An Investigation Into PAR (Photosynthetically Active Radiation) And Energy Performances In Small-scale Greenhouses In Northern China

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Abstract

The availability of Photosynthetically Active Radiation (PAR) and energy demand are critical factors for assessing performances of greenhouses in indoor farming industry. They are significantly affected by configurations and orientations of greenhouses. Two small scale barrel-vault greenhouses combined with 5 orientations were studied under a climate of northern China, including the type with glazed roof and back and side walls (C1), and the type with fully glazed surface (C2). Using RADIANCE (ray-tracing lighting/solar packages) & TRNSYS (dynamic energy modelling), these greenhouse were evaluated in terms of PAR levels received at the floor and annual heating and cooling demands. Key findings are: 1) PAR varies in a similar trend over the year in the two greenhouses. C2 can achieve higher PAR levels at each month than C1, ranging from 57.6% (south) to 93.6% (east). 2) Annual energy demand of C2 is slightly higher than C1 at each ordination. 3) Given both PAR and energy performances, C2 facing east/west could be an optimal design. These findings could be developed into design strategies to improve the PAR availability, which is used for effectively supporting the growth of plants and vegetables, and at the same time help reduce energy consumption in greenhouses.

Keywords: PAR availability, Heating and cooling demand, Small-scale greenhouse, Numerical simulation, Northern China

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1. Introduction

The greenhouse used in indoor farming industry has been recognized as a new building type with a potential to achieve net-zero-energy consumption in the near future (Wang et al., 2019). Environmental and energy performances of greenhouses are receiving increasing attention in China, due to growing activities of indoor farming (Tong et al., 2013). Photosynthetically Active Radiation (PAR) is a spectral range of solar radiation from 400 to 700 nm, which the photosynthetic organisms are able to use in the process of photosynthesis (McCree, 1977). PAR is critically required for sustaining plant and vegetable growth and varies seasonally and changes based on the time of day and latitude (McCree, 1977). It can be generally found that the higher PAR accelerates the growth of most common plants and vegetables. Apparently, orientation is one of most important environmental factors to determine the amount of solar gains (including PAR) and energy demand of the building (Pai et al., 2015). The solar radiation received across surfaces of greenhouses is directly influenced by orientations and climate zones which the buildings are located in (Tong et al., 2013). In addition, both orientation and latitude have significant impact on the direct solar radiation transmissivity of transparent envelope (Kurata 1993). One study investigated effects of shape and orientation selection of a greenhouse on energy demand and solar radiation availability, and experimentally validated the thermal model (Sethi 2009). Pacheco et al. reported that the building orientation is one of the largest repercussions on energy demand in buildings (Pacheco et al., 2012). Optimizing both orientation and shapes could reduce the energy consumption up to approximately 36% (Aksoy et al. 2006). A proper planning of orientation, landscape factors and location could potentially decrease the building energy demand by 20%, such as via increasing the quantity of solar radiation entering an internal space (Spanos et al. 2005). In China, Chen et al. (2018) developed a theoretical model to determine the optimal orientation for a simple greenhouse placed in diverse latitudes. It seems that further studies relating to greenhouses will be required to meet an increasing requirement of indoor farming, especially for the types that can be easily built up (e.g. small scale).

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As for environmental and energy performances of greenhouse, most studies focus on an overall evaluation of indoor climates, thermal transfer, energy demand, and solar gains using theoretical, experimental and numerical approaches. However, few studies have been conducted to analyze the availability of PAR (similar to light) that will be directly used for sustaining vegetation growth, and the relevant energy performances that vary with the variations of PAR availability. To achieve a more accurate analysis, this article presents a simulation investigation into two small-scale greenhouses in China, using professional simulation packages: TRNSYS (energy and thermal modelling) (TRNSYS, 2018) and RADIANCE (ray-tracing solar modelling for solar and PAR) (RADIANCE, 2018). The optimized solutions for effectively growing plants and reducing whole energy consumption were produced to improve the development of similar greenhouses in Northern China.

2. Methods and Materials

The location studied is Beijing (Latitude: 39.9042° N, Longitude: 116.4074° E), northern China. Beijing has a typical temperate continental climate (www.weatherbase.com). The average temperature for the year in Beijing is 12.8 °C. The warmest month on average is July with an average temperature of 26.1 °C. The coolest month on average is January with an average temperature of -3.3 °C. The average daily sunshine in Beijing is 9.8 hours. The total annual sunshine time of Beijing is 2671 hours, with monthly percent possible sunshine ranging from 47% in July to 65% in January.

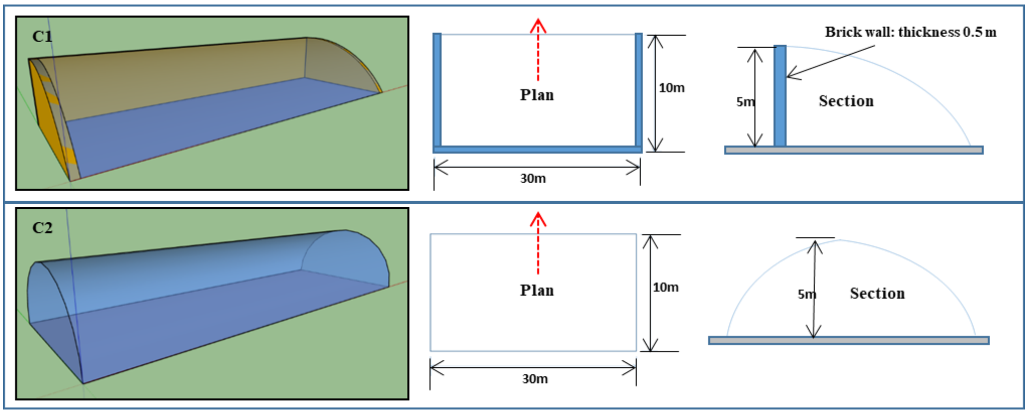

Fig. 1: Two small-scale greenhouse models studied in this article: C1 & C2.

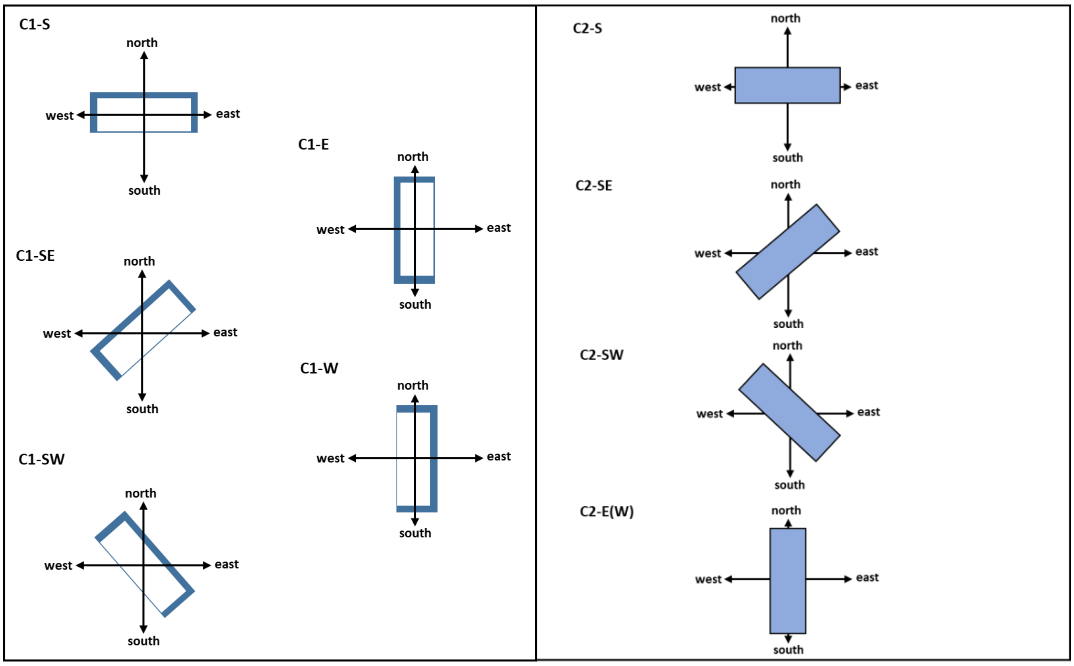

Fig. 2: Orientations of two small-scale greenhouse models (C1 & C2).

As shown in Figure1, two small-scale greenhouse models (C1 & C2) were studied. Both models have a rectangular plan (length × width: 30 × 10 m) and a height of 5 m. C1 has a half barrel-vault section (Laouadi, 2005) and its three sides were covered by the brick wall (thickness: 0.5 m); while C2 has a fully glazed barrel-vault envelop. If the main orientation is set along the width (marked by the red dash arrow), five orientations were studied for each model: south, south-east, south-west, east and west, as shown in Figure 2. For C2 model, facing east is the same as facing west due to the symmetric plan.

RADIANCE (v.5.0) (RADIANCE, 2018) was adopted to calculate the global solar irradiance (W/m^2) at the greenhouse floor and under various sky conditions. PAR values were then achieved using an empirical equation (Dong et al., 2011):

$$PAR = \delta^0 Q \quad \text{(eq. 1)},$$

where Q is global solar irradiance, W/m^2; η0 is the factor related to the location [η0 = 0.43 in Beijing (Bai, 2009)]. TRNSYS (TRNSYS, 2018), an advanced energy modelling package, was employed to calculate indoor temperature and predict energy demand (heating and cooling) in these greenhouses. Overall heat transfer coefficients (U-values) of the greenhouse envelope were set as follows: 1.365 W/m^{2}K (brick wall), 1.1 W/m^{2}K (glazing wall and roof) and 0.313 W/m^{2}K (floor). The visual transmittance of glazing wall and roof (double glazing) is 0.62. The annual heating and cooling demands have been calculated using various set-points for heating and cooling systems based on the requirements of different types of plants and vegetables (Li, 1989; Brewster, 2018). The energy demand calculation was based on an ideal heating/cooling system. As suggested in the guidances (Li, 1989; Brewster, 2018), the set-points of heating/cooling ($T_{heating}$/$T_{cooling}$) in greenhouses were 22 ºC/28 ºC (for normal plants and vegetables), 20 ºC/32 ºC (typical thermophilic plant and vegetables), and 15 ºC/20 ºC (typical plant and vegetables preferring the cool climate). All set-points have been applied in an annual energy consumption calculation. For all calculations, 0.2 l/h was used as the infiltration rate (Wang et al., 2019).

3. Results

This section mainly includes: effect of greenhouse type and orientation on PAR; effect of greenhouse type and orientation on indoor air temperature and energy demand.

3.1. Effects of greenhouse type and orientation on PAR

Table 1 shows the annual-averaged PAR for the various greenhouse types and orientations. For model C1, the highest annual-averaged PAR 33.66 W/m^2 could be obtained by south orientation. Model C2 is different from C1, the highest annual-averaged PAR 52.30 W/m^2 could be obtained by south-west orientation (C2-SW).

Tab. 1: Annual-averaged PAR in two greenhouses with different orientations

Greenhouse type with different orientations	PAR in W/m^2
C1-S	33.66
C1-E	25.63
C1-W	28.65
C1-SE	29.66
C1-SW	31.90
C2-S	51.92
C2-E(W)	52.28
C2-SE	51.96
C2-SW	52.30

In Table 2, monthly-averaged PAR levels have been simulated and calculated in terms of 12 months. The varying trends are given for greenhouse C1 and C2. It can be found that PAR varies in a similar trend all over the year. Both model C1 and C2 can see the highest values of PAR in June. The maximum PAR values of various models are 45.8 W/m^2 (C1-S), 38.9 W/m^2 (C1-E), 44.0 W/m^2 (C1-W), 41.4 W/m^2 (C1-SE), 45.0 W/m^2 (C1-SW), 72.2 W/m^2 (C2-S), 75.3 W/m^2 (C2-E(W)), 74.4 W/m^2 (C2-SE), and 74.3 W/m^2 (C2-SW). PAR level of model C2 is higher than model C1 for the same orientation, by 57.6% ((72.2 W/m^2 – 45.8 W/m^2)/(45.8 W/m^2)) (South), 93.6% ((75.3 W/m^2 – 38.9 W/m^2)/(38.9 W/m^2)) (East), 80.4% ((74.4 W/m^2 – 41.4 W/m^2)/(41.4 W/m^2)) (Southeast), 65.1% ((74.3 W/m^2 – 45.0 W/m^2)/(45.0 W/m^2)) (Southwest). According to the aforementioned findings, it can be found that model C2 could obtain more PAR than model C1 across the whole year, which can be explained by its larger glazing area.

Tab. 2: Monthly-averaged PAR performances in two greenhouse models (C1 & C2) and with various orientations; C1: south (C1-S), east (C1-E), west (C1-W), south-east (C1-SE), and south-west (C1-SW); C2: south (C2-S), east or west (C2-E(W)), south-east (C2-SE), and south-west (C2-SW).

PAR(W/m^2)												
Month **Model**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
C1-S	20.4	29.8	36.9	44.0	44.8	45.8	41.0	41.0	33.3	27.6	21.5	17.8
C1-E	11.8	19.1	27.0	34.9	37.4	39.0	35.1	34.0	25.6	19.3	13.4	11.0
C1-W	13.7	21.7	30.4	39.0	41.4	44.0	38.6	37.7	28.4	21.6	15.2	12.1
C1-SE	16.6	25.1	32.2	39.3	40.5	41.4	37.4	37.1	29.5	23.9	18.0	14.9
C1-SW	18.2	27.1	34.7	42.3	43.4	45.0	39.8	39.7	31.6	25.6	19.4	15.9
C2-S	29.4	43.8	56.6	68.7	69.1	72.2	64.9	65.7	52.1	42.1	31.8	26.6
C2-E(W)	27.8	42.4	56.4	70.2	71.6	75.3	67.2	67.3	52.3	41.3	30.4	25.2
C2-SE	28.3	42.3	55.9	69.4	70.8	74.4	66.4	66.6	51.9	41.1	30.8	25.7
C2-SW	28.9	43.0	56.5	69.7	70.8	74.3	66.4	66.8	52.2	41.6	31.3	26.1

3.2. Effect of greenhouse types and orientations on energy performances

Figure 3 shows the distributions of indoor air temperature in two greenhouses with five orientations and with glazing wall and roof (C2) or brick wall and glazing roof (C1) (U values mentioned in section 2). This simulation did not include HVAC systems, i.e. only unconditioned environment was evaluated. The aim of this analysis was to show if it is necessary to adjust the indoor environment using HVAC systems to achieve a proper living condition for plants and vegetables in these greenhouses.

For the variations of indoor temperature in the unconditioned greenhouses, the maximum and minimum values in various models are 82.9 ^{o}C and 1.4 ^{o}C (C1S), 77.7 ^{o}C and -0.567 ^{o}C (C1E), 80.7 ^{o}C and -1.09 ^{o}C (C1W), 80.7 ^{o}C and 0.843 ^{o}C (C1SE), 82.5 ^{o}C and 0.805 ^{o}C (C1SW), 83.1 ^{o}C and 1.51 ^{o}C (C2S), 81.8 ^{o}C and -1.11 ^{o}C (C2E(W)), 81.9 ^{o}C and 0.95 ^{o}C (C2SE), and 83.6 ^{o}C and 0.91 ^{o}C (C2SW). It can be clearly found that only the passive solutions would not be able to sustain a normal growth of plant/vegetation in these greenhouses.

Generally, given typical types of plant and vegetable in Beijing region, the indoor farming using greenhouses would require three various temperature ranges (Li, 1989), such as 22 ^{o}C~28 ^{o}C for normal plant and vegetables (e.g. zucchini, loofah), 20 ^{o}C~32 ^{o}C for typical thermophilic plant and vegetables (e.g. legume. tomato), and 15 ^{o}C~20 ^{o}C for typical plant and vegetables preferring the cool climate (e.g. Chinese leaf, cabbage). Therefore, HVAC systems will have to be applied in the nine greenhouse models to provide the plant and vegetable with a proper growing condition. In this study, the HVAC system modelled by TRNSYS has been set under an ideal condition.

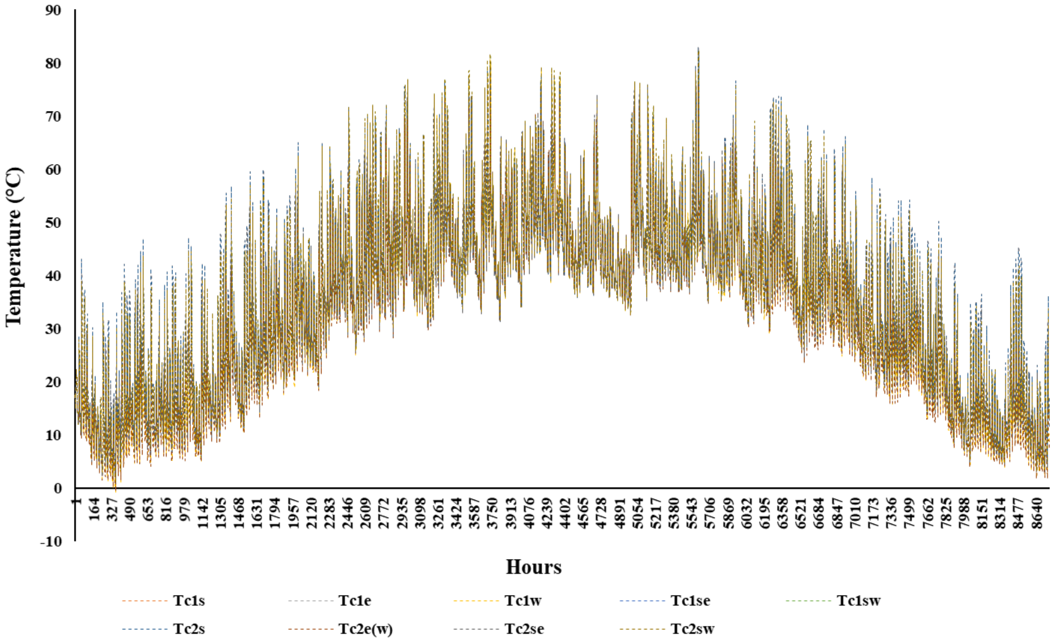

Fig. 3: Distributions of indoor air temperature in nine greenhouse models (unconditioned)

For the set-point of $T_{heating}/T_{cooling}$ = 22/28 °C, Figure 4-6 show the energy performances of nine greenhouses with five orientations. The names of all models are mentioned in Figure 2.

For annual energy demand (Figure 4), C2-S would achieve the lowest value of heating (70.66 kWh/m^2), whilst other eight models have the difference approximately 30 kWh/m^2 in between, in the ranges of 72.94 kWh/m^2 to 101.39 kWh/m^2. For annual cooling energy demand, C1-W would achieve the lowest value of cooling (246.39 kWh/m^2), C1-E (246.67 kWh/m^2) is similar to C1-W, whilst other eight models have no big differences in between. Considering overall annual energy demand, C1-W would achieve the lowest value 347.13 kWh/m^2. Thus, based on the aim to save heating energy, C2-S would be the best option among all nine models, for normal plant and vegetables. On the other hand, the performance of annual energy demand would support that C1-W could be considered as the first choice compared with other models.

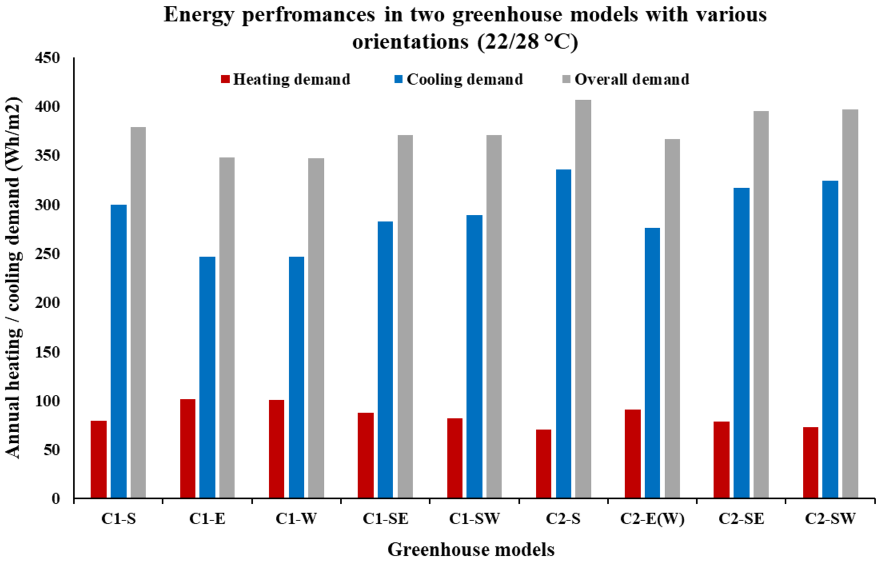

Fig. 4: Annual heating and cooling demands and overall demand in two greenhouse models with five orientations ($T_{heating}/T_{cooling}$: 22/28 °C).

Figure 5 indicates the heating demand of nine greenhouses in January (winter) and October (autumn). C1-W and C1-E have the highest monthly heating demand in January (9071 kWh) and October (445 kWh) among all nine models. C2-S and C2-SW have the lowest heating demand compared with other eight models in January (6402 kWh) and October (214 kWh), respectively.

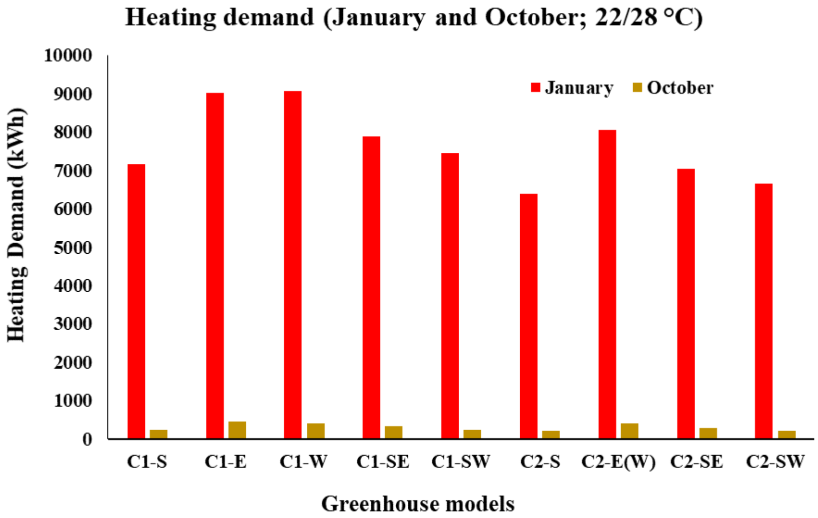

Fig. 5: Heating demand (January & October) of nine greenhouses ($T_{heating}/T_{cooling}$: 22/28 °C)

Moreover, Figure 6 demonstrates the cooling demand of nine greenhouses in April (spring) and July (summer). For all models, C1-E and C1-W have the lowest cooling demand 8470 kWh in April and 10300 kWh in July, respectively. There are no clear differences of cooling demand between other seven models. They have a monthly cooling demand ranging from 8530 kWh to 11984 kWh in both April and July.

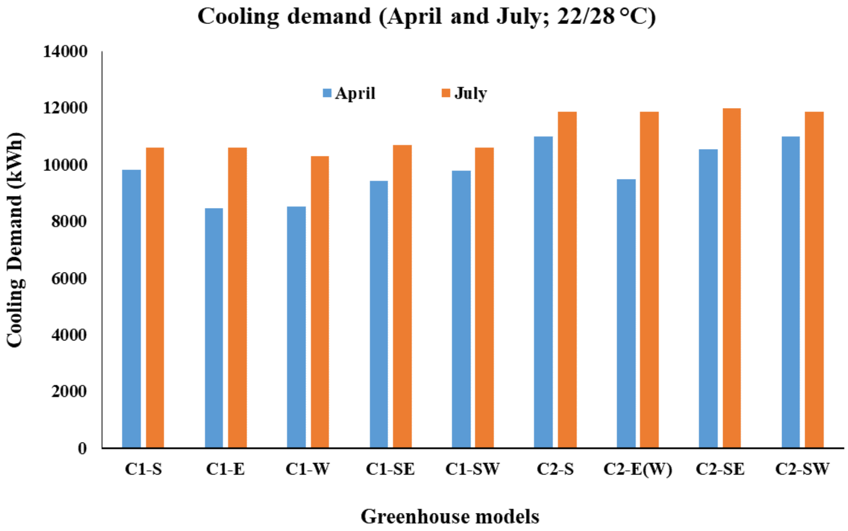

Fig. 6: Cooling demand (April & July) of nine greenhouses ($T_{heating}/T_{cooling}$: 22/28 °C)

For the set-point of $T_{heating}/T_{cooling}$ = 20/32 °C, Figure 7 indicates annual overall energy performances of nine greenhouses with five orientations. Similar to the set-point of $T_{heating}/T_{cooling}$ = 22/28 °C, C2-S would achieve the lowest value of heating (50.54 kWh/m^2), whilst other eight models have the difference approximately 26 kWh/m^2 in between, in the ranges of 52.92 kWh/m^2 to 78.41 kWh/m^2. For annual cooling energy demand, C1-E would achieve the lowest value of cooling (190.65 kWh/m^2), C1-W (190.83 kWh/m^2) is similar to C1-E, whilst other seven models have no big differences in between. Considering overall annual energy demand, C1-W would achieve the lowest value 268.15 kWh/m^2. Therefore, it can found that the findings with typical thermophilic plants and vegetables are the same as the normal plant and vegetables.

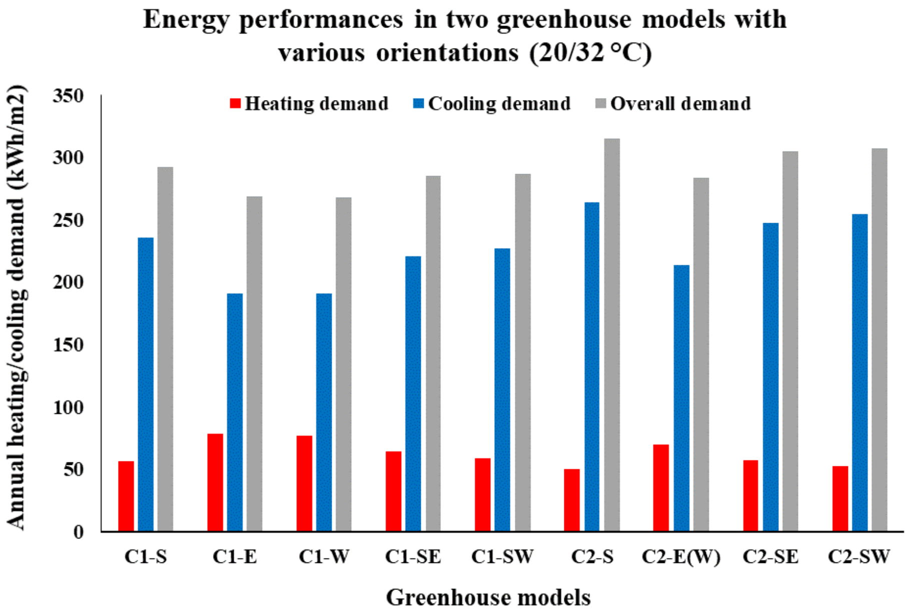

Fig. 7: Heating and cooling demand, and overall demand in two greenhouse models with five orientations ($T_{heating}/T_{cooling}$: 20/32 ºC).

Figure 8 indicates the heating demand of nine greenhouses in January (winter) and October (autumn). As shown in Figure 7, C1-W has the highest monthly heating demand in January (9070 kWh) and in October (396 kWh), among all nine models. C2-S has the lowest heating demand compared with other eight models in January (4955 kWh) and in October (38 kWh).

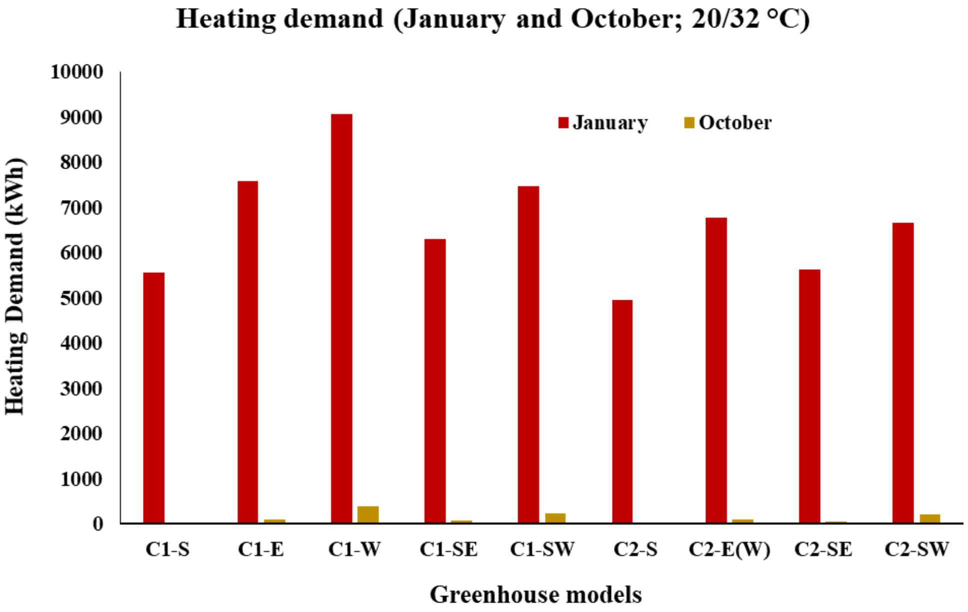

Fig. 8: Heating demand (Jan & Oct) of nine types of greenhouse ($T_{heating}/T_{cooling}$: 20/32 ºC

Moreover, Figure 9 demonstrates the cooling demand of nine greenhouses in April (spring) and July (summer). For all models, C1-E and C1-W have the lowest cooling demand 6710 kWh in April and 8200 kWh in July, respectively. There are no clear differences of cooling demand between other seven models. They have a monthly cooling demand ranging from 6750 kWh to 10687 kWh in both April and July.

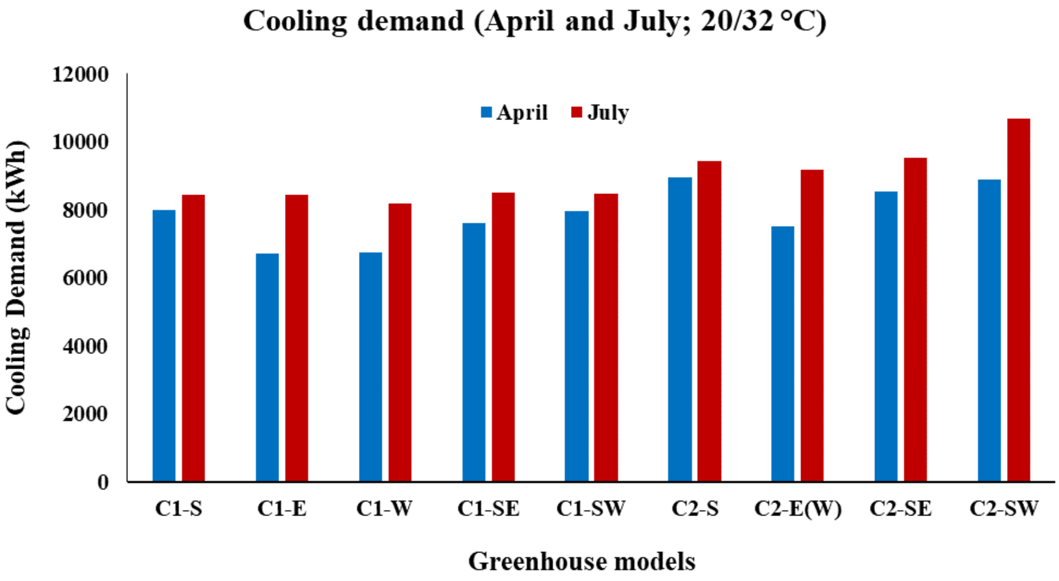

Fig. 9: Cooling demand (April & July) of nine types of greenhouse ($T_{heating}/T_{cooling}$: 20/32 ºC)

For the set-point of $T_{heating}/T_{cooling}$ = 15/20 ºC, Figure 10 indicates annual overall energy performances of nine greenhouses with five orientations. Similar to the set-point of $T_{heating}/T_{cooling}$ = 22/28 ºC, C2-S would achieve the lowest value of heating (30.21 kWh/m^2), whilst other eight models have the difference approximately 15 kWh/m^2 in between, in the ranges of 31.16 kWh/m^2 to 46.98 kWh/m^2. For annual cooling energy demand, C1-W would achieve the lowest value of cooling (362.22 kWh/m^2), C1-E (362.69 kWh/m^2) is similar to C1-W, whilst other seven models have no big differences in between. Considering overall annual energy demand, C1-W would achieve the lowest value 408.17 kWh/m^2.

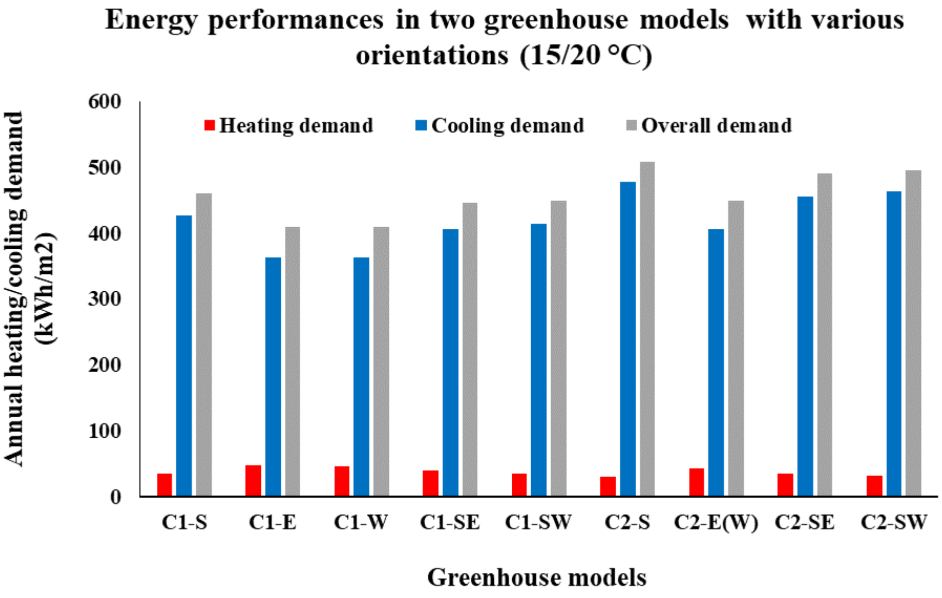

Fig. 10: Heating and cooling demands, and overall demand in two greenhouse models with five orientations ($T_{heating}/T_{cooling}$: 15/20 ºC).

Figure 11 indicates the heating demand of nine greenhouses in January (winter) and October (autumn). C1-E has the highest monthly heating demand in January (4850 kWh) and in October (7.72 kWh), among all nine types. C2-S and C2-SW have the lowest heating demand compared with other eight models in January (3151.79 kWh) and in October (1.23 kWh), respectively.

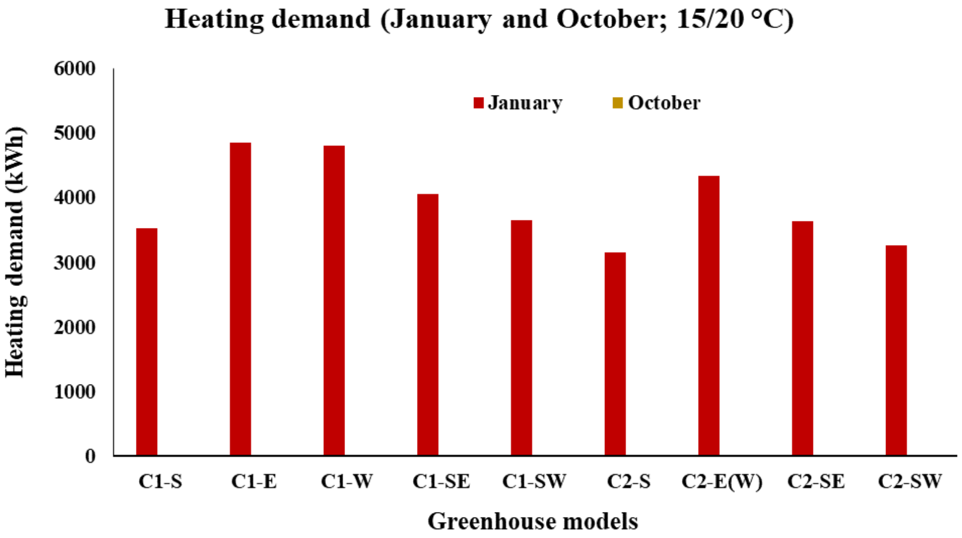

Fig. 11: Heating demand (Jan & Oct) of nine types of greenhouse ($T_{heating}/T_{cooling}$: 15/20 °C)

Moreover, Figure 12 demonstrates the cooling demand of nine types of greenhouse in April (spring) and July (summer). For all models, C1-E and C1-W have the lowest cooling demand 12400 kWh in April and 14800 kWh in July, respectively. There are no clear differences of cooling demand between other seven models. They have a monthly cooling demand ranging from 12500 kWh to 16912 kWh in both April and July.

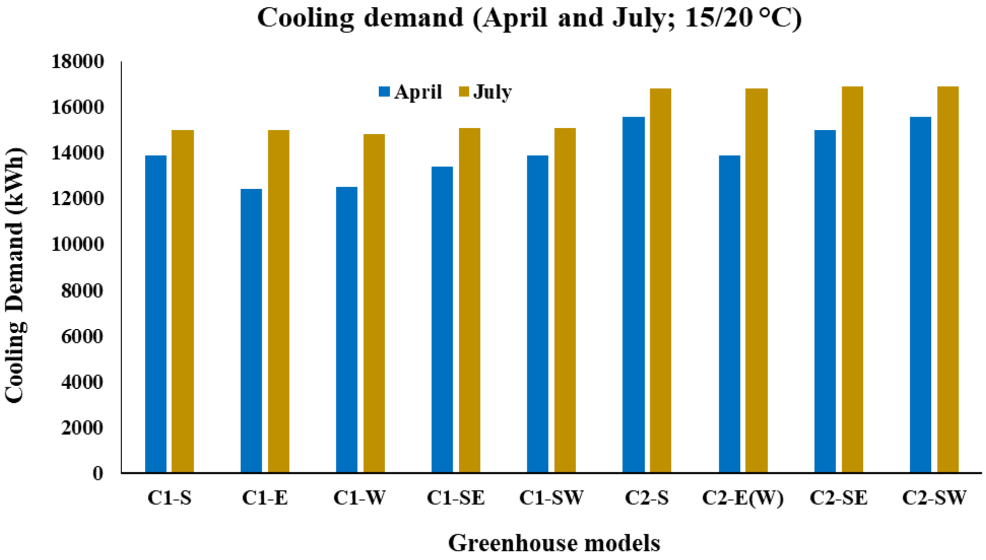

Fig. 12: Cooling demand (April & July) of nine types of greenhouse ($T_{heating}/T_{cooling}$: 15/20 °C)

4. Discussions

Based on the results above, some discussions are given in this section.

First, since PAR is one part of solar gain, the greenhouse models with a larger glazing surface will achieve higher PAR levels. It is normal that with a fully glazed envelop, C2 can receive a higher PAR level at each orientation than C1 (with a much smaller glazing envelop). Compared with C2, C1 has a higher sensitivity of PAR availability to the orientation due to its asymmetric plan. The higher PAR can be only found when its glazing façade is placed towards specific orientations, e.g. south or south-west. This can also be explained by the local climates of Beijing (i.e. higher solar gains are from south or south-west sky).

Second, annual energy demand of greenhouse is directly associated with local climate conditions. Beijing has a temperate continental climate, which could require a balance of energy system design between cold winter and hot summer. With a fully glazed envelop, C2 could mitigate the internal heat losses through the external solar gain in winter, but would need more cooling energy in summer. C1 would need higher heating energy due to the lower solar gain in winter. However, the smaller glazed envelop would benefit C1 with a lower cooling demand in summer. In addition, Beijing's climate can explain the west facing is an optimal solution in terms of annual energy performance.

5. Conclusion

Several key findings could be drawn from results and discussions above as follows.

1) PAR varies in a similar trend over the year for greenhouses C1 and C2. Greenhouse C2 will achieve higher PAR levels at each month than C1, ranging from 57.6% (south) to 93.6% (east). For greenhouse C1, significant effects of orientation can be found on PAR levels across 12 months. Facing south or south-west could deliver the highest PAR values, while the lowest PAR values can be found with facing east. Facing west and south-east will achieve medium PAR values in between. However, for greenhouse C2, there is no significant influence of orientation on PAR performances. Only facing south can see a slightly lower PAR than other orientations during the summer (from May to August).

2) Annual overall energy demand of C2 is slightly higher than C1 at each orientation. Greenhouse C1 has a relatively higher annual heating demand and a lower annual cooling demand than greenhouse C2 at each orientation.

3) The minimum values of annual overall energy demand of normal plant/vegetables (22 ^{o}C/28 ^{o}C), typical thermophilic plant/vegetables (20 ^{o}C/32 ^{o}C) and typical plant/vegetables preferring the cool climate (15 ^{o}C/20 ^{o}C) are 347 kWh/m^2 (C1-W), 268 kWh/m^2 (C1-W) and 405 kWh/m^2 (C1-W) respectively. Facing west can lead to the minimum annual energy demand in greenhouses.

4) Given both PAR and energy performances, C2E(W) could be an optimal design, since it can give rise to a relatively higher PAR levels and lower annual energy demand. For other models, a balance would have to be considered between PAR and energy demand during the early stage of design.

Limitations and future work: this study was conducted using two simulations packages and two typical greenhouse models. The shading systems and natural ventilation strategy could mitigate the effect of excessive solar gains on the higher cooling demand. However, the two environmental solutions were not included in the analysis, which could be clear limitations. More investigations, including passive solutions, the on-site measurements for PAR and energy performances, and more greenhouse structures and configurations, will be implemented in the next stage.

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