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Full Research Paper

Degree-Day Index for Estimating the Thermal Requirements of a Greenhouse Equipped with an Air-Earth Heat Exchanger System

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Abstract

In this research, an attempt was made to utilize an Earth-Air Heat Exchanger (EAHE) system as a source of shallow geothermal energy to provide thermal demands of a commercial greenhouse located in Alborz province, Iran. The degree-day index was applied to estimate the EAHE system's potential to meet the thermal requirements of the greenhouse including cooling and heating demands. The results indicated that this region needed more energy to reach to the relevant temperature inside the greenhouse for the heating demand comparing to the cooling one. The average potential of the EAHE system based on the degree-day index was 10.76ºC for increasing temperature in the cold and 17.96ºC for decreasing temperature in the warm season. This means that the EAHE system was capable of supplying the greenhouse thermal demands in this area according to the calculated values of Heating Degree-Day (HDD) and Cooling Degree-Day (CDD). This method would be beneficial in monitoring and optimizing plant growth conditions as the best crop type or cultivation selection which in turn can help in irrigation and fertigation management of the crop grown.

Keywords: Degree-Day, Heat exchanger, Geothermal, Greenhouse

Introduction

In 1973, the oil shocks increased the considerable importance of energy and forced the world toward other energy sources and their optimal consumption. Alternative policies, energy efficiency, and the achievement of sophisticated technologies were the strategies taken by different countries, especially developed countries, to address the energy resource shortage challenge (Franczak, 2017; Faridi *et al.*, 2019a). For this reason, the optimal use of energy resources in the process of economic development has always been considered as a vital objective in sustainable development. The renewable or environmentally friendly energies such as solar, wind, geothermal, etc. are suggested to prevent the more tremendous impact of these harms. Among all renewable energies, the geothermal one can offer a valuable source of thermal energy for a building because it is not limited to season, time, and conditions. At present, this renewable energy source is used to generate electricity at a significant scale as well as for direct applications like environmental heating, greenhouses and aquaculture (Dreidy *et al.*, 2017).

The closer to the depth of the earth, the fewer changes occur in the earth's temperature during the year, so that from a depth of 1.5 to 2 meters from the surface of the earth, temperature fluctuations throughout the year are negligible (Sehli *et al.*, 2012; Bisoniya 2015). This near-constant temperature at this depth is called Earth's Undisturbed Temperature (EUT). In fact, the earth capacity is considered as a passive method for the purpose of heating and cooling buildings. For the effective use of the thermal capacity of the earth, a heat exchanger system should be created which usually uses a various arrangement of buried pipes along the length

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of a building, or vertically on the ground. The concept of Earth-Air Heat Exchanger (EAHE) is quite simple. As observed in Figure 1, in the summer, a rotating environment (water or air) is operated to extract heat from the building and transfer it to the ground and inversely in the winter from the same rotating medium to extract heat from the ground and transfer it to the building (Sehli *et al.*, 2012; Ciriaco *et al.*, 2020). Geothermal energy can be employed as an EAHE system for the inactive cooling in greenhouses exerting renewable energies (Abbaspour-Fard *et al.*, 2011; Faridi *et al.*, 2019b). In tropical and semi-tropical countries, the development of heat exchangers has been widely studied in greenhouses in different climates such as South Asia (Misra *et al.*, 2013).

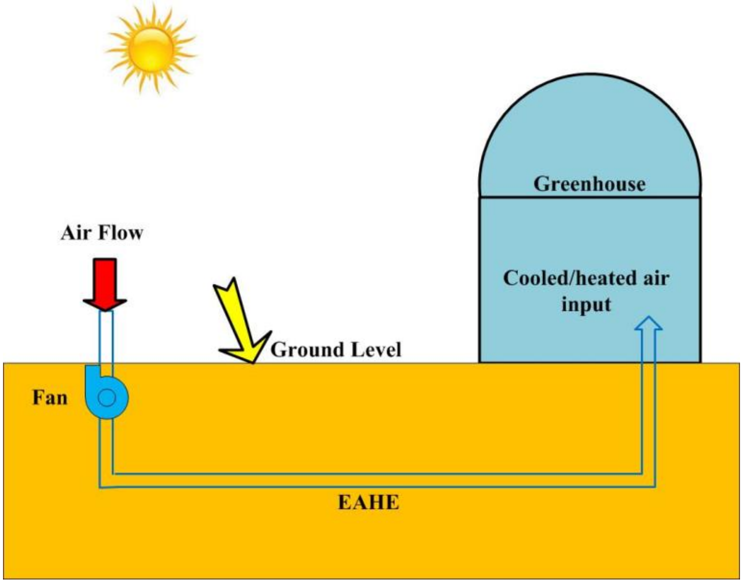


Fig.1. Simple concept of the EAHE system with the aim of heating and cooling a closed space

The arid climate of Iran, the shortage of rainfall, as well as high evapotranspiration rate, has struck the country with severe water scarcity (Amiri and Eslamian, 2012). As a result, greenhouse production can be a worthy choice for reducing water consumption compared to outdoor production (Kabeel and El-Said, 2015). However, energy consumption in greenhouses is higher than traditional ones to provide the necessary environmental conditions (heating, cooling, ventilation, etc.) and has made the energy consumption as a crucial challenge (Mongkon *et al.*, 2014). On the other hand, the energy essential management in greenhouses performs a critical role in the sustainable development of agriculture (Vadiee and Martin, 2014). Supplying the demands of heating, cooling and ventilation in greenhouses are dependent of external weather conditions. The use of climate information during the design or management of heating, cooling and ventilation systems for the greenhouse will be useful for easily obtaining more accurate and realistic results (Yucel *et al.*, 2014; López-Aguilar *et al.*, 2020).

Climate conditions are the primary factors influencing on the energy consumption in producing greenhouse crops in a region, so that it is possible to scientifically investigate the climate history (minimum/maximum biological temperature) of the region for certain periods and identify the conditions necessary for cultivating the desired crops regarding to the reduction of energy consumption. One of the factors used to check the weather history of a region is the degree-day index (Day, 2016; Zheng *et al.*, 2020). Changes in this index will carry out a substantial role in environmental issues, including the intensity of energy consumption for heating and cooling of the environment (Roshan and Grab, 2012; Day, 2016). The sum of degree-days from an appropriate start date is expended for crop production plan, pest management, scheduling pest and energy consumption control and related objectives. A degree-day is calculated as a functional integral of time that changes in general with air temperature (Verbai *et al.*, 2014; Moreno *et al.*, 2014). This function reduces the deviations of temperature from the optimal temperature thresholds changed by components or the range for which the air conditioner is appropriate (Ciulla *et al.*, 2015; Goff, 2015; Way, Lewkowicz and Bonnaventure, 2017). In other words, measuring the average temperature of the air using the threshold temperature is called degree-day. These temperature thresholds for calculating the cooling and heating day depend on the specific objectives that can vary according to the type of research and location being studied (Romanovskaja and Baksiene, 2011; Mourshed, 2012). Identifying the areas susceptible to agriculture based on the recognition of natural potential can play a major role in environmental and land use planning, while providing suitable grounds for human activities (Romanovskaja and Baksiene, 2011). Climate is a determinant factor in the distribution of plants and their physiological and phonological processes (Mideksa and Kallbekken, 2010).

Significant increase in total energy consumption will more appreciably increase extention of the necessity of continuity and acceleration in energy efficiency measures in the energy supply and demand. The first step in this field is accurate calculations based on the region’s climatic conditions.

The continuation of this process will lead to a dependence of the country on energy imports. In recent years, climate policy in the energy sector has been more extremely limited to reduce emissions (Ebinger and Vergara, 2011; Schaeffer *et al.*, 2012). However, knowing about the adaptation and vulnerability of the energy sector to climate and spatial changes can lead to an understanding of the energy management and efficiency (Marimon *et al.*, 2020). As the heat dissipation of the building is directly proportional to the difference between the internal and external air of the building, the energy consumption of a building over a period of time is related to the total temperature difference in this period. Therefore, it is necessary to obtain sufficient knowledge of the spatial variations of the heating and cooling needs in a region to better manage energy. The degree-day computing techniques depend on spatial data.

There are numerous studies reported about the application of degree-day index by researchers. Jiangsu district heating and cooling day trend were studied by Jiang *et al.* (2009). An alternative modelling presented to estimate the amount of energy needed for heating and cooling of greenhouse products (Papakostas *et al.*, 2009). Rehman *et al.* (2011) calculated the monthly and annual heating and cooling requirements of industries in five coastal cities of Saudi Arabia with temperature thresholds of 13, 18, 20 and 24ºC. Chai *et al.* (2011) compared the interpolated models in the zoning and temperature estimation of China's Xinjiang province. Marimon *et al.* (2020) studied a support system based on degree-day index to start fungicide spray programs for peach powdery mildew.

In most cases, the enormous expenses in greenhouse production belong to the energy consumption for cooling in summer and heating in winter (Ghasemi Mobtaker *et al.*, 2017). There is a possibility of break in fuel and electricity supply at the peak times of energy consumption. Plants in the greenhouse are sensitive to temperature shocks, so any disruption or shortage in energy supply causes severe problems and sometimes with consequential damages. The EAHE system could represent as an alternative for such cases to decrease the risks. The knowledge about the potential of EAHE system and the degree-day are useful for the grower to select an agricultural production, which fits better to energy balance during the production period.

The objective of this study is to investigate and determine the potential of EAHE system for the purpose of energy consumption in the greenhouse based on the degree-day method.

Materials and Methods

A multi-span commercial greenhouse with North-South arrangement was selected for this research project with the area of 3840 m^2 located in Alborz province, Iran (with latitude and longitude of 35°52' N and 50°40' E, respectively, at 1300 m above sea level). The greenhouse is equipped with the EAHE system for each unit which employs an autonomous air-conditioning system based on the geothermal principle to supply the greenhouse cooling demands without any conventional cooling system (such as pad-fan, mist, fog, etc.). The EAHE system partly provides the greenhouse heating requirement by reducing the consumption of fossil fuels compared with the conventional greenhouses of the region (Figure. 2). It is worth noting that the shallow geothermal system as EAHE one used in this study is different from the conventional systems as illustrated in Figure 1. This system has two external air (ambient) inputs, 30 outputs along the greenhouse floor and one umbrella roof vent for each span. First, the temperature changes of the target area were investigated for 10 years ago (2007-2017) for surveying the EAHE potential in order to supply the energy demands of a tomato greenhouse. Then, the degree-day of heating and cooling for the given time period was calculated and analysed for the temperature of the greenhouse by the EAHE system.

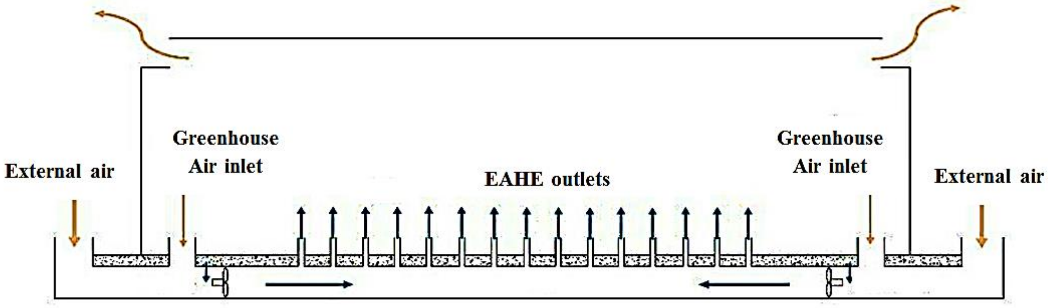


Fig.2. Geothermal model used in the greenhouse’s unit

The cooling and heating requirements for a given period including N days are referred to Cooling Degree-Day (CDD) and Heating Degree-Day (HDD), respectively. The CDD and HDD are derived from Equations (1) and (2) according to the ASHRAE equation (ASHRAE, 2016):

$$CDD = \sum_{1}^{N} (T_{ave} - \theta_1)^+ \quad \text{If } \theta_1 < T_{ave} \qquad (1)$$

$$HDD = \sum_{1}^{N} (\theta_2 - T_{ave})^+ \quad \text{If } \theta_2 > T_{ave} \qquad (2)$$

In which:

θ_1: Cooling threshold temperature (ºC)

θ_2: Heating threshold temperature (ºC)

T_{ave}: Average daily temperature (ºC)

CDD: Cooling Degree-Day for a given period of N days

HDD: Heating Degree-Day for a given period of N days

The + sign means that the sole difference between positive numbers is considered. Threshold temperature for cooling and heating will be replaced by the tomato optimal temperature range of 16 to 23ºC (Adams, 2012). The degree-day values defined in this way endure in fact a kind of energy index. In other words, the degree-day is an indicator for energy consumption to heat or cool the protected environment (Day, 2016).

In this research, the average daily temperature of the Hashtgerd weather station in Alborz province (the most neighbouring station to Kouhsar district of the case-study greenhouse) was selected during the period of

2007-2017. Next CDD and HDD were calculated in the desired statistical period for cultivation tomato without considering the EAHE system effect on cooling and heating the greenhouse unit. After the calculation stage of CDD and HDD, two 12-channel data loggers were connected to 12 temperature sensors in numerous locations of the greenhouse with 960 m^2 area for monitoring the potential of the EAHE system (Figure 3). To check the heating potential of EAHE system from December 3, 2017, it was totalled for 30 days at the intervals of 10 minutes. The similar procedure was performed to check the cooling potential of EAHE system in July 2018. The key reason for choosing the specific time period prominently mentioned for the purpose of databases is having the peak values for the cooling and heating needs. The ambient temperature during the given period was measured by the ST-171 sensor. The steps in this study are in accordance with the flowchart of Figure 4.

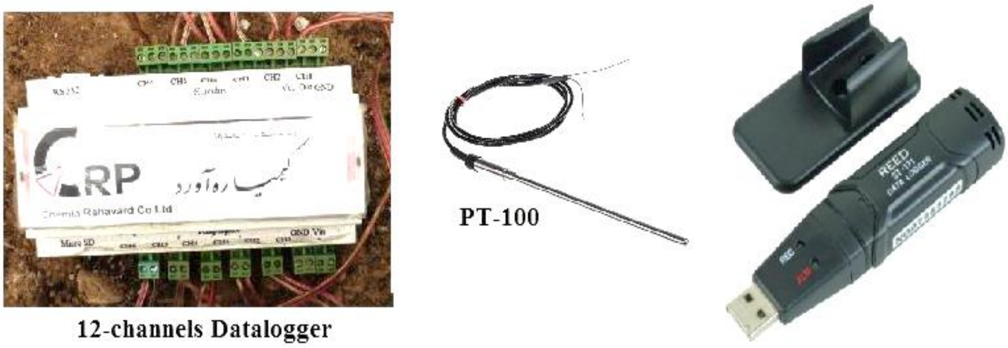


Fig.3. Measurement tools for recording the greenhouse outside and inside temperature

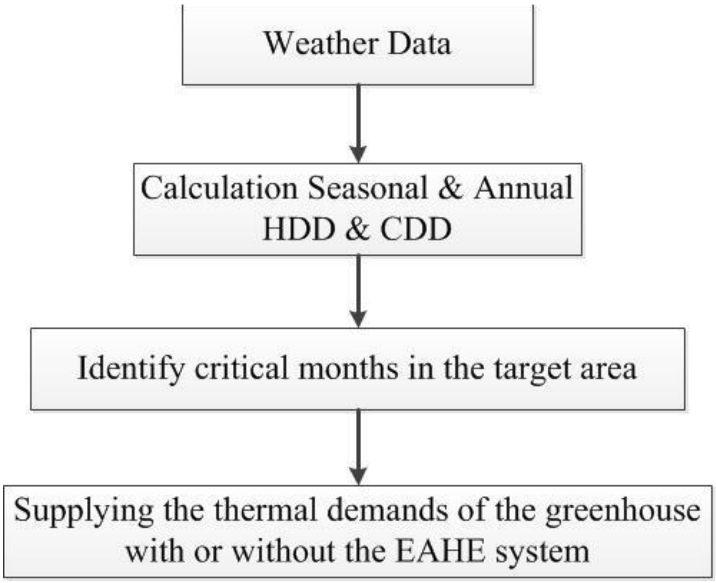


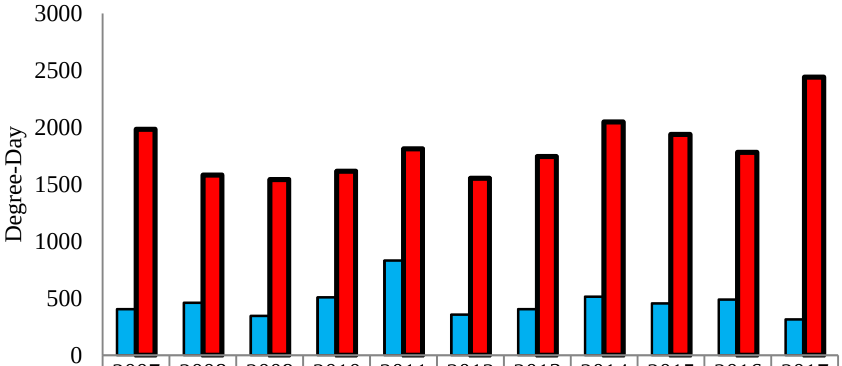
Fig.4. The flowchart of research's steps

Results and Discussion

The HDD and CDD levels

The CDD and HDD were calculated according to Equations (1) and (2) for the eleven years (2007-2017) based on meteorology data. Tomato cultivation is selected for this period in the greenhouse. Figure 5 shows the annual values of HDD and

CDD for each year during 2007-2017. According to the results demonstrated in Figure 5, the highest amount of HDD was 2444.31 degree-days for year 2017 as the coldest year in this period, while the lowest CDD was 315.29 degree-days for 2017. Furthermore, the lowest HDD was 1540.1 degree-days for 2009, while the highest CDD was 830.07 degree-days for 2011. According to the results, it can be declared that the Kouhsar area is one of the areas which need a higher heating requirement than the cooling one for the ambient temperature modification in Alborz province due to the geographical location. As a result, a degree-day index can be used to optimize and crop selection for protected agriculture. In this area a more resistant crop to cooler weather (for example lettuce or strawberry) should be selected during the winter (As shown in Figure 4). The results are in consistent with the results reported by other researchers despite utilizing the EAHE system for the greenhouse energy demands (Abdolhosseini *et al.*, 2013; Goff, 2015).



	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
🟦CDD	403.9	460.8	344.5	507.2	830.1	355.8	403.1	514.5	454.4	489.5	315.3
🟥HDD	1982	1581	1540	1614	1810	1552	1745	2047	1937	1779	2441

Fig.5. The tomato annual cooling and heating degree-days for 2007-2017 meteorology periods.

The values of HDD (Figure 6) and CDD (Figure 7) were calculated for two critical seasons of each year separately including the cold season during December to March for heating and the warm season during June to September for cooling. The results obtained from degree-day calculations of each month in the meteorology period studied by the critical seasons. The highest HDD was equal to 611.92 degree-days for February (2007), and the lowest HDD was equal to 129.04 degree-days for March 2012. Figure 6 shows the trend of changes in HDD charts, which indicates that in recent years, the degree-day of heating for the studied region area has decreased progressively. The reason for this can be related to the exacerbation of the greenhouse effect caused by the human activities, climate change, global warming, and the changes in rainfall pattern from snow to rain (Borah *et al.*, 2015). It is expected that the degree-day of cooling will increase for ecosystem balance by reducing the amount of HDD, which indicates a gradual increase in temperature in the target area (De Rosa *et al.*, 2015; Borah *et al.*, 2015).

As shown in Figure 7, the lowest CDD is equal to 12.8 degree-days for September 2012 and the highest CDD is equal to 297.68 degree-days for July 2011. The trend of the changes in CDD charts in Fig. 7 shows that in recent years the degree of cooling day has increased for the study area (Abdolhosseini *et al.*, 2013; Borah *et al.*, 2015; Azimi and Narangifard, 2017). The obtained results from this study and the thermal energy requirement of this greenhouse constructed in Kouhsar, Alborz province can be used not only for planning outdoor agricultural production as well as managing and controlling pests, but can be also used for the purpose of energy consumption monitoring of the greenhouse by selecting the proper type of crop in accordance with the characteristics of the desired area, as well as selecting the appropriate heating and cooling systems.

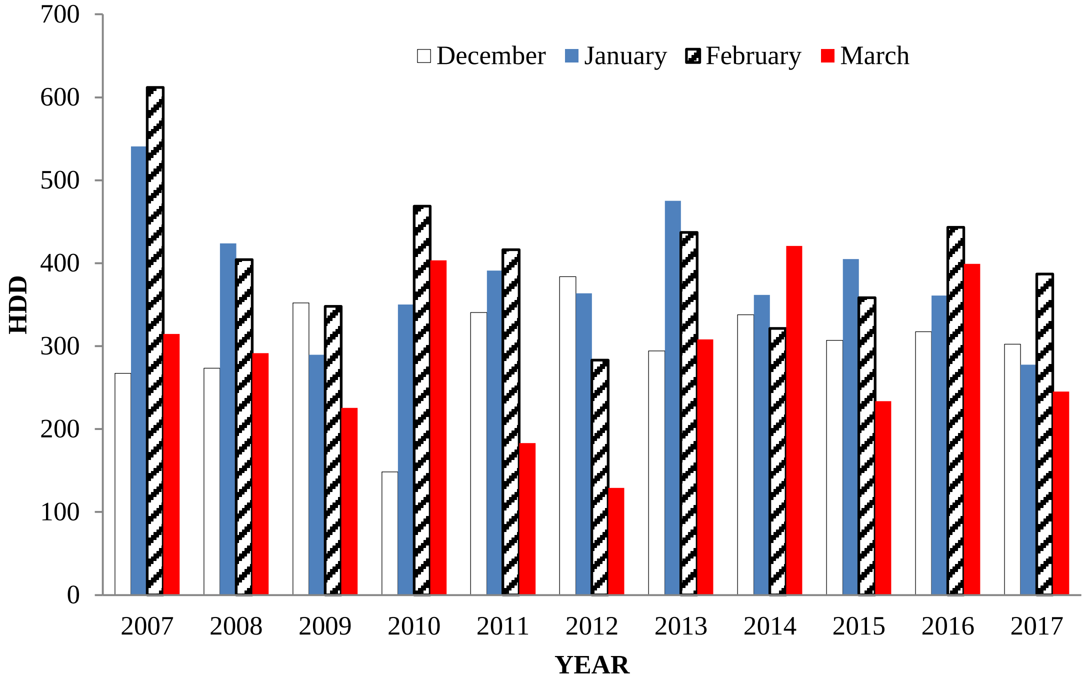


Fig.6. Heating Degree-Day (HDD) results of the cold months for 2007-2017 meteorology periods

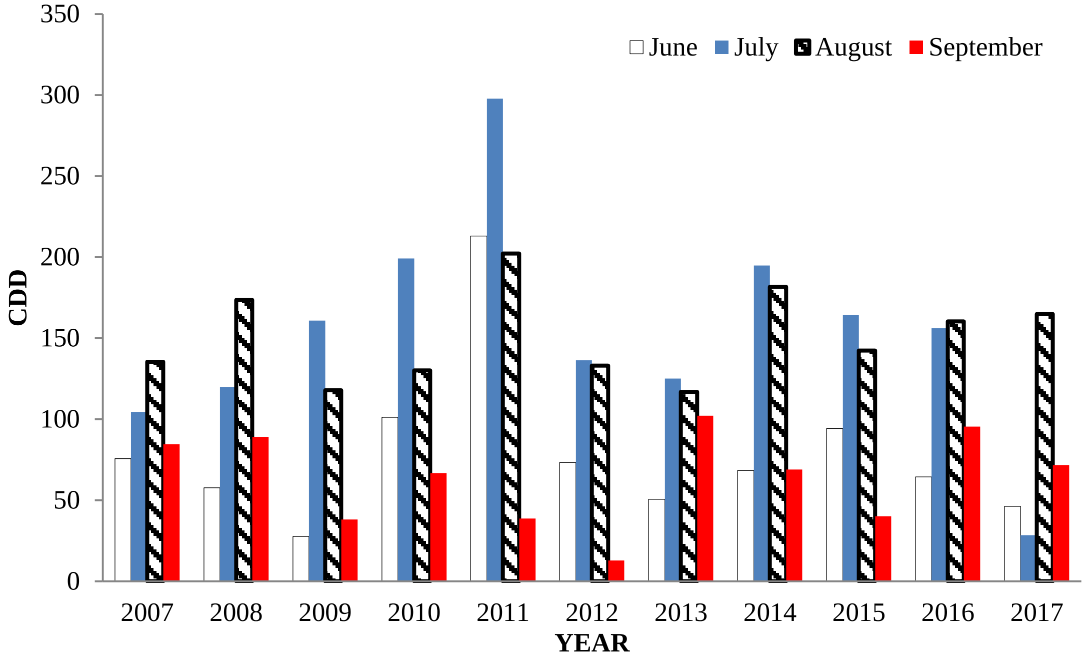


Fig.7. Cooling Degree-Day results of the hot months for 2007-2017 meteorology periods

The degree-day values stated by several researchers in the previous information of the seasonal and annual heating and cooling requirements of buildings such as greenhouses using weather data from the last years (Krese *et al.*, 2012; Atilgan *et al.*, 2016). This will be effective method for managing and optimizing energy consumption. Moreover, the EAHE system can considerably contribute to the supply of heating, cooling energy and air ventilation in the greenhouse according to the results.

EAHE Potential for tomato HDD and CDD requirements

There is a significant difference between the ambient air temperature and the temperature measured in the greenhouse for tomato production according to the results presented in Figure 8. The temperature inside the greenhouse undergoes fewer fluctuations than the ambient air temperature using the EAHE system, which indicates a uniform distribution of temperature in the greenhouse. According to the calculations, the CDD value for July as the warmest month in the study area resulted in the highest cooling degree-days of 18, indicating that the system was capable to provide the cooling needs for the desired product less than the threshold temperature (23°C). It's worth noting that the energy of the system was provided only by geothermal energy without any kind of pad and fan system. As a result, this system can be considered in terms of energy saving and the use of geothermal energy as renewable and clean energy in the target area and for tomato crop. For this reason, the application of such EAHE system is advised to other conventional greenhouses as an energy-saving technology to adjust the temperature with an initial investment for this system.

Figure 8 also indicates the difference between the outside and inside temperature of the greenhouse ($T_{greenhouse}$-$T_{ambient}$) as occurred by the potential of the EAHE system. Since the monthly cooling requirement of the tomato is 468 degree-days and the monthly ability of the EAHE system is 538.7 degree-days, this system is quite capable of providing the cooling demands for the crop in July as the hottest month of the year in this area.

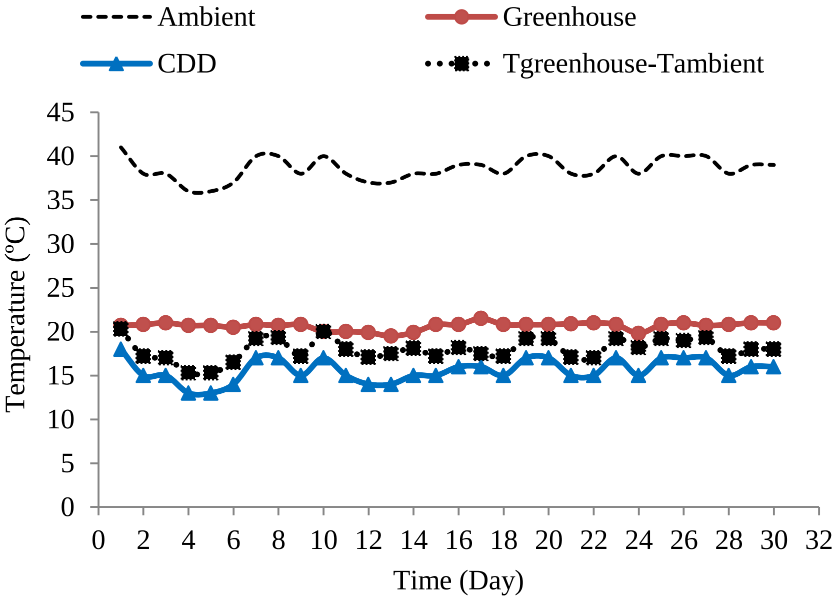


Fig.8. The EAHE potential to supply the cooling demands of the greenhouse using CDD index

The results of this study analogously indicate that there is a significant difference between the outside and inside temperatures in the cold season in order to evaluate the system's potential of providing the required greenhouse heating demands. As shown in Fig. 9, the sum of the monthly required HDDs for the tomato is 280.94 degree-days, and the monthly potential of the EAHE system for supplying the required greenhouse heating demands is 323.03 degree-days. Given that the average ambient air temperature for this period is approximately 7ºC (6.63ºC), and the required tomato temperature (at least 16ºC), it is necessary to increase the temperature by approximately 9ºC (9.37ºC), which easily utilizes geothermal energy to satisfy this crop's thermal requirement.

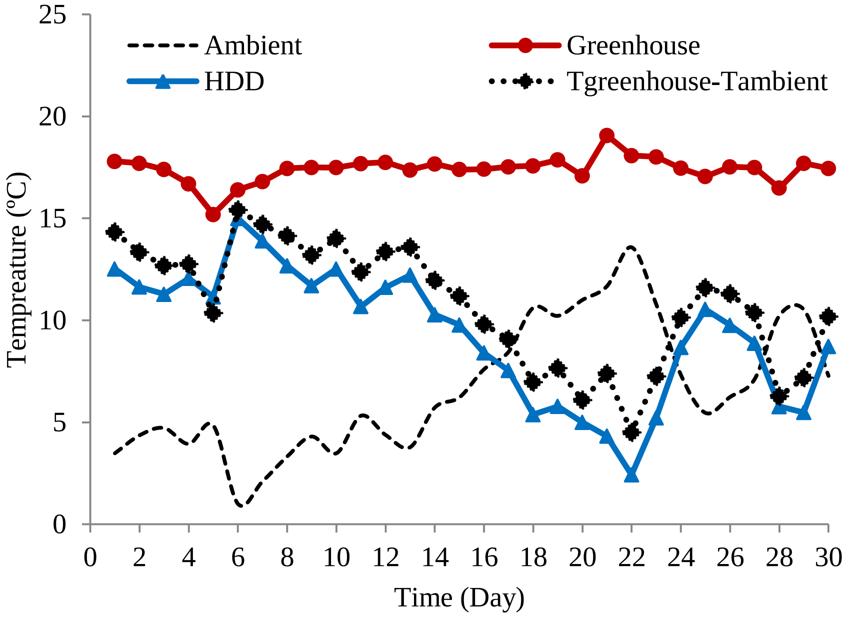


Fig.9. The evaluation of EAHE potential to supply the heating demands of the greenhouse using HDD index

Conclusions

Energy consumption in greenhouses is higher than outdoor traditional agriculture to provide the necessary environmental conditions (heating, cooling, ventilation and etc.). The degree-day is one of the most leading climatic indicators that indicates the intensity and duration of the ambient temperature. The aggregate number of degrees-days from an appropriate start date can be used to crop production planning as well as pest management and control disorder schedules. Weekly or monthly statistics also could be used for the energy consumption monitoring plan and related targets to typically determine the cost of cooling and heating systems and air conditioning for agricultural buildings like greenhouses while annual Figures can be properly employed to estimate future costs.

During the meteorology period from 2007 to 2017 in Kouhsar area of Alborz province, Iran, the annual cooling and heating degree-day was calculated for the purpose of the tomato cultivating. On that occasion, the potential of the EAHE system was investigated to satisfy the greenhouse heating and cooling requirements based on the degree-day index. The average potential of the EAHE system is 10.76ºC for increasing temperature in the cold and 17.96ºC for decreasing temperature in the warm season. The results showed degree-day index can be considered as one of the most significant fundamental information in estimating the amount of energy needed to warm up the greenhouse in the cold season and cool down it in the warm season. The degree-day index utilizes them to produce fruitful results in planning and decision making in the energy sector. According to the calculations and the results obtained, it can be declared that Kouhsar area in Alborz province is one of the areas with more heating requirements than that of the cooling ones. Consequently, this feature can be used to construct a greenhouse, as well as to select the appropriate crop, taking into account the geographical location and weather conditions.

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مقاله علمی-پژوهشی

پیش‌بینی نیازهای حرارتی یک گلخانه مجهز به مبدل حرارتی هوا-زمین به کمک شاخص درجه-روز

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چکیده

در این تحقیق، استفاده از مبدل حرارتی زمین-هوا (EAHE) به‌عنوان منبع انرژی زمین گرمایی کم عمق برای تأمین نیازهای حرارتی یک گلخانه تجاری واقع در استان البرز، مورد بررسی قرار گرفت. از شاخص درجه-روز برای برآورد پتانسیل سیستم EAHE به‌منظور تامین نیازهای حرارتی گلخانه از جمله سرمایش و گرمایش استفاده شد. نتایج نشان داد که این منطقه برای رسیدن به دمای مناسب در داخل گلخانه برای تامین گرمایش نسبت به نیاز سرمایشی، نیاز به انرژی بیشتری دارد. متوسط پتانسیل سیستم EAHE بر اساس شاخص درجه-روز برای افزایش دما در فصل سرد ۱۰/۷۶°C و برای کاهش دما در فصل گرم ۱۷/۹۶°C است. این بدان معنی است که سیستم EAHE قادر به تأمین نیازهای حرارتی گلخانه در این منطقه با توجه به مقادیر محاسبه شده درجه-روز گرمایش (HDD) و درجه-روز سرمایش (CDD) است. این روش می‌تواند در نظارت و بهینه‌سازی شرایط رشد گیاه به‌عنوان انتخاب بهترین نوع محصول یا نوع کشت و همچنین در آبیاری و مدیریت باروری محصولات زراعی مفید باشد.

واژه‌های کلیدی: درجه-روز، زمین گرمایی، گلخانه، مبدل حرارتی

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