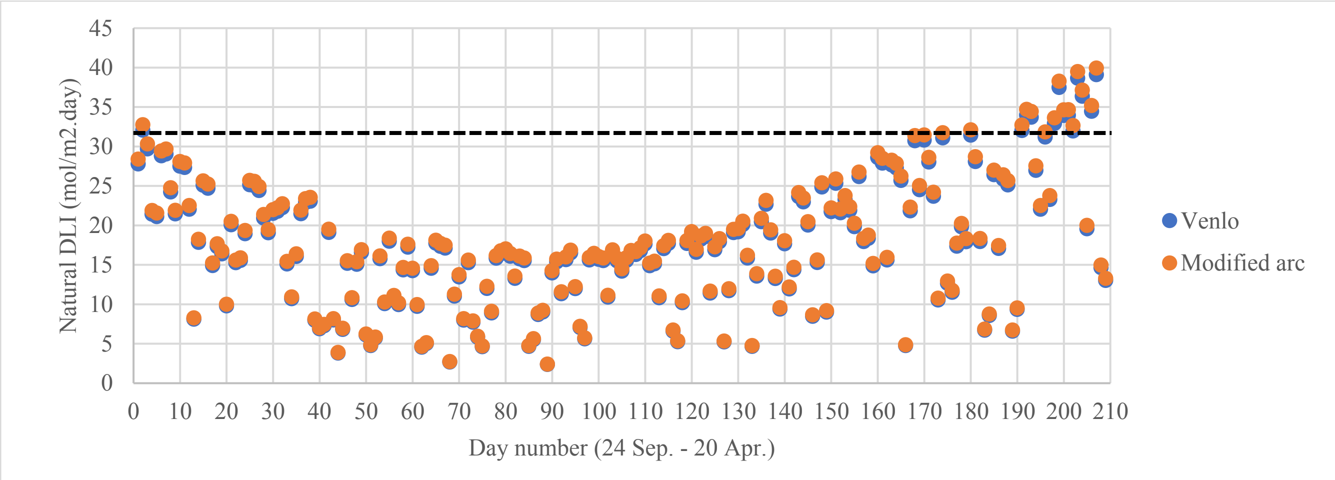

Figure 10. Available daily light integral during the cultivation period in Rasht

In order to evaluate the natural DLI deficit, the indicators introduced in Table 4 have been used. The first indicator is the PDNLD which is shown in Table 9. The percentage of days with a natural light deficit in the best case is equal to 75 % that belongs to Isfahan, and the worst one with 91 % belongs to Rasht. This fact indicates that even the best case faces light deficit in a high percentage of days during the cultivation period. Between Venlo and modified arc structures, the percentage of days when the insufficient light reaches the plant is slightly lower in the modified arc structures.

The second indicator, shown in Table 9, is the amount of light deficit (ALD). Modified arc structure in Isfahan with 1321.9 mol m^{-2} has the least amount of light deficiency, while Venlo structure in Rasht with 2653.5 mol m^{-2} has the highest amount of light deficiency. While the difference in the percentage of days with light deficiency between Isfahan and Rasht is 16.27 %, the amount of light deficiency in Rasht is 93 % more than Isfahan. This fact shows that although the number of days with light deficiency for Isfahan is high, the amount of light deficiency is much less than that in other cities. Among other cities, Varamin and Mashhad are close to each other in terms of light deficit. There is only a difference of 3 mol m^{-2} between the two cities in the modified arc structure regarding the light deficit; in the Venlo structure, this difference increases to 40 mol m^{-2}.

Table 9. The percentage of day with a natural light deficit and the amount of light deficit for 5 different regions and two greenhouse structures from Sep. 24 to April 20

	Venlo		Modified arc	
	PDNLD (%)	**ALD (mol m^{-2})**	**PDNLD (%)**	**ALD (mol m^{-2})**
Varamin	82.7	1859.7	81.9	1793.4
Ahvaz	80.3	1749.6	78.9	1688.9
Mashhad	84.6	1899.6	82.7	1790.3
Isfahan	75.1	1373.0	73.2	1321.9
Rasht	91.3	2653.5	90.9	2588.1

3.3. Evaluation of the artificial light impact

In this section, the effect of adding a supplementary lighting system on the greenhouse lighting indicators is investigated. The lighting plan strategy is developed according to supplementary lighting algorithm, which was previously illustrated in the methodology section. Figures 11 to 15 show the effect of the lighting system for Venlo structure for two different light capacities: (1) high lighting capacity at Photosynthesis Photon Flux Density (PPFD) of 200 $\mu mol\ m^{-2}\ s^{-1}$ and (2) low lighting capacity at PPFD of 100 $\mu mol\ m^{-2}\ s^{-1}$. These figures show the Natural Daily Light Integral (NDLI) and the Total Daily Light Integral (TDLI). TDLI is the sum of NDLI and Artificial Daily Light Integral (ADLI).

As shown in Figure 11 to Figure 15, artificial light has improved the daily light integral in the greenhouse, but even PPFD 200 $\mu mol\ m^{-2}\ s^{-1}$ has not completely met the needs of the tomato plant. Detailed information available in Figure 11 to Figure 15 as well as in Table 10 is provided by two indicators, PDNLD and ALD. Comparison between Table 9 and Table 10 shows the effect of adding artificial light. As can be seen, for PDNLD, the low light capacity leads to 6.2 % and 13.88 % decrease rates in Varamin and Mashhad, respectively. Also, it leads to a decrease of 17.7 % in Rasht to 32 % in Isfahan in high capacity. The ALD index shows that although the number of days with light deficiency has been reduced to 30 % in the best case, the amount of light deficiency has changed significantly due to the lighting system so that in the case of high light capacity, the amount of light deficiency in Isfahan for Venlo structure with 1373.07 mol m^{-2} (Table 9) has decreased to 288 mol m^{-2} (Table 10) or, in other words, 78 %. As shown in Table 10, the amount of light deficiency has also decreased significantly in other cities.

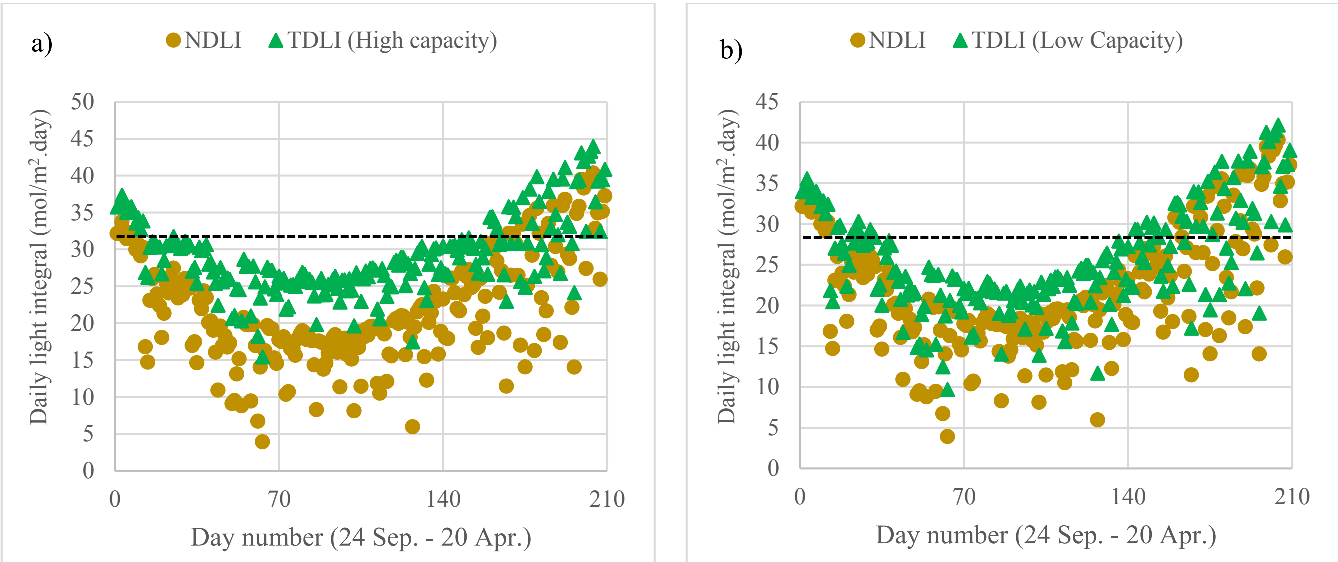

Figure 11. Natural daily light integral and Total Daily Light Integral (TDLI) for Venlo structure in two different artificial light capacities of a) 200 $\mu mol\ m^{-2}\ s^{-1}$ and b) 100 $\mu mol\ m^{-2}\ s^{-1}$ in Varamin

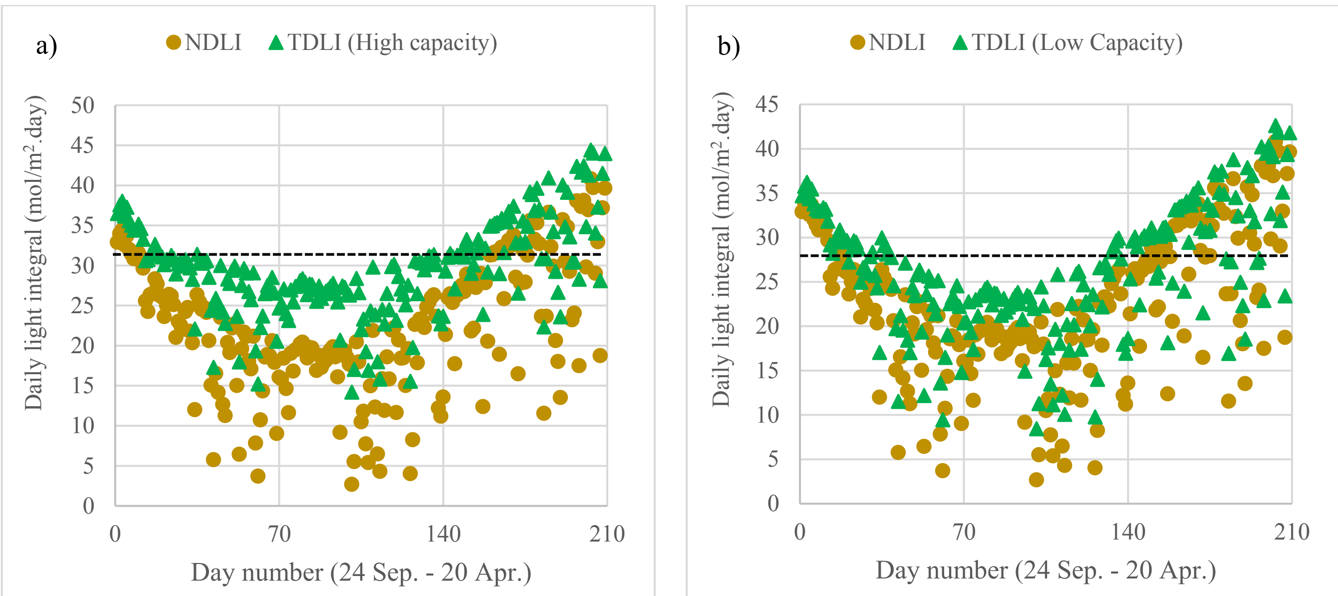

Figure 12. Natural daily light integral and Total Daily Light Integral (TDLI) for Venlo structure in two different artificial light capacities of a) 200 $\mu mol\ m^{-2}\ s^{-1}$ and b) 100 $\mu mol\ m^{-2}\ s^{-1}$ in Ahvaz

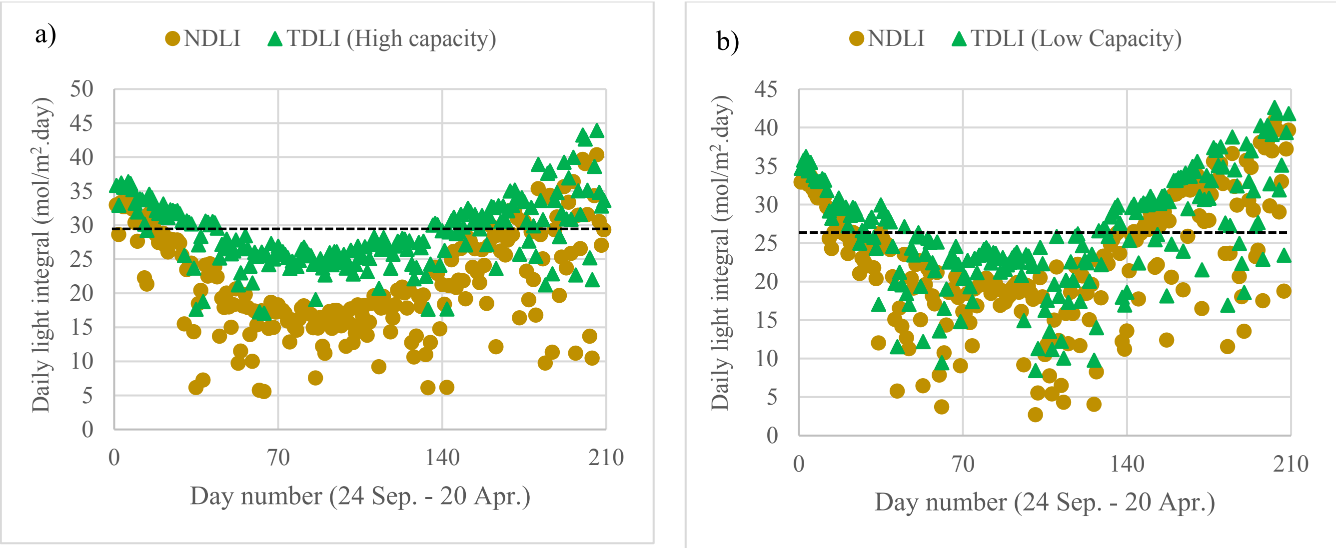

Figure 13. Natural daily light integral and Total Daily Light Integral (TDLI) for Venlo structure in two different artificial light capacities of a) 200 μmol m^{-2} s^{-1} and b) 100 μmol m^{-2} s^{-1} in Mashhad

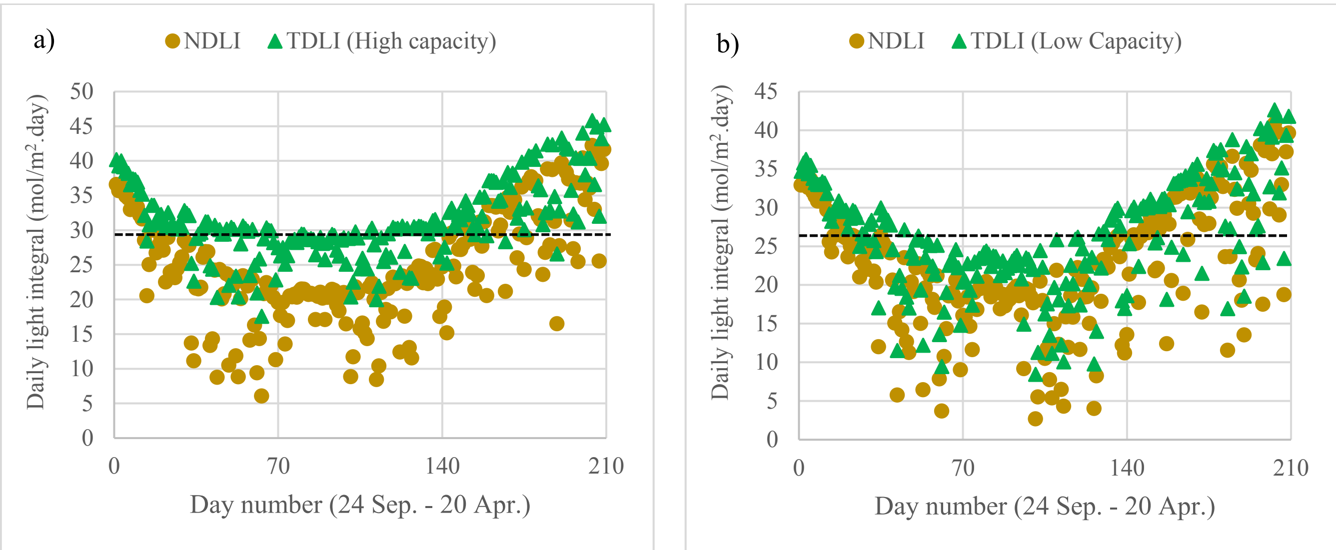

Figure 14. Natural daily light integral and Total Daily Light Integral (TDLI) for Venlo structure in two different artificial light capacities of a) 200 μmol m^{-2} s^{-1} and b) 100 μmol m^{-2} s^{-1} in Isfahan

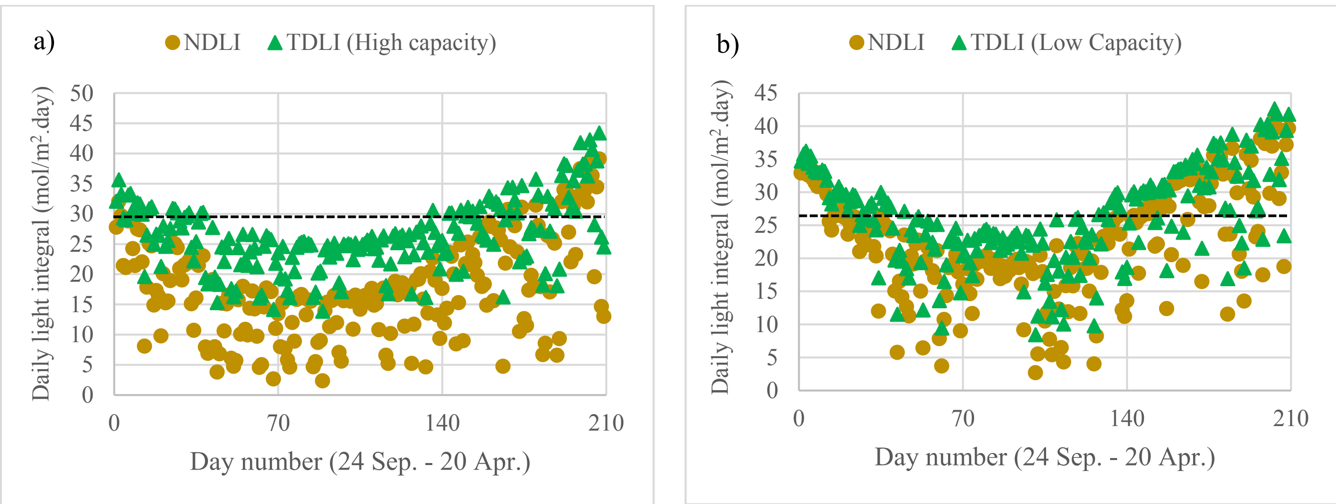

Figure 15. Natural daily light integral and Total Daily Light Integral (TDLI) for Venlo structure in two different artificial light capacities of a) 200 μmol m^{-2} s^{-1} and b) 100 μmol m^{-2} s^{-1} in Rasht

Table 10. The percent of day with a natural light deficit and the amount of light deficit for 5 regions and Venlo structure, from September 24 to April 20

	High capacity		Low capacity	
	PDNLD (%)	ALD (mol m^{-2})	PDNLD (%)	ALD (mol m^{-2})
Varamin	76.5%	1148.5	58.3%	529.8
Ahvaz	70.8%	1070.9	52.1%	502.4
Mashhad	70.8%	1181.8	57.8%	566.4
Isfahan	61.7%	774.7	41.1%	288.5
Rasht	84.6%	1777.4	73.2%	966.8

3.4. The required area of the photovoltaic panel to meet the energy demand of the lighting system

Based on the methodology presented in Section 2.4, the first step is to calculate the energy demand during the year, as shown in Table 11. After calculating ac and dc power, the required area of the panel for a square meter of greenhouse can be estimated with the help of conversion efficiency and panel efficiency, as shown in Table 12. The conversion efficiency rates for Varamin, Ahvaz, Mashhad, Isfahan, and Rasht are calculated to be 0.77, 0.74, 0.78, 0.77, and 0.77, respectively.

Table 12 shows the ratio of the photovoltaic panel area to the greenhouse area. The color green, which indicates low values of this ratio, is mainly in the low-capacity LED section. Venlo greenhouse in Rasht with a high capacity of HPS lamp is the largest, and the modified arc greenhouse in Isfahan with low capacity of LED lamp has the lowest ratio. Isfahan has the lowest ratio of PV area to greenhouse area, followed by Mashhad, Varamin, Ahvaz, and Rasht, respectively. In all cities, the performance of the modified arc structure is slightly better than that of the Venlo structure.

Another point of view shown in Table 12 is the impact of LED technology on reducing the PV area required to meet the energy demand of the lighting system. The impact of LED and HPS technologies is particularly effective in regions with high lighting demand similar to the situation with a high capacity in Rasht. The difference between the two technologies is close to 0.8 $m^2_{PV}\ m^{-2}_{greenhouse}$. It is implied that 50 % energy saving could be achieved when LED lamps are used; this result is in the range reported in Martineau et al. [36], illustrating that energy savings by LED lamps could be between 33.8 % to 77.8 % in comparison to HPS lamps.

The LG Neon model panel cost is about $ 364 per square meter [37] due to its advanced technology and high efficiency. Therefore, the cost of photovoltaic panels to compensate for the energy consumption of supplementary lighting ranges from $ 171 per greenhouse area in Isfahan (modified arc with LED technology) to $ 939 per greenhouse area in Rasht (Venlo with HPS technology). Also, it can be seen that up to $ 291 per greenhouse area can be saved using LED technology instead of HPS in Rasht with the high-capacity lighting system. However, the cost of photovoltaic panels is decreasing which can improve the economic aspect of supplementary lighting in the future. Of note, the application of the semi-transparent photovoltaic technology could also diminish the land use for photovoltaic system, which is to be the subject of our future study.

Table 9. Annual Energy Demand of the lighting system in greenhouses for two different lighting technologies, LED and HPS

City	LED (kWh m^{-2} y^{-1})				HPS (kWh m^{-2} y^{-1})			
	Low capacity		High capacity		Low capacity		High capacity	
	Venlo	Modified arc	Venlo	Modified arc	Venlo	Modified arc	Venlo	Modified arc
Varamin	109.90	108.65	211.10	207.90	164.85	162.98	316.65	311.85
Ahvaz	108.10	106.15	206.80	203.00	162.15	159.23	310.20	304.50
Mashhad	110.05	107.10	211.40	205.90	165.08	160.65	317.10	308.85
Isfahan	99.45	97.90	189.40	186.10	149.18	146.85	284.10	279.15
Rasht	128.20	126.05	251.40	246.90	192.30	189.08	377.10	370.35

Table 10. Panel area required for each square meter of the greenhouse to supply energy consumption of the lighting system for two different lighting technologies, LED and HPS, from Sep. 24 to April 20

City	LED ($m^2_{PV}\ m^{-2}_{greenhouse}$)				HPS ($m^2_{PV}\ m^{-2}_{greenhouse}$)			
	Low capacity		High capacity		Low capacity		High capacity	
	Venlo	Modified arc	Venlo	Modified arc	Venlo	Modified arc	Venlo	Modified arc
Varamin	0.60	0.59	1.14	1.13	0.89	0.88	1.72	1.69
Ahvaz	0.64	0.63	1.22	1.20	0.96	0.94	1.83	1.80
Mashhad	0.58	0.57	1.12	1.09	0.87	0.85	1.68	1.64
Isfahan	0.48	0.47	0.92	0.90	0.72	0.71	1.38	1.35
Rasht	0.88	0.86	1.72	1.69	1.31	1.29	2.58	2.53

4. CONCLUSIONS

Due to the natural light deficiency for optimal plant growth, there is a tremendous interest to investigate the effect of adding a supplementary lighting system in conventional greenhouses systems. For this purpose, first, the available natural light considering greenhouse structures (Venlo or modified arc) in the five regions of Iran including Varamin, Ahvaz, Mashhad, Isfahan, and Rasht were estimated. After determining the amount of natural light deficiency, the effects of adding two artificial light system with capacities of 100 and 200 $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$ were investigated. Finally, the electrical energy consumption of the lighting system was calculated considering the efficacies of two lamp technologies (LED and HPS), and the area of the photovoltaic panel required to supply this energy was calculated. The most important results of this study are as follows:

- The effect of greenhouse structure on solar radiation transmission coefficient was greater at sunrise and sunset, but was almost the same during the day.
- In winter, when the solar altitude angle was low, the modified arc greenhouse had a higher light transmission coefficient due to its roof structure and solar incidence angle.
- In general, the Venlo and modified arc structures of the greenhouse did not have much effect on the total light integral during the year.
- The natural light deficiency in the studied regions was significant, e.g., Isfahan with the most natural light available in about 75 % of the cultivation days (24 Sep.-20 Apr.) suffers from insufficient light considering optimum light, which is reported for tomato by 1373.07 mol m^{-2}.
- Among the case study regions, the lowest available natural light belonged to the city of Rasht such that in more than 91 % of the cultivation days, the optimum DLI (30 mol/m^2.day) is not achieved during considered cultivation period (24 Sep.-20 Apr.).
- The low and high capacities of artificial lighting system can effectively compensate for the natural light deficiency. The low capacity of artificial light on average leads to nearly a 10 % reduction in the number of days with the light deficit and 38.3 % in the total amount of light deficiency. The high capacity on average leads to a 25 % reduction in the number of days with light deficiency and 70 % in the amount of light deficiency.
- LED technology can save energy from 48.95 kWh per square meter in Isfahan to 123.45 kWh per square meter in Rasht during the cultivation period in comparison with HPS technology.
- Due to the greater availability of natural light, the electricity demand for lighting system in the modified structure was less than that for the Venlo structure.
- The area of photovoltaic panels to compensate the energy consumption of supplementary lighting ranged from 0.47 m^2 per greenhouse area in Isfahan (modified arc with LED technology) to 2.58 m^2 per greenhouse area in Rasht (Venlo with HPS technology).
- Among the studied regions, Isfahan has the lowest PV area to meet energy demand, orderly followed by Mashhad, Varamin, Ahvaz, and Rasht.
- The prospects of current research are (1) studying other common shapes or innovative new structures of greenhouses (e.g., advances solar greenhouses); (2) improving the on-off scheme of the lighting system by predicting natural light availability through previous horizon methodologies; (3) using semi-transparent Photovoltaic technology to diminish the land use for photovoltaic system; and (4) investigating the environmental impact of the greenhouse lighting system, e.g., life cycle analysis of supplementary lighting system.

5. ACKNOWLEDGEMENT

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NOMENCLATURE

A	Area (m^2)
ALED	Artificial light energy demand (kWh m^{-2})
h	Hour
I	Solar radiation (W m^{-2})
K	Extinction coefficient (m^{-1})
L	Thickness of the glass cover (mm)
Lat	Latitude (°)
Lon	Longitude (°)
n	Refraction index
NOCT	Nominal operating cell temperature (°C)
NOD	Number of days
P	Power (kW)
PR	Power reduction due to the temperature difference (% °C^{-1})
PPFD	Photosynthetic photon flux density
PV	Photovoltaics
$r_{\parallel}$	Parallel component of unpolarized radiation
$r_{\perp}$	Perpendicular component of unpolarized radiation
T	Temperature (°C)
TIE	Temperature impact efficiency
Greek letters	
α	Solar altitude angle (°)
B	Tilted angle (°)
η	Efficiency
θ_1	Incident angle (°)
θ_2	Angle of refraction (°)
τ	Transmissivity
Subscripts	
a	Absorption
ac	Alternating current
amb	Ambient
dc	Direct current
opt	Optimum
r	Reflection
STC	Standard test conditions

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