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Assessment of heating and cooling demands of a glass greenhouse in Bucharest, Romania

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ABSTRACT

In southern parts of Europe, a balanced use of both heating and cooling is required to control the greenhouse temperatures throughout the year. Especially, with climate change and increasingly hot summers, the need for efficient greenhouse cooling and humidity control has become more and more important. In this work, we investigate the heating and cooling demands of a glass greenhouse located in Bucharest, Romania (latitude 44°28′12″ N, longitude 26°3′41″ E). The IDA Indoor Climate and Energy (IDA ICE) software is applied for the assessment of the energy demands, with weather data supplied using the integrated International Weather for Energy Calculations (IWEC) file for Bucharest. With a 2-degree wide deadband, the temperatures of the greenhouse compartments are set to 25°C and 19°C for day and night, respectively. The simulation gives an annual heating demand of 1,715 MWh for the greenhouse, corresponding to 638 kWh/m^2. The annual cooling demand is 1739 MWh, corresponding to 647 kWh/m^2. The maximum daily cooling load averages about 730 kW during the hottest summer months, while the maximum heat load averages about 590 kW for the coldest winter months. A novel, energy-efficient concept to be installed at the greenhouse, comprising an integrated heat pump system, air handling units, dry coolers, and the utilization of borehole thermal energy storage (BTES), is discussed in terms of the main principles and the required capacities of the system.

1. Introduction

Agricultural production accounts for a significant amount of global anthropogenic greenhouse gas (GHG) emissions. To quantify this, the Food and Agriculture Organization of the United Nations (FAO) estimates that the combined contribution from agriculture and related land use emissions adds up to about 17% of the total global GHG emissions [1]. The agricultural sector therefore has a serious impact on global warming and climate change.

At the same time, agricultural production is adversely affected by global climate change. Extreme weather conditions in the form of heavy rainfall, floods, heatwaves, and droughts are already negatively impacting crop production, and the pressure on agricultural food systems is likely to increase in the years ahead. This is magnified by the global population growth, which requires a substantial increase in food production by 2050 [2,3]. Hence, sustainable food and nutrition security is a major global issue.

Sustainable production of fruits and vegetables in greenhouses is a viable alternative to ensure safe and nutritious food for a growing human population [4]. Greenhouses offer favourable growing conditions and protect the crops from external threats such as extreme weather and various pests [5]. Furthermore, greenhouses with satisfactory heating and cooling amenities enable extended growing seasons, as well as production outside the typical geographical location for a given crop variety. Greenhouse farming allows crops to be produced in a controlled environment, leading to faster growth and higher yields [6]. Another benefit of this is that greenhouse operation requires less space than outdoor crop production, which means that greenhouses can be located in cities or urban areas where property is scarce or too expensive for outdoor farming. This minimizes the farm-to-fork distance, i.e. the cost and environmental impact of transportation is kept to a minimum.

Greenhouse operation is generally energy consuming, however, with an energy consumption that in some cases accounts for up to 50% of the total greenhouse production costs [7]. The high energy consumption and corresponding high operational costs are factors that affect the overall productivity and profitability of greenhouses. For producers, energy-efficient operation of greenhouses is therefore crucial, in addition to the urgent need for a transition to greener and more environment-friendly technologies.

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Nomenclature

AHU	Air handling unit
BTES	Borehole thermal energy storage
CAV	Constant air volume
CFD	Computational fluid dynamics
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
GSHP	Ground source heat pump
HPS	High pressure sodium
IDA ICE	IDA Indoor Climate and Energy
IWEC	International Weather for Energy Calculations
RH	Relative humidity
TRNSYS	Transient System Simulation Tool
USAMV	University of Agronomic Sciences and Veterinary Medicine of Bucharest

Energy-efficient operation of a greenhouse requires precise control of the indoor climatic conditions, determined by the temperature, humidity and CO_2 concentrations. For greenhouse operations in northern Europe, e.g. in the Netherlands, most of the energy consumption is associated with heating [8]. In southern parts of Europe, however, both heating and cooling are required to control greenhouse temperatures throughout the year [9]. Especially, with a warmer climate and recent hot summers [10], the need for efficient greenhouse cooling becomes more and more important in many countries [5,11].

Dynamic building simulations are powerful tools to assess the energy use in greenhouses and evaluate potential efficiency measures. Few previous studies have applied the IDA Indoor Climate and Energy (IDA ICE) software to simulate the energy use in greenhouses. In a master's thesis work, Rudén [12] used IDA ICE and the computational fluid dynamics (CFD) tool Ansys Fluent to investigate the possibility of using waste heat from a data centre to heat a prospected greenhouse located in Boden, Sweden. Similar analyses of the heating demands of greenhouses in a Nordic climate using IDA ICE have been performed for a greenhouse in Söderhamn, Sweden [13] and for a virtual greenhouse in Narvik, Norway [14].

Ljungqvist et al. [15] used IDA ICE to carry out a more detailed analysis of the heating demands of different greenhouse models connected to a data centre in northern Sweden. In this work, transpiration from crops was modelled using regression models of transpiration rates taking into account the solar radiation, the air vapour pressure deficit, and the speed of air inside the greenhouse. The greenhouse humidity was regulated by ventilation through the roof windows, and thus no mechanical dehumidification was needed in the models.

The Transient System Simulation Tool (TRNSYS) is another powerful building simulation software that recently has been used to analyse the energy performance of greenhouses. For instance, Agrebi et al. [16] performed a comparative analysis of a solar-assisted and a conventional heat pump for heating a greenhouse during the winter period in Tunisia. Similarly, Choab et al. [17] used TRNSYS to investigate the effect of key design parameters, such as cladding materials, shape, orientation, and air change rate, on the heating and cooling demands of a greenhouse located in Agadir, Morocco. Both of these studies took into account the effect of plant evapotranspiration on the greenhouse thermal behaviour.

In another study, Banakar et al. [18] used TRNSYS to evaluate the heating and cooling demands of three types of greenhouses, a conventional, a semi-closed, and a closed greenhouse in Tehran, Iran. The analysis showed that the heating demand of the closed greenhouse was about half that of the conventional greenhouse, while its cooling demand was about three times higher than the cooling requirement of the conventional greenhouse. Similarly, Carlini et al. [19] used TRNSYS to compute the heating and cooling demands of a photovoltaic and a conventional greenhouse model for three different locations in Italy. In a review of heating and cooling technologies for greenhouses, including various solutions for thermal energy storage, Harjunowibowo et al. [20] discussed and suggested different greenhouse concepts for Mediterranean and Nordic climates, respectively.

In another simulation study, Baglivo et al. [21] adapted the TRNSYS software to enable a more detailed dynamic thermal simulation of a solar greenhouse located in Crotone, Italy, including the effects of longwave and shortwave radiative exchanges, airflow exchanges, evapotranspiration, and convective heat transfer. The adapted simulation model was validated against EnergyPlus, an open-source building energy simulation program, with an average relative error of 11.1% of the greenhouse air temperature over the year. Rasheed et al. [22] used TRNSYS to model a multi-span greenhouse in Taean Gun, South Korea, investigating the effect of different thermal screens, natural ventilation, and heating setpoint controls on the annual and maximum heating loads of the greenhouse. In a similar study, Rasheed et al. [23] investigated possible energy saving solutions, considering both the heating and cooling demands of a multi-span greenhouse.

Semple et al. [24] used TRNSYS to assess the heating and cooling demands of a modelled greenhouse in different locations in Canada. Validating the model against natural gas usage data of a reference greenhouse, it was concluded that the annual cooling demand was equal to or greater than the heating demand for all the locations. Further, using TRNSYS, Vadiee and Martin [25] performed a comparative energy analysis of a closed greenhouse design to a conventional greenhouse in Ulriksberg, Sweden. The model was validated with the annual heating demand of the real case, with the conclusion that the heating demand of the ideal closed greenhouse was about 20% of the heating demand of the conventional greenhouse.

In the present work, IDA ICE is applied to investigate the heating and cooling demands of a research greenhouse located in Bucharest, Romania. The greenhouse is a glass greenhouse used for research and horticultural growth studies at the University of Agronomic Sciences and Veterinary Medicine of Bucharest (USAMV). The main challenge of the greenhouse is to provide sufficient cooling during the hot summer months, as the indoor temperature rises to unacceptable levels for the plants and vegetables at this time of the year. The currently installed system for climate control does not provide the cooling that is needed, and the plan is to install a novel, energy-efficient concept that is able to control the greenhouse climate during the whole year. To this end, the current study is to aid in the design and dimensioning of the novel concept by estimating the needed heating and cooling capacity of the system.

As noted above, there are several previous studies that have used the TRNSYS software to simulate the energy demands of greenhouses in various climate zones, while a few studies have used IDA ICE to evaluate the heating demand of greenhouses in a Nordic climate. To the best of our knowledge, no previous studies have applied IDA ICE to estimate the heating and cooling demands of a greenhouse in a warmer climate, such as in Romania. In addition, IDA ICE has not previously been used to consider mechanical dehumidification of the air to control the greenhouse humidity. Thus, the present work demonstrates that IDA ICE is a suitable tool for assessing the heating and cooling demands of a greenhouse in a warm climate, incorporating important effects of evapotranspiration and mechanical dehumidification. The results of the applied model are validated with natural gas consumption data of the greenhouse gas-fired boiler and the results of a comparable study of a greenhouse in Iran.

2. The greenhouse case study

The greenhouse in this study is part of the Research Center for Studies of Food Quality and Agricultural Products at USAMV. The facility has a total surface area of 2,756 m^2 and is structured into 19 integrated greenhouse compartments, of which there are 8 compartments of 160 m^2, 10 compartments of 64 m^2, and one research room of 32 m^2. The greenhouse is equipped with systems for monitoring the indoor climate and optimizing the growing conditions for a variety of cultures. An automated Priva climate control computer regulates the heating, humidification, ventilation, irrigation, shading screens, and CO_2 enrichment to create the desired conditions for the various fruits, vegetables and flowers growing in the greenhouse. The heating is supplied by a gas-fired hot water boiler, which is also fired up to provide CO_2 to the greenhouse as needed.

The most challenging part of controlling the indoor climate of the USAMV greenhouse is to maintain cool and optimal growing conditions during the hot summer season. Researchers and students do horticultural growth studies during the summer, and hence it is important to maintain an accurate control of the greenhouse climate. Daytime ambient temperatures in July and August occasionally reach 35–40 °C, and measurements have shown that the indoor greenhouse temperature can rise to 60 °C or more in the summertime. Such temperatures are clearly too hot for the greenhouse plants and vegetables, which will cease to grow and perish long before reaching those extreme temperature levels.

The greenhouse is currently cooled by natural ventilation through roof hatches on warm days. The ventilation system is inadequate for sufficient cooling, however, as the roof hatches are too small for removal of all the excess heat. In addition, frequent ventilation leads to loss of CO_2, and it is more difficult to control the humidity levels.

The novel energy-efficient concept to be installed comprises an integrated heat pump system, dimensioned to provide sufficient heating and cooling to the greenhouse. The system will include air handling units in all the compartments and one or two dry coolers (eventually an e-chiller) outside of the greenhouse building. Hence, the integrated system will replace the current use of the fossil-fuelled gas boiler. CO_2 enrichment to the greenhouse will be provided from an installed CO_2 tank. The new concept thus represents a shift to a renewable and more environment-friendly energy system.

In the novel system, the greenhouse humidity will be controlled by air handling units that dehumidify the moist air by condensation and recycle the condensed water for watering the plants. The already installed fog system will be used for humidification when the humidity falls to unsatisfactory low levels for the plants. Although the roof ventilation will still be needed for cooling on very hot days, its use will be kept to a minimum to improve control of the humidity and the CO_2 levels in the greenhouse.

In addition to the above, thermal energy storage of the seasonal excess heat is planned as an integral part of the novel energy concept. Borehole thermal energy storage (BTES) will be used to store summer heat in the ground for winter usage. For this purpose, a number of boreholes with a depth of 110 m are part of the planned installation.

3. Method

In order to assess the total heating and cooling demands of the USAMV greenhouse, the IDA ICE software is applied in this work. In the current evaluation, the calendar year 2021 is simulated with different operational modes of lighting and shading control for the winter and the summer period.

Weather data for the location are supplied using the integrated International Weather for Energy Calculations (IWEC) file in IDA ICE. The IWEC file contains hourly values of the air temperature, the wind speed, the relative humidity (RH), solar irradiation, and the sky cover for a year. The data are based on weather measurements for the city of Bucharest that are generalized over several years.

3.1. The building energy simulation tool

IDA ICE is a dynamic simulation tool mainly used to investigate the energy consumption in buildings. This includes the energy usage for heating, cooling, lighting, fans and pumps, both for individual zones and for the entire building. For individual zones, the indoor climate can also be studied, using air temperatures, humidity, CO_2 concentrations, and surface temperatures, as well as airflows in the ventilation system or through openings in the construction. Various heating, cooling and ventilation units can be included in the zones and controlled through the software user interface.

3.2. Zone modelling

The USAMV greenhouse is modelled in IDA ICE as follows. The separate greenhouse compartments are modelled as individual zones, as shown in the layout of Fig. 1. The smaller compartments, represented by the zones C1–C10, are quadratic with a base of $8\ m \times 8\ m$, while the largest compartments, represented by the zones C12–C19, measure $8\ m \times 20\ m$. The small research room is labelled as zone C11 and measures $4\ m \times 8\ m$. In total, the building body is 80 m long and 40 m wide at the widest. The total surface area of the modelled part of the greenhouse is 2,688 m^2 and the total volume is 15,456 m^3.

The orientation of the building was estimated and included as an input to the model. This is indicated by the compass needle in Fig. 1, which shows that the upper left corner of the layout corresponds to the southernmost point of the greenhouse and the lower right corner is the northernmost point.

To simplify the model, zones of equal size and similar solar heat gains that have the same crops are modelled jointly using the IDA ICE zone multipliers. This is the case for the greenhouse compartments of the same size and with corresponding external and internal windows facing in the same direction. Thus, compartments C13–C15 (specified to contain tomatoes) and compartments C16–C18 (specified to contain lettuce) are modelled jointly, respectively. Likewise, compartments C2 and C5 (containing bromeliad flowers) are modelled jointly by the zone multipliers, and so are compartments C3, C6, and C7–C9 (also containing bromeliad flowers).

The largest corridor, labelled Corridor 1, is modelled as two zones with an 'opening' in between. Openings are also used to represent the doors between the corridors and the entrance area, and between the entrance area and the technical area, as these are normally open. The two sections of Corridor 1 (corresponding to an inverse T in the layout) are 32 m and 16 m long, respectively, and both have a width of 4 m. The second corridor, labelled Corridor 2, measures $32\ m \times 4\ m$.

Inside the entrance area, there are bathrooms, changing rooms and an office. Assuming that the small differences in the indoor climate of these sections are not important for the overall analysis, these sections are not modelled as separate zones but simply included as part of the entrance area. The entrance area measures $12\ m \times 24\ m$, while the technical area measures $16\ m \times 8\ m$.

The greenhouse has a deposit area at the very north side of the building which is used for storing insecticides, substrates, etc. This room does not require any heating or cooling and is therefore not included in the model. The greenhouse additionally has a basement which is not modelled. In total, the greenhouse is thus modelled using 24 zones, of which 9 zones are jointly modelled with other zones through the IDA ICE zone multipliers.

The IDA ICE 3D model is shown in Fig. 2. The full height of the side walls is 5.3 m, while the height of the front walls is 6.2 m in the middle of the gabled sections. All walls have a 0.3 m tall concrete foundation at the bottom, with a glass wall on top. For the external walls, the foundation is 0.26 m thick, while it is 0.15 m for the internal walls. The wall construction is therefore specified as 'concrete' at the foundation, and windows are made to cover the rest of the wall from a height of

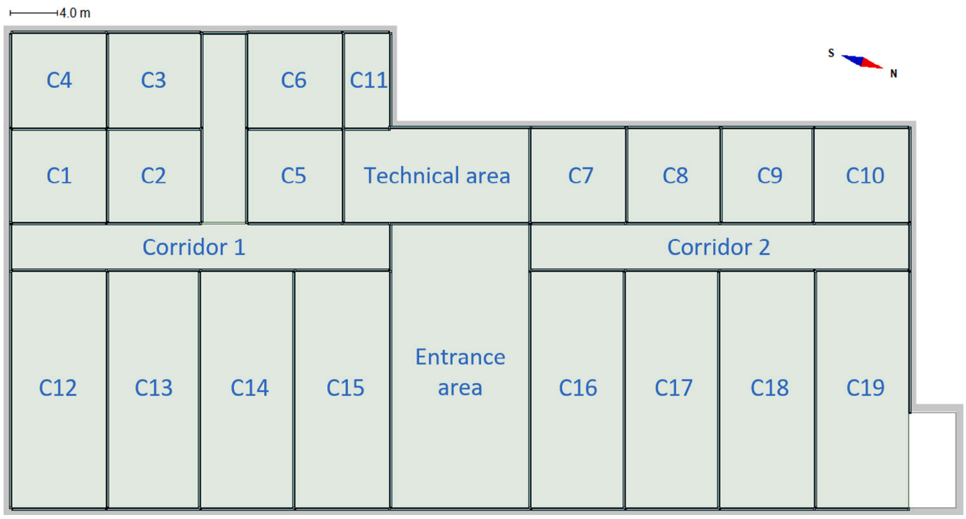

Fig. 1. Layout for the USAMV greenhouse model in IDA ICE. The orientation of the building is indicated by the compass needle in the upper right corner.

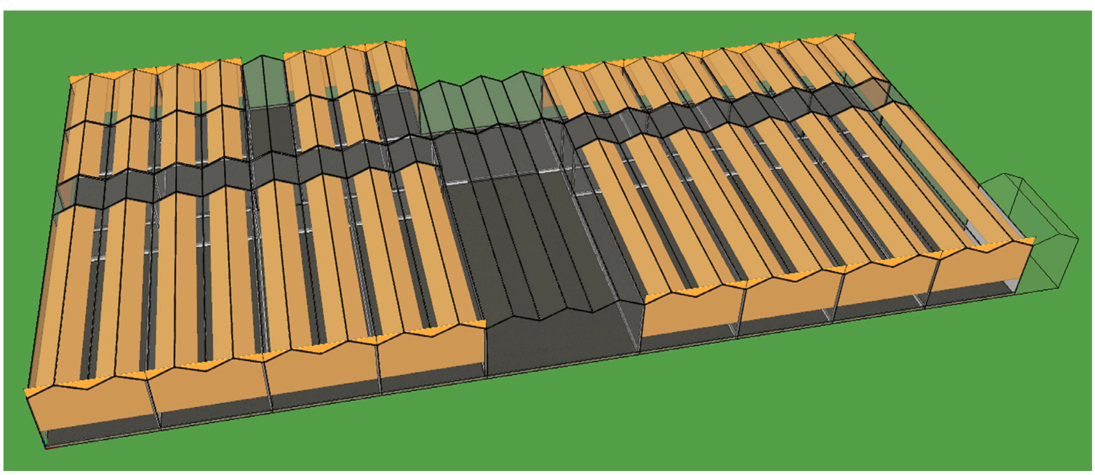

Fig. 2. 3D model of the USAMV greenhouse in IDA ICE. The light brown colour indicates the presence of shading screens in the compartments.

0.3 m and above. The roof is entirely covered with windows. The floor just consists of a concrete foundation, which is about 1 m thick.

The glass cladding of the walls and the roof consists of an aluminium structure and single pane glass of thickness 4 mm. The U-value of the window glass is calculated using the following relations [26]

$$U = \frac{1}{R_{si} + R_{glass} + R_{se}}, \tag{1}$$

$$R_{glass} = \frac{\Delta x}{\lambda}, \tag{2}$$

where R_{glass} is the thermal resistance of the glass, Δx is the thickness of the glass, and λ is the thermal conductivity of glass. Typically, $\lambda \approx 1\ \mathrm{W/(m \cdot K)}$. The quantities R_{si} and R_{se} are the heat transfer resistances on the internal and external surfaces, respectively. Taking into account the surface heat transfer resistances, IDA ICE automatically calculates the U-value for the window glass to be $U = 5.89\ \mathrm{W/(m^2{\cdot}K)}$.

For the internal walls, 140 mm thick steel poles are integrated into the wall structure. For the external walls, the steel poles are separate from the glass cladding and are therefore not considered. The aluminium structure and steel poles are taken into account through a frame fraction for the windows. The fraction of aluminium is estimated to be 4% for the roof and for the corners of the greenhouse. For the remaining external walls, the frame fraction is estimated to be 2%. For the internal walls, the frame fraction is set to 5.5% to account for the steel poles. The U-value of the window frame is calculated to be 5.88 $\mathrm{W/(m^2{\cdot}K)}$ based on the U-value for 5 mm aluminium. The steel poles have a similar U-value.

It is assumed that both the internal compartment doors and the external doors are of similar material to the glass walls and that they are rarely opened. They are therefore not modelled separately but included as part of the corresponding glass wall in the model.

3.3. Internal gains

3.3.1. Evapotranspiration from plants

The moisture released from the greenhouse plants is included using the IDA ICE ‘equipment’ component. The equipment is in this case specified to have liquid water emission, but with no emission of heat.

In reality, several different types of plants and vegetables are grown in the different compartments. To simplify the model, four of the largest compartments (C12–15) are assumed to have tomato plants, while the other four (C16–19) are assumed to have lettuce. The remaining smaller compartments (C1–C11) are specified to have bromeliad flowers.

For the tomato plants, the liquid water emission is calculated based on a study of tomatoes grown in solar greenhouses in northern China [27]. According to this work, the average evapotranspiration over the study periods for the whole growth stage, using full irrigation, is 2.59 mm/day. With a greenhouse area of 510 $\mathrm{m^2}$ and a plant density of 5.7 plants/$\mathrm{m^2}$ in the study, the evapotranspiration converts to $5.27 \cdot 10^{-6}\ \mathrm{kg/s}$ per plant. In the USAMV greenhouse, the larger 160 $\mathrm{m^2}$

compartments growing tomatoes will typically have 288 plants, which gives an evapotranspiration rate of 0.00152 kg/s per compartment.

For the lettuce plants, the evapotranspiration is based on a study of three lettuce varieties grown in open fields in Sergipe, Brazil [28]. The average evapotranspiration over the calendar year for the three varieties was found to be 3.46 mm/day, which in this case converts $3.21 \cdot 10^{-6}$ kg/s per plant. The 160 m^2 compartments of the USAMV greenhouse will typically have 1,400 lettuce plants, which gives an evapotranspiration rate of 0.00449 kg/s per compartment.

The evapotranspiration for flowers is based on a study of Guzmania and Vrisea bromeliads in a shaded greenhouse near Orlando, Florida [29]. The average evapotranspiration for these two varieties over the entire production period is $2.80 \cdot 10^{-7}$ kg/s per plant. Assuming that there will be about 300 plants in the smaller 64 m^2 compartments, this gives an evapotranspiration rate of $8.40 \cdot 10^{-5}$ kg/s per compartment. For the smallest 32 m^2 compartment, we assume that there are 150 plants which gives an evapotranspiration rate of $4.20 \cdot 10^{-5}$ kg/s.

3.3.2. Lighting

High pressure sodium (HPS) lamps for lighting are installed in the greenhouse compartments. On a general basis, these lamps are turned on during the day from 07:15 a.m. to 07:15 p.m. when the solar radiation in the compartments is less than 100 W/m^2. For simplification, we choose to turn on the lighting between 07:15 a.m. and 07:15 p.m. in the winter period from September to April. In the summer months, from May until August, we assume that no lighting is needed. In each of the 160 m^2 compartments, there are 27 HPS lamps of 600 W each. In the smaller 64 m^2 and 32 m^2 compartments, there are four and two HPS lamps, respectively.

The corridors, the entrance, and the technical area have LED lights that are turned on only if staff is working in the greenhouse in the evening. This is rarely the case, and the heat gains from the LED lights are therefore neglected.

3.3.3. Occupancy

We assume that two persons are present in the office from 8 a.m. to 5 p.m. on weekdays. Since the office space is incorporated as part of the entrance area, the occupants are included in this zone. The activity level is set to 1.2 MET, which corresponds to sedentary behaviour [30].

3.4. Temperature requirements

In order to provide appropriate growth conditions for the greenhouse plants, the temperature is set to 25 °C during the daytime and 19 °C at night. The lower night temperature is used between 09:15 p.m. and 05:15 a.m. the following morning. To avoid consecutive heating and cooling, we apply a 2-degree wide deadband for the setpoints. The deadbands for the day and night setpoints therefore are 24–26 °C and 18–20 °C, respectively. To avoid unnecessary cooling, it is assumed that the corridors, the entrance and the technical area are allowed to have a higher temperature at night, and the maximum temperature here is therefore set to be constant at 26 °C.

3.5. Air handling units

To handle the heating, cooling, and dehumidification of the greenhouse, one air handling unit (AHU) is associated with each of the compartments in the model. Since the AHUs will be recirculating air from the respective zones rather than supplying fresh air from the outside, these are modelled as constant air volume (CAV) fan coils. The fan coils are modelled with a cooling coil for cooling and dehumidification, followed by a heating coil for heating. The airflow rate is set to a constant value of 15.63 l/(s·m^2), which corresponds to 9,000 m^3/h for the 160 m^2 compartments.

In order to reach the heating and cooling setpoints more efficiently in the zones, the supply air temperature is set to be in the range 2–40 °C. This does not imply that this range of supply temperatures will be applied in reality, however. In the current model, the supply temperature range is selected to predict the heating and cooling demands more accurately.

In the greenhouse, a relative humidity of 50%–80% is optimal for tomatoes and lettuce [11]. This is easily achievable during the cooler months of the year. However, in summer it is more challenging to maintain an RH above 50%. In the simulations, the maximum RH in the compartments is set to 80%.

For the corridors, the entrance, and the technical area, ideal coolers are used to evaluate the cooling demand. Ideal coolers will deliver the necessary cooling to reach the maximum temperature setpoint at any time. Heaters are not included in these zones, as these areas will not be heated. In reality, the office space, the bathrooms, and the changing rooms in the entrance area are in fact heated, but this is not included in the model.

3.6. Energy supply

The energy supply of the IDA ICE model is specified as a standard plant with a gas boiler and an electric chiller. These are the sources for the AHUs in the model and provide heating and cooling, respectively. In order to obtain the actual heating and cooling demands, the efficiencies for these components are set to 1. To enable the AHUs to provide supply air between 2 and 40 °C, the supply water temperature for cooling is set to 0 °C, while the supply water temperature for heating is set to 70 °C.

3.7. Shading

The greenhouse compartments are equipped with internal rolling screens inside the external glass walls and horizontally in the ceiling below the gabled section. Typically, these curtains are used during the summer to reflect radiant heat. They are also used as a thermal barrier at night in the colder months of the year to retain heat.

To model the greenhouse curtains, internal roller shades are used in IDA ICE. Due to difficulties with modelling curtains that are not connected to windows, the curtains in the ceiling are placed directly on the ceiling window glass. It is assumed that the effect of this is not very different from the real situation with the curtains located just below the ceiling glass. During the summer months from May until August, the curtains are set to be drawn whenever there is sun. During the rest of the year, the curtains are drawn at night between 09:15 p.m. and 05:15 a.m. in order to retain heat. When the rolling curtains are included, the U-value of the windows is reduced to 4.14 W/(m^2·K) in the model.

3.8. Climate input

The climate file of the model is set to Bucharest, Romania. The exact location for the file data has a latitude that is very close to that of the USAMV greenhouse, while it is somewhat further east (4–5 km) than the greenhouse location. The IWEC file data are therefore assumed to be a valid representation of the climatic conditions at the location of the greenhouse. Fig. 3 shows the daily maximum and minimum outdoor air temperatures throughout the year, as given by the climate file. This shows the varied climate in Bucharest, with temperatures as low as −20 °C in the winter and above 35 °C in the summer.

Considering that the greenhouse is located in a large city but with no tall buildings in the vicinity, the wind profile is set to ‘suburban’. Similarly, the pressure coefficients for the wind are set to ’semi-exposed’.

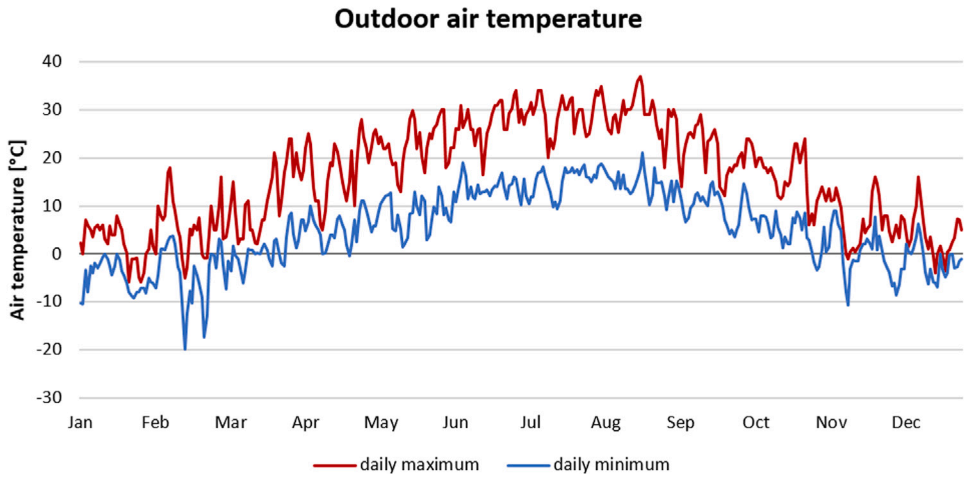

Fig. 3. Daily maximum and minimum temperatures of the IWEC climate file for Bucharest.

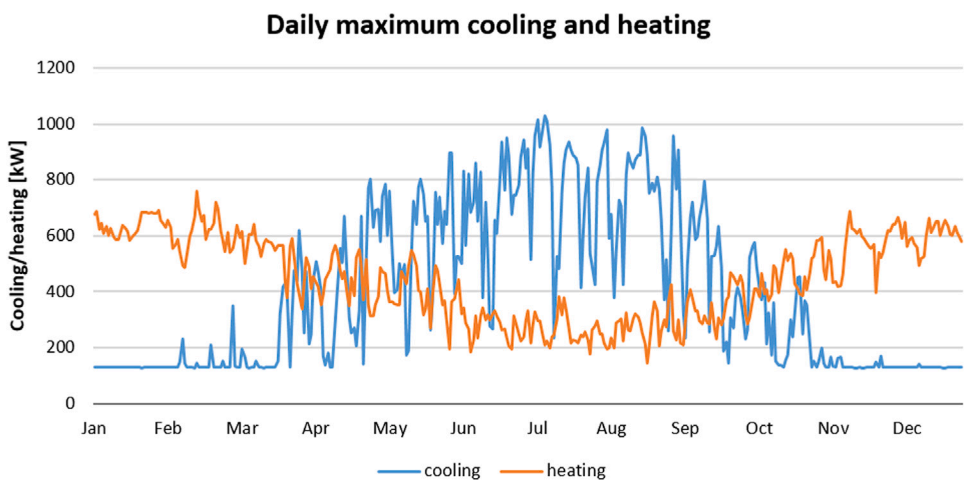

Fig. 4. Daily maximum cooling and heating loads in the greenhouse throughout the year.

4. Results and discussion

4.1. Energy usage

We here present the heating and cooling demands for the greenhouse for one year, along with the energy usage for lighting. The heating and cooling demands are based on the heating and cooling delivered by the compartment AHUs, respectively, in order to satisfy the day and night temperature setpoints and the maximum setpoint value of the relative humidity. The cooling demand also includes what is provided by the ideal coolers in the remaining zones of the greenhouse. The consequent greenhouse indoor climate is discussed in Section 4.2.

Fig. 4 shows the daily maximum cooling and heating loads in the greenhouse over the year. The peak cooling demand is in the month of July with a maximum of 1,028 kW. The heating demand peaks in February at a maximum of 760 kW. We observe that there is a clear inverse correlation between the daily maximum heating load and the daily minimum outdoor temperature (shown in Fig. 3). The daily maximum cooling load is affected by the solar irradiation, as well as by the dehumidification of the compartments, and it is therefore not directly correlated with the outdoor temperature.

The maximum cooling and heating loads of Fig. 4 show fairly large variations on a day-to-day basis. In the hottest summer months from June through August, the average daily maximum load for cooling is about 730 kW. This provides an estimate of the maximum cooling capacity needed for the greenhouse. Similarly, for the coldest periods of the year (January–March and November–December), the average daily maximum load for heating is about 590 kW. This gives a rough estimate of the needed heating capacity of the greenhouse.

Fig. 5 shows the total monthly energy usage for cooling, heating, and lighting of the greenhouse. The cumulative cooling demand for the entire year sums up to 1,739 MWh, corresponding to 647 kWh/m^2 for the modelled part of the greenhouse. We note that there is a cooling demand throughout the entire year, with the cooling demand in the winter months mainly being caused by the need for dehumidification. The cumulative heating demand is 1,715 MWh for the year. This corresponds to a heating demand of 638 kWh/m^2 for the modelled part of the greenhouse. We note that there is a small heating demand even in summer. This is mainly due to cooler nights and the ensuing heat demand when the temperature setpoint is changed from the night to the day setpoint in the mornings.

As seen in Fig. 4, the peak demand for cooling is significantly higher than that of heating. However, the maximum monthly energy usage for heating is higher than that for cooling (shown in Fig. 5). This is caused by the large variation in the cooling demand between day and night in summer, whereas the heating demand is at a more stable level throughout the day.

Fig. 5 shows that no energy is used for lighting during the summer, and for the rest of the year the simulated lighting is close to constant due to the simplified use of lighting described earlier. The lighting demand for the months of full lighting is about 56 MWh, and the

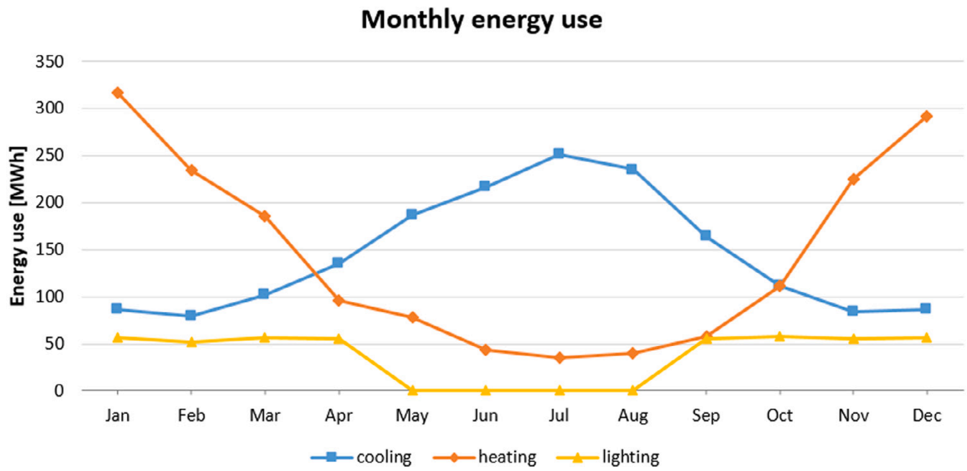

Fig. 5. Total monthly energy usage for cooling, heating, and lighting of the USAMV greenhouse.

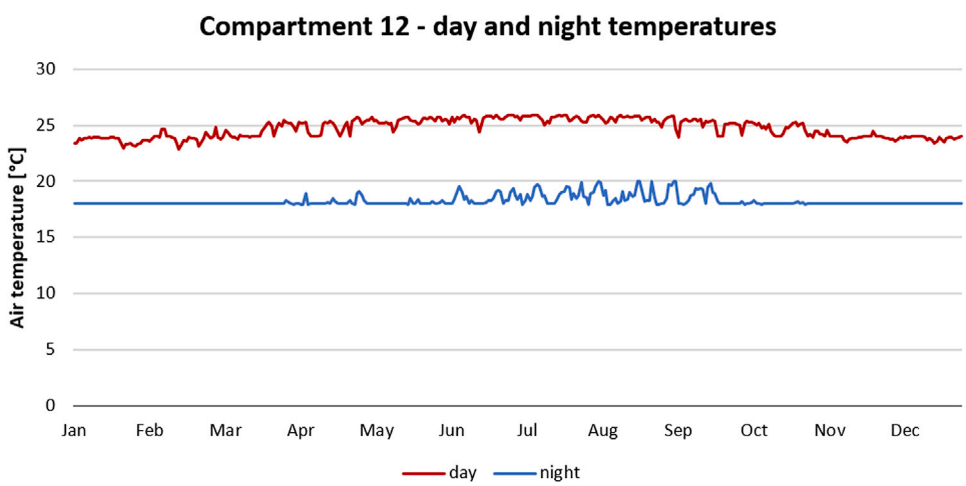

Fig. 6. Average day and night temperatures in Compartment 12 throughout the year.

cumulative demand for the entire year is 447 MWh. This corresponds to a lighting demand of 166 kWh/m^2 for the modelled part of the greenhouse.

4.2. Indoor climate

In this section, we consider the indoor climate of the greenhouse, as obtained in the simulation. For simplicity, we show the resultant air temperature and relative humidity of Compartment 12, which is the only large 160 m^2 compartment of the greenhouse faced to the south. The other compartments show similar profiles for the temperature and the relative humidity, but their corresponding heating and cooling demands vary somewhat according to their respective number of south-faced or north-faced external walls.

Fig. 6 shows the average air temperature for each day between 6:00 a.m. and 9:00 p.m, and the average night temperature between 10:00 p.m. and 5:00 a.m. The temperature inside the compartment equals the temperature of the air extracted by the corresponding AHU, as the model assumes uniform air in the zone. The plot shows that the average night temperature stays close to the minimum setpoint of 18 °C most of the year, while the day temperature shows more variation in the range between 23 and 26 °C depending on the season. This can be explained by large variations in the solar heat gain. Overall, the average day and night temperatures are largely within the desired ranges, which indicates that sufficient cooling and heating capacities are provided by the model setup.

Fig. 7 shows the daily average relative humidity of Compartment 12 throughout the year. As for the temperature, this is equal to the RH of the air extracted by the corresponding AHU. The daily average RH always stays at or below the setpoint of 80%, which shows that the CAV fan coil effectively removes moisture from the air. However, the average RH dips to 42% during the hotter days of the year due to that moisture is removed when the greenhouse air is cooled. Such low humidities are not ideal for the plants, and under these circumstances the fogging system will be applied to raise the humidity to acceptable levels. In the simulations, due to lower cooling demands, the RH does not drop to equally low values in the compartments with no south-facing facades.

The type of plants in the compartments also affects the RH during the summer. Thus, the compartments with lettuce (C16–C19) show higher RH values than the tomato compartments (C12–C15) due to higher total evapotranspiration rates for the lettuce crop compared to the tomatoes.

The amount of water that is removed by the AHU in Compartment 12 is calculated by taking the difference between the absolute humidity of the extracted and the supplied air. The dehumidification rate, shown in Fig. 8, varies throughout the day and year due to the variation in air temperatures. The higher values in the warmer parts of the year are caused by the low temperature of the supply air, which leads to a significant cooling of the compartment air and higher water removal than strictly needed.

The average amount of water removal throughout the year is 0.00147 kg/s, which is close to the evapotranspiration rate of 0.00152

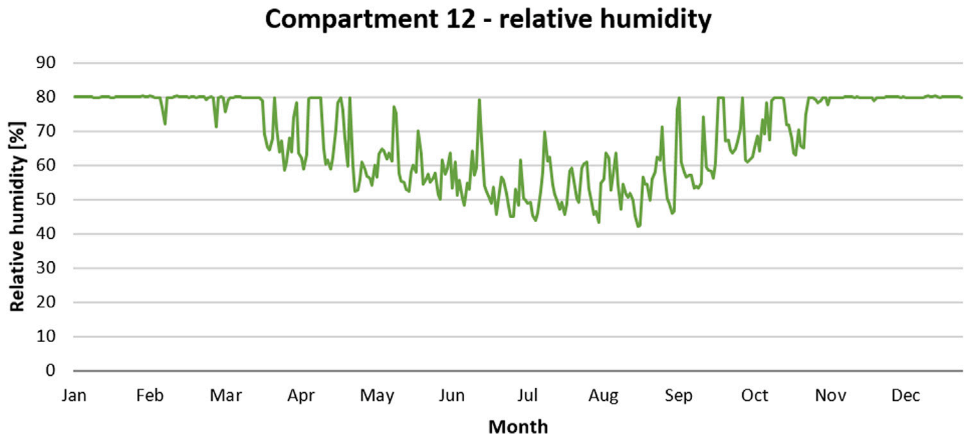

Fig. 7. Daily average relative humidity in Compartment 12 throughout the year.

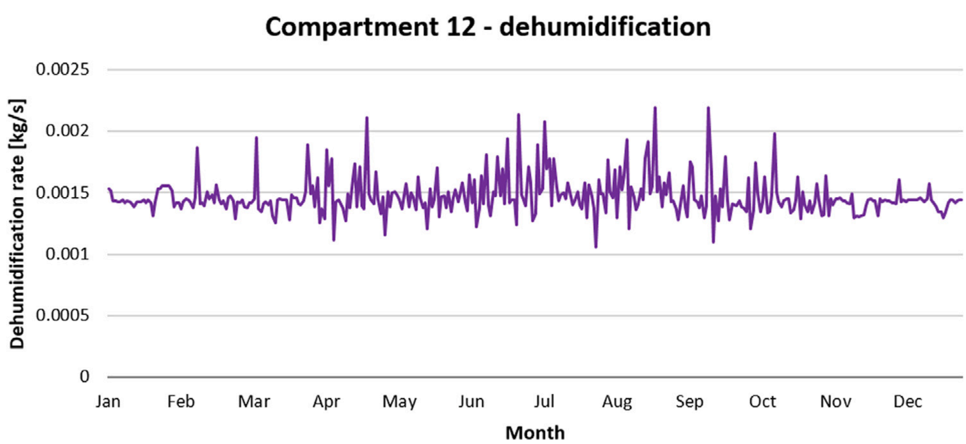

Fig. 8. Daily average dehumidification rate in Compartment 12.

kg/s in Compartment 12. This shows that the AHU roughly removes the same amount of water as the plants add to the air. A small amount of water is transported through the external surfaces of the compartments due to air infiltration.

To illustrate the effect of the described model on the areas with no plants, the daily average temperature in the largest section of Corridor 1 is shown in Fig. 9. Due to the model choice of an ideal cooler in the corridor, the temperature is always close to or below the maximum setpoint. Since there is no heating in the corridor, the temperature can be quite low during the winter period, with a daily average down to 6 °C. For the entrance and the technical area, the temperature is found to be even lower, which is likely caused by larger external wall areas and connection only to one compartment in the model. Thus, small amounts of heat are being transferred to these areas from warmer zones.

The low temperatures in the corridors, the entrance and the technical area are acceptable, however, since there will be no plants and staff does not stay in these areas for longer periods. Moreover, in reality an air-to-air heat pump is installed in the office space of the entrance area that provides the heating needed for a comfortable working environment here. The amount of heat provided by this heat pump is relatively small and has not been taken into account in the model.

4.3. Validation of the model

For validation of the simulation model, the computed heating demand for a particular month can be compared with the natural gas consumption data of the greenhouse gas boiler for the same month. To this end, the outdoor temperatures measured at the greenhouse site in January 2021 were used as model input. With an average outdoor temperature of 2.4 °C for the month, the IDA ICE simulation shows a total heating demand of 290 MWh. This is smaller than the estimated heating demand of 317 MWh for January based on the IWEC climate file input, as shown in Fig. 5. This was, however, expected since the average temperature of the climate file for January is −1.7 °C and thus colder than the measurements from 2021. To compare with the computed heating demand, the gas consumption of the gas boiler in January 2021 was 30,257 m^3 with an energy content of 10.55 kWh/m^3. Assuming an efficiency of 90% for the gas boiler, this corresponds to 287 MWh of generated heat. This gives a deviation of only around 1% between the computed heating demand and the heat produced by the greenhouse boiler.

In reality, some heat might be lost in the wintertime due to roof ventilation for letting fresh air into the greenhouse. Comparably, for the simulation, dehumidification in the winter leads to a higher heating demand which may be of a similar magnitude. Hence, it can be concluded that the applied IDA ICE model provides a fairly accurate description of the actual greenhouse heating demand during the colder months of the year.

During the summer, heating by the gas boiler is normally not applied due to high costs and the short-time heating needs, typically in the cooler early mornings, hence do not justify its use. A comparison of the computed heating demand with the gas usage data is therefore not possible. As seen in Fig. 5, however, the simulation shows a small heating demand also in the summer months. This is due to the daily minimum outdoor temperatures of Fig. 3 often being lower than the minimum night temperature setpoint of 18 °C, and heating is therefore called for in the model. In addition, dehumidification of the air in the

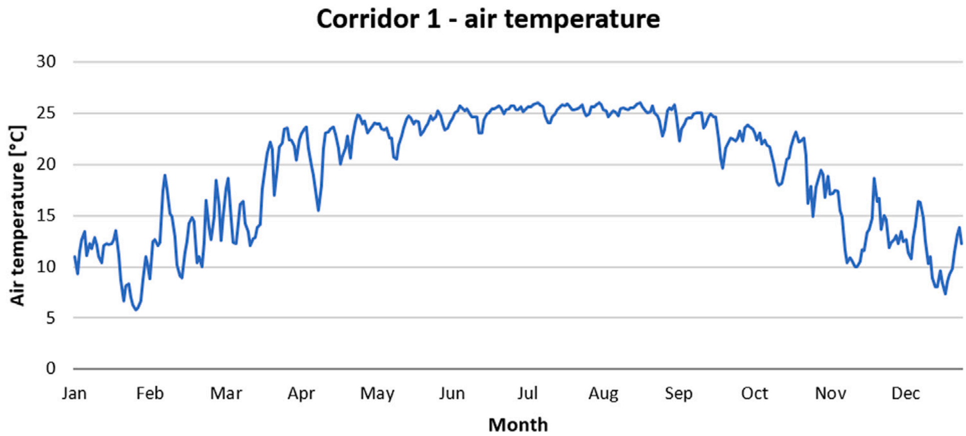

Fig. 9. Daily average air temperature in the largest section of Corridor 1.

AHUs requires heating since the air is reheated after being cooled down for removal of the moisture. Based on this, and comparing the energy usage for heating in the summer with the demand for the rest of the year, the prediction is that the simulation gives a reasonable estimate of the heating demand during the summer months.

For cooling, we compare the computed demand for the month of July with the corresponding cooling demand in the TRNSYS analysis of Banakar et al. [18] for a closed greenhouse in Iran. From Fig. 5, the current IDA ICE simulation gives a cooling demand of about 252 MWh for July, corresponding to 93.6 kWh/m^2 for the greenhouse. In comparison, Banakar et al. obtained a monthly cooling demand of about 83.7 kWh/m^2 in July for the closed greenhouse. Thus, the computed cooling demand for July in our study is about 12% higher than that of the Iranian study. However, the cooling setpoint in that study is 29 °C, i.e. at a higher level than the 26 °C and 20 °C day and night setpoints of the present work, and this difference could to a large degree explain the difference between the computed cooling demands. Another difference between the studies is that the AHU dehumidification in our case requires cooling also during the colder winter months. Other than this, the comparison of the two cases is reasonable since the free-floating, average greenhouse temperatures shown by Banakar et al. [18] are very similar to those observed for the USAMV greenhouse.

In summary, the validation of the model depends on several factors such as the assumed gas boiler efficiency, the actual use of the ventilation hatches, and the true number of plants growing in the greenhouse. Also, while the novel concept with the planned compartment AHUs is not yet installed, the effect of dehumidification on the heating and cooling demands is difficult to predict. Nonetheless, given the uncertainties already known, the implemented IDA ICE model seems to provide reasonable estimates for the greenhouse heating and cooling demands over the year.

4.4. Limitations

Several modelling simplifications were made in the present work. For instance, the bathrooms, the changing rooms, and the office space were included as part of the entrance area, while in reality these areas are separately heated. Furthermore, the greenhouse lighting was assumed to always be turned on in the daytime during the winter period, and completely switched off during the summer months. Concerning the rolling shading screens, these were modelled to be located directly on the ceiling window glass instead of horizontally below the gabled section. In addition, shading from nearby buildings and vegetation was not included in the model.

For the evapotranspiration, only three types of plants were included in the model: tomatoes, lettuce, and bromeliad flowers. The evapotranspiration rates were set to be constant for the different plants, while in fact the rates depend on the growth stage and the irrigation of the plants. The evapotranspiration also strongly depends on the climate and other growing conditions, which means that the rates found in the literature and used here may not accurately represent the actual evapotranspiration in the present greenhouse study. Also, the thermal mass of the plants and the plants' interaction with the solar radiation have been neglected. Finally, the greenhouse fogging system used to increase the humidity was not included in the model, which has an effect on the relative humidity especially during the summer.

The above simplifications imply that the IDA ICE model may not precisely predict the indoor climate and the energy demands in each individual zone of the greenhouse. However, the validation of Section 4.3 indicates that the present simulation gives sufficiently accurate estimates of the total heating and cooling demands for the greenhouse over the year. In future work, it would be of interest to compare the simulated energy demands of each greenhouse compartment with measured energy usage data from the planned novel energy system.

5. Novel energy-efficient greenhouse concept

As shown by the IDA ICE simulation, there are large annual heating and cooling demands in the USAMV greenhouse of 638 kWh/m^2 and 647 kWh/m^2, respectively. Thus, on a yearly basis, the cooling demand is only slightly higher than the heating demand. However, as seen in Fig. 4, the daily maximum cooling demand in the summer season is at a higher level than the corresponding heating demand in the wintertime. This is in line with the main challenge of operating the greenhouse at satisfactory temperatures in summer. The greenhouse gets heated to unacceptable temperature levels, and the roof ventilation is insufficient in keeping the temperatures down.

In the novel, energy-efficient concept planned for the greenhouse, the integrated heat pump system will provide both heating and cooling as needed. To make use of the seasonal excess heat in the greenhouse, the heat pump system will be coupled to an array of boreholes for thermal energy storage. Ground source heat pumps (GSHPs) coupled to BTES is a well-known and widely used technology for long-term thermal energy storage [31,32]. For greenhouses, the feasibility of the technology to fulfil the heating and cooling demands has been studied in detail by Skarphagen et al. [33]. Vadiee and Martin [34] used TRNSYS to carry out an energy analysis and thermo-economic assessment of a closed greenhouse concept integrated with BTES, while Paksoy and Beyhan [35] discussed the adaption of thermal energy storage for greenhouses to different climatic locations.

At the USAMV greenhouse, the plan of the first instalment stage is to drill fifteen boreholes (array of 3 × 5 holes) to a 110 m depth. The BTES system will be charged in the summer by the heat pumps, and eventually an e-chiller, at an estimated capacity of about 75 kW. In winter, the heat pump system will extract an equivalent amount of heat stored in the ground surrounding the boreholes and provide heating by distributing hot water to the greenhouse compartments.

In a second instalment stage, an additional array of boreholes will be drilled to enhance the BTES cooling and heating capacity with another 125 kW. Thus, the capacity of the expanded BTES will be about 200 kW. Clearly, the cooling and heating capacity of the planned BTES system will not cover the estimated maximum cooling and heating demands for the greenhouse of 730 kW and 590 kW, respectively. The remaining demands of approximately 530 kW cooling and 390 kW heating will be provided by the integrated heat pump system with a number of heat pumps, dry coolers, an e-chiller, and fan coils as needed. In addition, so-called free cooling by using the cooler outside air will also be employed.

Since the simulation shows that the total heating and cooling demands for the year are roughly the same, there will be a balanced heat extraction and rejection for the BTES. In this operational scheme, defined as "Ambient BTES" by Skarphagen et al. [33], the temperature of the BTES fluctuates around the ambient ground temperature on an annual basis. This is opposed to a high-temperature BTES system in which the BTES is charged (heated) over several years, before the ground temperature reaches a certain plateau and the system enters into a long-term steady state. The advantage of the ambient-temperature BTES is that the system provides both heat and cold storage over the year, allowing for a very energy-efficient operation of the heat pump system. In addition, extreme temperature differences and consequent large heat losses in the ground are avoided.

One effect of the improved control of the greenhouse indoor climate is that the need for roof ventilation will be reduced. In the new concept, dehumidification of the greenhouse compartments will be provided by the AHUs. The condensed water can be reused as irrigation water, and the water consumption will be furthermore reduced due to decreased evaporation losses via ventilation. The semi-closed operation of the greenhouse also reduces the risk of insect pests and fungal diseases [36]. An additional advantage is that the reduced ventilation leads to a better control of the CO_2 levels in the greenhouse. Thus, CO_2 enrichment for enhancing the photosynthesis of the plants can be reduced, which in the end also minimizes emissions of CO_2 to the atmosphere.

6. Conclusions

The annual heating and cooling demands for the research greenhouse located on the campus of USAMV in Bucharest, Romania have been simulated using IDA ICE. The respective demands are based on the heating and cooling delivered by air handling units associated with each greenhouse compartment, plus cooling delivered by ideal coolers in the corridors, the entrance, and the technical area.

The model simulation of the greenhouse shows a large cooling demand in the summer season with a peak demand of 1,028 kW. The average daily maximum cooling load in the hottest period from June through August is about 730 kW. There is also a cooling demand in the wintertime due to the need for dehumidification, and the cumulative cooling demand on an annual basis is 1,739 MWh. This corresponds to a total cooling demand of 647 kWh/m^2 for the modelled part of the greenhouse.

The heating demand of the greenhouse is qualitatively inverse to the cooling demand, with a peak of 760 kW in the winter season. For the coldest periods of the year, i.e. January-March and November-December, the average daily maximum heating load is about 590 kW. The heating demand in the summer, due to colder nights and the change from night to day temperature setpoint in the mornings, is also relatively lower than the corresponding cooling demand in the wintertime. However, the heating demand in the winter months is fairly high, and the cumulative heating demand is 1,715 MWh for the entire year. This gives an annual heating demand of 638 kWh/m^2 for the modelled part of the greenhouse.

The model shows good thermal environment in the greenhouse compartments, with the air temperature staying within the desired ranges for day and night. The corridors, the entrance, and the technical area show very low temperatures during the winter due to no heating applied in these zones. The AHUs provide adequate dehumidification to keep the relative humidity in the compartments below 80%. However, the humidity is occasionally very low during the summer, especially for the compartments with large cooling demands and lower evapotranspiration rates. In reality, this situation is improved by using the installed fogging system.

To validate the simulated heating demand, a second simulation was run where measured temperature data from January 2021 were used as input to the weather file. A comparison of the resulting heating demand with the gas consumption of the greenhouse's gas boiler for the same month, assuming a boiler efficiency of 90%, showed a very close agreement between the simulated result and the heat produced by the greenhouse boiler. For cooling, the computed demand was compared with the results of a TRNSYS analysis for a closed greenhouse in Iran. Here, the simulated cooling demand for the month of July is about 12% higher than the corresponding demand obtained in the Iranian study. Among other differences between the two cases, this deviation can be explained by the lower cooling setpoints for day and night applied in our study.

In conclusion, the applied IDA ICE model is considered to provide a fairly accurate description of the heating and cooling demands of the USAMV greenhouse over the year. The model incorporates the important effects of evapotranspiration and mechanical dehumidification, and the simulated results have been useful for the design and dimensioning of the novel energy system which is to be installed in the greenhouse.

CRediT authorship contribution statement

August Brækken: Methodology, Validation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Sigurd Sannan:** Conceptualization, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Ionut Ovidiu Jerca:** Conceptualization, Investigation, Supervision, Project administration, Funding acquisition. **Liliana Aurelia Bădulescu:** Conceptualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request

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