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INTEGRATION OF RENEWABLE ENERGY SOURCES INTO THE ENERGY SUPPLY FLOWS OF GREENHOUSES: DEVELOPMENT AND VALIDATION OF A FORECASTING MODEL

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ABSTRACT

The objective of this research was to develop a climate forecasting model for cyber-physical greenhouses. The essence of the professional problem is that usage of renewable energy systems in greenhouses is in a premature stage due to the lack of information about these resources and the high installation costs of the machinery. A critical issue is integration of renewable energy sources into the energy provisioning system of greenhouses. Assuming that application of renewable energy should reach a higher percentage in the next years, our goal was to develop an energy balance forecasting model based on the investigation of the energy flows and heat demand of greenhouses for different climate zones. This paper discusses the development and validation of the proposed forecasting model which uses external climate data as input and heat demand with losses as output. The latter information was also used to support choosing appropriate renewable energy options for greenhouse climate systems. The model was tested under different influential factors and was validated for the Netherlands and China. The model proved to be appropriate and acceptable because the computed results showed only a relatively small deviation from the reference empirical values. Hydraulic design and integral design of the climate systems of greenhouses are largely influenced by the selection and integration of the renewable energy sources. To support these aspects of designing, the so-called loading curves were determined. Our future research will focus on the exploration of design principles for renewable energy sources inclusive energy provisioning for cyber-physical greenhouses.

KEYWORDS

Sustainable greenhouses, energy supply for greenhouses, renewable energy sources, energy balance calculation, heat demand, forecasting model

1. INTRODUCING THE ADRESSED RESEARCH PROBLEM

Greenhouses are crucial infrastructural resources with respect to the fulfillment of the increased need for food, while the population of the world is rapidly growing [1]. They are the basis of a protected cultivation system [2]. They make it possible to grow and harvest vegetables, fruits and flowers at geographical locations where the soil, climate and social circumstances are not optimal or would not even allow it otherwise [3]. Greenhouses also protect the crop against pests, insects and extreme climate conditions such as heavy precipitations or draught and winds. It is an important expectation towards greenhouses to be ecologically, economically and socially feasible and sustainable [4]. In addition, they are also supposed to be rentable, that is, to provide positive balance in terms of investments and revenues [5].

Obviously, there are many different types of greenhouses. As discussed by Hanan, J.J., the particular choice of the protected cultivation system depends on many factors [6]. Currently, an intensive research is going on towards innovation and optimization of greenhouses, including the energy supply and utilization. Growing attention is given to the exploitation and application of renewable energy sources [7]. However, the usage of renewable energy systems in greenhouses is in a premature stage due to the current stage of technological development, lack of information about these resources, and the high installation costs of the renewable energy equipment and devices. Crucial is integration of rather different renewable energy sources in the energy provisioning system of greenhouses. The main issues are selection of the relevant combinable options, integration into the climate system of greenhouses, and achieving a trade of in terms of the investments and the benefits [8].

It has been indicated by both the scientific literature and the professional practice that addressing the abovementioned three issues need model-based investigation and decision making [9] [10]. Consequently, the objective of our research was to develop a climate forecasting model for cyber-physical greenhouses and to apply this model for supporting environment benign design and operation of greenhouses. Assuming that the usage of renewable energy should reach a higher percentage in the next years, our goal was to construct a model that is able to inform about the usability of various renewable energy sources and the energy balance, based on the investigation of the energy flows and the heat demand of greenhouses for different climate zones. As a comprehensive forecasting scheme, the model proposed in this paper considers and describes: (i) the influence of the outside environment on the greenhouse environment, (ii) the plants grown in the greenhouse environment (regarding CO_2 extraction, transpiration etc.), and (iii) the greenhouse equipment (heating/cooling, ventilation, etc.) [11] [12].

This paper presents the knowledge aggregated for the development and validation of the proposed forecasting model, which uses external climate data as input and heat demand with losses as output. The latter information was also used to support the selection of appropriate renewable energy options for greenhouse climate systems. The model was tested under different influential factors, and was validated based on data related to the Netherlands and China. The importance of our research and the proposed model is underpinned by the fact the renewable energy sources will play a growing role in both future production-oriented and alternative (e.g. urban, floating, space) cyber-physical greenhouse systems (CPGS). CPGS are greenhouses of high level automation, adaptive control, and knowledge-intensive operation. The paper continues with an overview of the possible renewable energy technologies for greenhouses in Section 2. A concise state of the art review is presented in Section 3, based on a specific scheme of reasoning. In Section 4, the factors influencing the energy balance of greenhouses are determined and investigated, and the assumptions concerning the forecasting model are presented. In Section 5, the contents of the proposed computational forecasting model are explained and the kernel part of the formal specification is discussed. The validation and adjustment of the model based on empirical data are discussed in Section 6. Finally, Section 7 discusses the work and the major findings, and offers some propositions concerning the possible use of renewable energy systems in greenhouse climate installations.

2. RENEWABLE ENERGY TECHNOLOGY FOR GREENHOUSES

Renewable energy is derived from natural processes that are replenished constantly [13]. Appearing in various alternative forms, renewable energy can be obtained, for instance, by means of photovoltaic technologies from sun light, or from the geothermic heat source of the earth [14]. Literature deals with the following renewable energy categories and technologies: (i) solar electricity and heat, (ii) wind energy, (iii) ocean energy, namely: (iii-a) ocean thermal, (iii-b) tidal, and (iii-c) wave energy, (iv) dynamic hydropower, (v) biomass energy, (vi) geothermal resources: (vi-a) heat pumps, (vi-b) deep geothermal systems, and (vi-c) enhanced geothermal systems, (vii) bio fuels, and (viii) hydrogen from renewable sources. In this spectrum of renewable energy technologies, not each technology has equal potential to be applied in advanced or cyber-physical greenhouses [15]. Specifically, hydropower, tidal and wave energy, reversed osmosis, and enhanced geothermal systems [16] are currently not considered as technologically integratable and economically rentable forms of energy provisioning [17]. For this reason, we do not consider them in our below overview.

Photovoltaic technologies and systems

Photovoltaic (PV) technology uses semiconducting materials and semiconductors that exhibit the photovoltaic effect to generate electrical power by converting solar radiation into direct electric current [18]. PV systems are based on different types of photovoltaic cells [19]. The most widespread are the (i) wafer-based crystalline silicon, (ii) thin film amorphous silicon, and (iii) multi crystalline silicon solar cells. Intense research is devoted to the capacities and performance by involving nano-materials and nano-technological solutions [20]. Unfavorable is that the otherwise high efficiency thin film panels are not transparent, that is, panels placed on the roof of greenhouses causes shading and influences the light available for the crop. The wafer-based and the amorphous silicon solar cells are preferred in the greenhouse industry due to their low costs, but novel thin-film technologies also appeared recently as competitors [21].

Solar concentrator technologies and systems

Concentrating solar collectors (CPCs) gather solar energy through use of mirrors or lenses. Industrial versions can achieve a concentration factor may be greater than 10,000 ("number of suns"). Their major advantage is variability, that is, systems can vary from a small camping cooker to a large, utility-scale electricity generation plant up to 900 MWe. The best known technologies are: (i) parabolic through lenses, (ii) lens concentrators, (iii) linear Fresnel reflectors, (iv) solar furnace, (v) parabolic dish and engine, and (vi) solar central receiver. The furnace temperatures can be as high as up to 3800 °C [22]. Another advantage is that concentrated solar power (CSP) can be considered and scaled up fast without the constraints of critical bottleneck and scarce materials, such as silicon. As energy source for greenhouses, their costs are expected to fall below natural gas in the next few years. CPCs are able to fulfill the thermal, hot water and steam production, waste incineration, seawater desalination, absorption air conditioning, and hydrogen production needs of greenhouses in certain regions of the world depending on the sun radiation. There were some pilot projects with sustainable CPC-based greenhouses in Australia [23].

Wind turbine technologies and systems

Electricity generating windmills (wind turbine technologies, WTTs) are already widely used for industrial power generation due to the opportunities of generating electricity with good efficiency by a renewable resource. Both horizontal and vertical axis generators are applied depending on location and wind characteristics [24]. The typical capacities of WTTs range from small generators (1 - 10 kW) for homes and farms, through intermediate turbines (10 - 250 kW) for village and company power supply systems, to large (250 kW - 5+ MW) central wind farms and distributed power stations [25]. The speed of the wind is the most important factor to the amount of generated power. However in the greenhouse industry these technologies have been not applied extensively yet. The reason is that the investment cost is still high and to cover the heat demand of a 5 hectare greenhouse a plenty of wind turbines are needed. With adequate governmental investment support and increase in gas market prices can contribute to the success of greenhouse projects with wind turbines. Additional systems can support direct heating for air-handling units or the electricity from the wind turbine for other equipment in the greenhouse [26].

Ocean thermal energy conversion

The upper layer of the oceans works as a reservoir of infinite heat storage capacity because the upper surface collects the solar energy as a natural collector [27]. This lends itself to the promising ocean thermal energy conversion (OTEC) technology, which is still in the stage of research and development, with few pilot projects around the world. OTEC power systems are implemented as cyclic heat engines. The drawback of OTEC systems is that the technology is viable where the year-round temperature differential is at least 20 °C. These are located primarily in the equatorial regions, for instance, the coastal regions of Mexico, Indonesia, and other equatorial countries. Generating electricity indirectly from solar energy, the efficiency of the OTEC technology is relatively low, but its relative low costs are an advantage. It can also be used for desalination of seawater, which can then be used for irrigation in greenhouses [28]. The deep seawater is also rich in nutrients, and can be used to culture plants.

Ground source heat pump with aquifers

After combined heat and power (CHP) plants [29], this technology is the most used sustainable energy technology in the Netherlands [30]. The advantage of the technology is the long term storage possibility with the aquifers and the high efficiency and low operation and maintenance costs of the system [31]. The ground source heat pump (GSHP) utilizes practically constant temperature of the subsoil at depths of a few meters (2 - 150m). This temperature is raised by a heat pump for tap water/heating or cooling in summer. The capacity ranges from 5kW$_{th}$ (small applications) to 500 kW$_{th}$ (offices, large buildings and greenhouses).

Deep geothermal systems

Deep systems have been used rarely for greenhouses due to their extremely high costs [32]. Nevertheless, there have been some experimental projects successfully completed in Mexico and the Netherlands. The reason why these projects were successful is actually the gas and/or oil, which was found in the subsoil. It should be also mentioned that these projects could not be successful without the provided governmental support. As some 50-70% of the total costs are the cost of the drilling process, most of the governmental support was mainly allocated to drilling holes [33].

Fuel cell technologies and systems

Fuel cells are devices to convert the chemical energy of a fuel into electric power by means of a chemical reaction with oxygen or another oxidizing agent. Various technologies exist that use different electrolytes: (i) hydrogen (most common fuel), (ii) hydrocarbons, such as natural gas, (iii) alcohols, such as methanol, or (iv) other special fuels. Fuel cells are the most promising future energy producing units with high efficiency and generating high quality heat as output [34]. Different systems can be set up. The most promising ones are the proton exchange membrane fuel cell (PEMFC) which uses H_2 as fuel with low operating temperatures, the solid oxide fuel cell system which makes electricity, heat, and hot water from fuels at the same time [35]. The advantage of these systems are: (i) high electrical efficiency, (ii) possible use of different fuels for SOFC (H_2, CH_4, NH_3, bio syngas, and CH_3OH), (iii) they can be set up with gasifier, and (iv) the high waste heat can used in joint gas turbine, (v) meaning less pollution and high overall efficiency [36].

Biogas fuelled combined heat and power

Energy production by gasification of renewable biomass resources (e.g., wood, straw and crops) and organic residues is increasing all over the world [37]. A variety of procedures can also be used to generate heat. Biogas fuelled combined heat and power (CHP) is one of the best options for greenhouse heating systems, because with flue gas cleaners the generated CO_2 can be directly used in the greenhouse [38]. Widely used in the Netherlands, CHP is of high efficiency and the generated extra electricity can be utilized on the grid. However, the use of the technology is influenced by both fluctuations of the sale prices and the market price of used fuel (which is to a large extent is still methane, and biogas makes only a smaller portion). Nevertheless, it has high potentials from both a technological and an applicability point of view in the context of the greenhouse industry [39].

3. REVIEW OF THE ACADEMIC AND INDUSTRIAL STATE OF THE ART

The knowledge domain this paper is based on is extremely wide. It ranges from sustainability policies of greenhouses through provisioning and utilization of renewable energy sources to modeling material, energy and information flows within greenhouses. The total picture is further articulated by regional approaches and issues concerning the development of sustainable greenhouse systems [39] [40] [41] [42] [43]. Being aware this complexity, below we concentrate only on the aspects closely related to the rest of the paper that focuses on forecasting the energy demands and decision making on using renewable energy sources. The opportunities of using specific renewable energy systems (RES) in different geographical regions and countries are discussed in the literature, but the usage of renewable energy systems in greenhouses is in a premature stage due to the lack of information about these resources and the high installation costs of the machinery. A critical issue is the integration of renewable energy sources into the energy provisioning system of greenhouses. The research in modeling the energy balance by considering alternative renewable energy sources as part of the energy flows of greenhouses seems to be in a premature stage. The number of publications dealing with dynamic and semi-dynamic forecasting models that can be adapted to various RES and specific climate conditions is still limited.

3.1. Modeling the energy systems of greenhouses

The first scientific publications related to modeling the operation and energy flows of greenhouses were published more than 40 years ago. The early efforts focused on the development of mathematical models that could be used as the basis of computer programs. A rather comprehensive overview of these efforts and results is provided in [45]. In this paper: (i) empirical systems models, (ii) static single-component models, (iii) dynamic multi-component models, and (iv) plant development implied models are differentiated. Physical models that have been built for the purpose of experimentation and measurements are one part of the empirical models [46] [47] [48]. Over the years, the other part, i.e. computational models, have developed into two distinct categories: (i) overall climate models, which intend to capture, simulate and predict the whole greenhouse environment, and (ii) partial models, which focus on specific aspects of modeling, such as energy balance, thermal flows, air management, or plant growth. From the very beginning, not only numerical models, but also genetic algorithms- and fuzzy reasoning-based models have also been developed for climate and operation modeling [49] [50]. An overview of the greenhouse climate models can be found in [51]. Efforts have also been made to combine the technical processes together with the growth processes of plants [52]. As automation of greenhouses increasing, a growing number of publications focuses on design and control issues [53] [54] [55].

3.2. Utilization of renewable energy systems in greenhouses

In the last four decades, exploiting renewable energy in the context of greenhouses has been addressed from many aspects [56]. The importance of simulation of the energy balance was recognized long time ago [57]. Over the years, several computer models have been developed for the calculation of the energy generation of various renewable energy technologies [58]. Recently soft computing approaches have also been applied [59]. Photovoltaic technologies were among the firstly and most comprehensively studied renewable energy technologies. The study of Santamouris, M. and Balaras, C.A. listed 95 passive solar greenhouses, which have been realized until the mid-1990s [60]. They also classified them into various categories in order to help improve future applications. Solar energy is used in many different forms and purposes in greenhouses [61] [62] [63]. Although, the use of solar energy has been very successful in the horticultural practice [64], other renewable energy technologies, e.g., biogas, are also proliferating fast [65]. A critical issue, begging for more future attention, is energy storage in greenhouses [66]. Photovoltaic energy is also used in the control of greenhouse infrastructure and machinery, as well as communication devices [67] [68]. De Zwart, F. et al. argued that use of solar energy is a strategic issue in future greenhouses [69]. This is also underpinned by the current industrial trends. [70] [71] [72] [73].

3.3. Some concluding remarks and explaining the objective

In the Netherlands, the horticultural industry is active in enhancing the sustainability of greenhouses and the effect of its activities reaches well beyond the borders of the country [74] [75]. The above review explored that current efforts are made to: (i) develop specific renewable energy systems, (ii) demonstrate the improvement of energy efficiency by small scale experimental projects, (iii) model the overall climate conditions for diagnosis, and (iv) use PV systems for multiple purposes in greenhouses. On the other hand, it is difficult to achieve the national goals concerning sustainability without supporting the growers with proper tools that make the decision and selection processes by clarifying the advantages and disadvantages of RES [76]. Consequently, we have observed the lack of models which can be the baseline of helping growers or investors at choosing renewable energy systems for their greenhouses. Assuming that application of renewable energy should reach a higher percentage in the next years in cyber-physical greenhouses, our objective has been to develop an energy balance forecasting model based on the investigation of the energy flows and heat demand of greenhouses for different climate zones. The rest of this paper discusses the contents and validation of the proposed forecasting model, which uses external climate data as input and heat demand with losses as output. The latter information was also used to support choosing appropriate renewable energy options for greenhouse climate systems.

4. FACTORS INFLUENCING ENERGY BALANCE OF GREENHOUSES

There are two major set of factors that influence the energy balance of traditional, advanced, as well as cyber-physical greenhouses, namely, (i) inside conditions, and (ii) external climate conditions [77]. The inside climate of a greenhouse is a context-sensitive system.

4.1. Inside conditions

The inside climate conditions are eventually determined by the functional needs for living inside the greenhouse and the photosynthesis process of the plant. This is different for each plant and crops [78]. Research findings indicated that photosynthesis is accelerated by increased temperatures. However, photosynthesis slows down above 35 °C and below 10 °C due to denaturation of proteins. Thus, the optimal temperature inside the greenhouse should be between 10 °C and 30 °C.

Basically, every plant consists of two key elements: dry matter and water [79]. The dry matter is a product that is generated mainly by photosynthesis. Water content is the result of the balance between uptake and loss of water, or, in other words, between the water dosage and the evaporation [80]. Due to the evaporation process, which results in an increase in the relative humidity of the air inside the greenhouse, ventilation is needed [81]. In turn, it means enormous latent and sensitive heat loss from the greenhouse. A plant also uses energy for its own processes. This energy is generated by the reversed photosynthesis process, called respiration [82].

Respiration takes place in the entire plant. It is a continuous process, but not correlated with light. Respiration contributes to cell division and cell growth in the green parts, but also to the active uptake of water in the roots. The speed of respiration in the green parts is strongly correlated with temperature. Respiration exponentially increases above 25 °C, and the use of energy changes with the temperature. At higher temperatures, the amount of energy used for maintenance also increases. However, the energy for building dry matter is hardly affected by temperature. It is very important that the evaporation (water out) and uptake (water in) should be in balance (the water control) [83].

The factors determining the inside climate conditions are correlated to and depend on each other [84] [85]. It can be concluded based on the above discussion that the major factors that influence the energy balance of greenhouses are: (i) temperature of greenhouse air and (ii) water control in combination with evaporation (that also influences the ventilation needs and losses). There are however many other influential internal factors such as: (i) (artificial) lighting (additional heat), (ii) soil conditions (density, water content), (iii) crop properties (leaf area index, volume, and mass), (iv) construction material properties of the greenhouse (absorption coefficient, mass, heat capacity, etc.), and (v) additional methods and solutions (thermal screens, white wash, shading screens, etc.)

4.2. External climate conditions

As one of the major influential factors, external climate determines the need for climate conditioning as well as the associated equipment and energy costs, and thus crop production. Together with the intensity and duration of wind forces and rainfalls, it also influences the construction of greenhouses. Global climate is determined by parallel climate zones in north-south direction, elevation, and influence of oceans/seas in different geographical regions. For the reason that global climates can be rather different, two climate zones were considered in our research. One of them is De Lier in the Netherlands, and the other is Shanghai in China. The related data have been considered as descriptors of external climate conditions at conceptualization of the proposed forecasting model. For the Netherlands, the year data of 1999, collected at the meteorological station in Hoek van Holland (number: 330, latitude: 51.99°, longitude: 4.12°) was used as the basis of calculations [86]. The total monthly radiation in the Netherlands in 1999 is shown in Figure 1. Also for Shanghai, the year data of 1999 were used as descriptors of the external climate conditions. The data were collected at a regional meteorological station (number: 58362, latitude: 31.39°, longitude: 121.45°) [87]. The total monthly radiation in Shanghai in 1999 is shown in Figure 2.

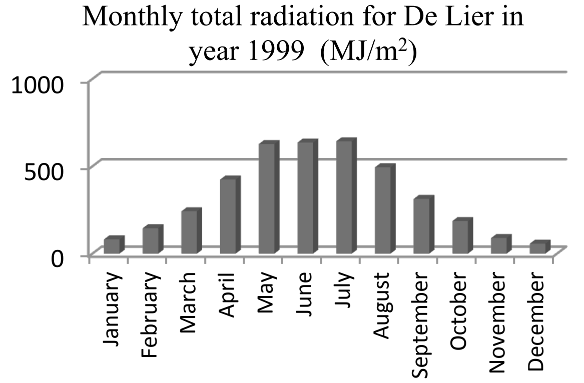


Figure 1 Solar radiation for De Lier

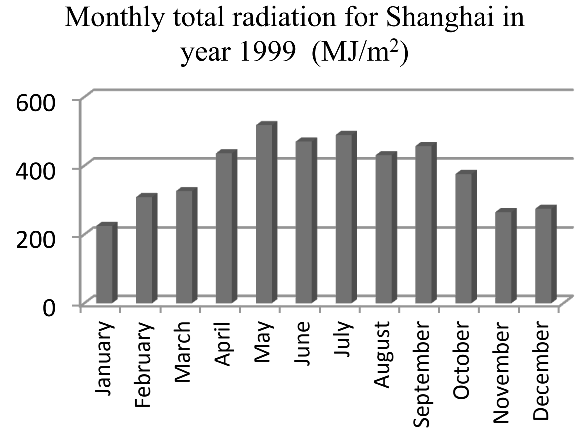


Figure 2 Solar radiation for Shanghai

5. A COMPUTATIONAL MODEL FOR ENERGY BALANCE CALCULATION

5.1. Basic considerations for climate modeling of greenhouses

One of the most important cycles in the greenhouse is the water cycle, which is influenced by factors such as evaporation, condensation and ventilation [88]. Radiation is the trigger of the evaporation process of the crop, and this is the beginning of the water cycle. Radiation is interconnected with factors such as: (i) the construction materials of the greenhouse, which influence absorption, reflection and transmission, (ii) the soil as absorptive surface, (iii) the crop itself, and (iv) indirectly, with the air within the greenhouse. Another influencing factor is the thermal screen, which is often used to diminish the losses. A comprehensive climate model is supposed to capture all of these factors as variables in the basic equations of the model [89] [90].

In our research, the Venlo-type greenhouse has been considered (Figure 3). The simple reason is that some 85% of the greenhouses in the Netherlands are of Venlo-type, while the rest is wider span or plastic tunnels. Obviously, for setting up of the climate model, various assumptions and simplifications concerning the energy flows were needed. Based on these, it became possible to set up the climate model and to obtain relatively well approximating output figures (e.g., in terms of the peak loads and the mean values of the greenhouse energy needs for different climate zones) for systems with integrated renewable energy sources. The proposed climate model considers all of the factors and variables, which influence the energy flows in and out from the greenhouse. The model describes the heat fluxes in a greenhouse (Figure 4). The next sub-sections provide a concise overview of the content of the climate model, intended to support 'what-if' type forecast calculations.

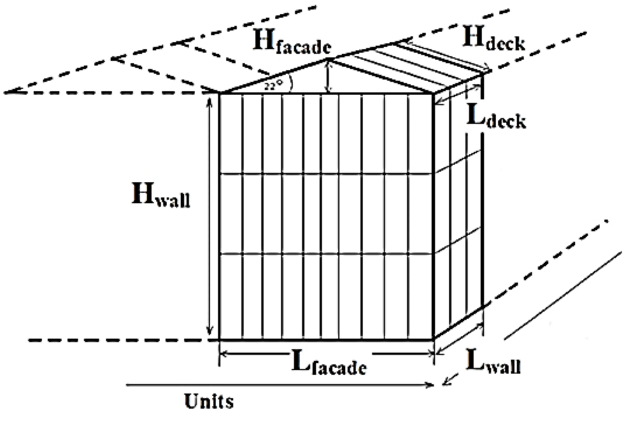


Figure 3 Venlo-type greenhouse

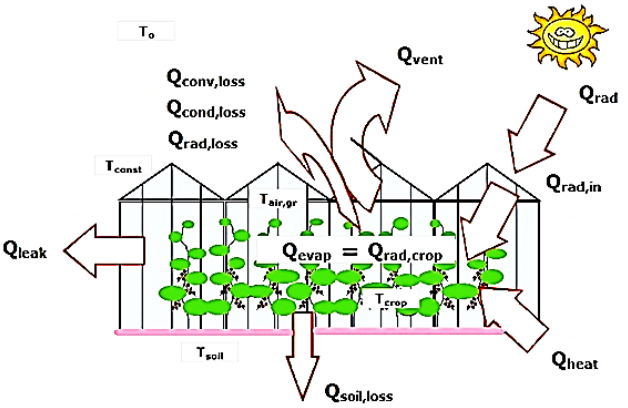


Figure 4 Graphical visualization of the energy balance underpinning the proposed model

5.2. Assumptions for the climate model

The climate model is based on the following assumptions for heat balance calculation:

- The inside (air) of the greenhouse is a "perfectly stirred tank", which means that there is no location dependent difference in temperature, vapor pressure, and CO_2 concentration. Consequently, all fluxes are described in the model as per square meter of greenhouse floor [9].
- The control volume of the greenhouse is considered as a rectangular body with flat roof. ($A_{floor} = 50.000$ m^2, $H_{wall} = 6$ m).
- Placed right next to the roof, thermal screens are used during the night to avoid difference in the heat flows and temperatures in the greenhouse. There is no influence on radiation, therefore: $f_{screen,day} = 1$. Assumed is a 50% decrease of outgoing radiation and convection (including the reduction of the leakage from the greenhouse as well), therefore: $f_{screen,night} = 0.5$ [90].
- Estimated is that 16 % of the radiation incoming from the sun is reflected back to the atmosphere, 7 % of it is absorbed by the construction materials, and 77 % goes through the construction materials. The transmission rate is defined based on practical measurements, while the absorption rate is adjusted to the temperature limits and heat losses for the construction materials.
- The radiation of the soil was set to 3.5 %, assuming that, due to the leaves and shading, just about 3 – 5 % of the radiation through the greenhouse is related to the temperature increase of the soil [90] [91].
- The radiation from the crop, soil, and construction materials is described by differential equations.

These radiation equations are simplified according to the practice. This means that an average of 90 - 130 W/m^2 heat loss is considered for clear sky radiation (which includes all outgoing radiations from the greenhouse). It should be noted that a variation interval of 0 - 90 W/m^2 is considered in the model to describe the effect of cloud coverage [76] [90] [91].

- For the sake of simplification, the construction material is considered as 100 % glass. This is underpinned by the fact that, in practice, more than 85 – 90 % of the roof surface of a greenhouse is covered by glass [90].
- The solar radiation that goes through the greenhouse is split into the radiation that directly reaches the crop and the radiation that is heats the air. 100 % of the former radiation is taken into consideration as the cause of the evaporation process on the crop leaves. That is, $f_{ratio} = 0$, and $Q_{rad,crop} = Q_{evap}$) [88] [90] [92].
- Re-evaporation from the surface of the construction material is considered in the condensation factor formula. However, this is only a rough estimate of the process, but should be accepted because the exact air flow conditions in the greenhouse are unknown and difficult to describe [91] [93].
- As crop, tomato is considered, which contains 90% water. This means that the specific heat of the crop can be approximated by the specific heat of the water. The same is applied in the case of the density of the crop, under standard conditions of T = 20 °C, p = 1 bar [78].
- The mass of tomato crop for 1 m^2 of greenhouse soil area is set to 15 kg/m^2 [78].
- The heat resistance of the construction material and the outside air ($k_{const,air}$) is determined by the average external heat coefficient ($\overline{h_e}$) to be calculated for each climate. Note that h$_e$ = 10 – 55 W/m^{2}K in practice [94]
- The density and specific heat of the compressed soil is taken as 1600 kg/m^3 and 2 - 2.5 MJ/m^{3}K, respectively [95].
- The average internal heat coefficient ($\overline{h_i}$) is set to 8 W/m^{2}K for the air of the greenhouse [90]. The $k_{crop,air,gr}$ was set to 10 W/m^{2}K, according to the ($\overline{h_i}$) from the practice [88] [90]. Based on practical experience, the irrigation factor f_{irr} is set to 3 cm^3/J. [78]
- The mass of the construction material is set to 18 kg/m^{2,} according to the physical dimensions and properties of glass. That is d_g = 5 mm, single glass is considered [88] [90].
- For leakage calculations, the air exchange rate of glass (A_c) is set to 1.5 1/hour, and is calibrated in every hour due to hourly wind speed variations [90][91][88].
- The time step of the model is set to 1 hour. As mentioned above, external climate data of 1999 are used.
- The specific numbers for different materials are according to [96], or calculated by respective equations.

5.3. Basic equations for the computational model

The equations used as the basis of the computational model are presented in Figure 5. The calculations have been done according to the assumptions and specifications mentioned above.

6. VALIDATION AND ADJUSTMENT BASED ON EMPIRICAL DATA

$$m_{const}c_{const}\frac{dT_{const}}{dt} = f_{solar,const}Q_{rad} \mp f_{screen}k_{const,air,gr}\left(T_{const} - T_{air,gr}\right) \mp k_{const,air}\left(T_{const} - T_o\right) - e_{glass}\delta\left({T_{const}}^4 - {T_o}^4\right) \tag{1}$$

$$m_{soil}c_{soil}\frac{dT_{soil}}{dt} = f_{solar,soil}f_{solar,in}Q_{rad} - k_{air,gr,soil}\left(T_{soil} - T_{air,gr}\right) - e_{soil}\delta\left({T_{soil}}^4 - {T_o}^4\right) \tag{2}$$

$$m_{crop}c_{crop}\frac{dT_{crop}}{dt} = -k_{crop,air,gr}\left(T_{crop} - T_{air,gr}\right) \pm f_{ratio}f_{solar,crop}f_{solar,in}Q_{rad} - \Delta h_{evap}\dot{m}_{gr,evap} - e_{crop}\delta\left({T_{crop}}^4 - {T_o}^4\right) \tag{3}$$

$$\begin{aligned} m_{air,gr}c_{air,gr}\frac{dT_{air,gr}}{dt} &= \\ f_{solar,air}f_{solar,in}Q_{rad} \pm Q_{heat} - f_{vent}Q_{vent} &\mp k_{const,air,gr}\left(T_{air,gr} - T_{const}\right) \mp \\ k_{crop,air,gr}\left(T_{air,gr} - T_{crop}\right) \mp k_{air,gr,soil}&\left(T_{air,gr} - T_{soil}\right) - f_{screen}ccQ_{rad,loss,av} - \\ f_{screen}k_{leak}\left(T_{air,gr} - T_o\right) &+ f_{condz}Q_{condz} \end{aligned} \tag{4}$$

Figure 5 Fundamental equations used in the forecasting model

6.1. Adjusting the model for the Netherlands

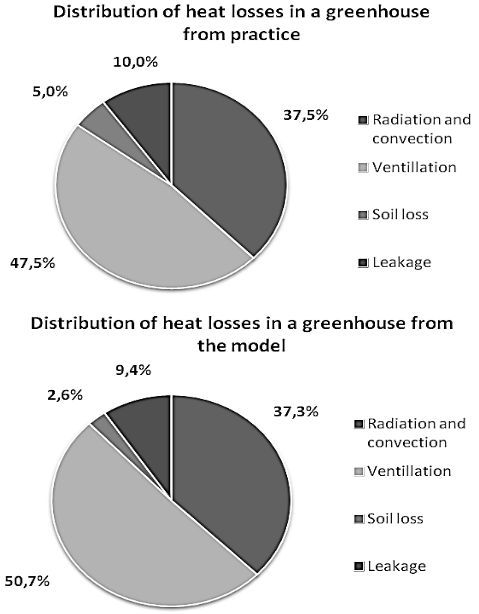
The results of the heat calculations can be seen in Figure 6. In the case of a Venlo-type greenhouse of 5 HA, the external climate input data for the year 1999 resulted in a heat demand of 1852 MJ/m^2 for the Netherlands. The computed maximum hourly heat demand is 213 W/m^2 with low irradiance, higher outer relative humidity, and low cloud coverage. This situation occurs only one time over 8760 hours. For a time period of 25 hours, the heat demand is above 160 W/m^2. This means 0.3 % deviation from the practical 160 W/m^2 peak demand [91] [94]. This deviation is observable when there are sun radiation changes during the day, or if the outside RH is higher than the inside RH [91].

$Q_{rad,tot}$:	3941 MJ/m$^2_{,year}$
$Q_{rad,in,tot}$:	3034 MJ/m$^2_{,year}$
$Q_{heat,tot}$:	**1852 MJ/m$^2_{,year}$**
$Q_{gr,tot}$:	4887 MJ/m$^2_{,year}$
CH_4 usage:	**53 m^3/m$^2_{,year}$**
$Q_{rad,totloss,}$:	1339 MJ/m$^2_{,year}$
$Q_{vent,sensible}$:	610 MJ/m$^2_{,year}$
$Q_{vent,latent}$:	1866 MJ/m$^2_{,year}$
$Q_{vent,totloss}$:	2476 MJ/m$^2_{,year}$
$Q_{soil,totloss}$:	127 MJ/m$^2_{,year}$
$Q_{conv,totloss}$:	484 MJ/m$^2_{,year}$
Q_{leak}:	461 MJ/m$^2_{,year}$
$Q_{loss,tot}$:	**4887 MJ/m$^2_{,year}$**

Figure 6 Energy calculations for the Netherlands based on the proposed model

The verification of the proposed model for losses is shown in Figure 7. The variances of the heat loss values obtained by the model and the values known from the practice are as follow: The difference in (i) ventilation losses is 3,2 %, (ii) radiation and convective losses is 0,2 %, (iii) soil losses is 2,4 %, and (iv) leakage losses is 0,6 %.

The resultant value of 1.85 GJ/m$^2_{,year}$ of the total heat demand also seems to be correct. Dutch greenhouse growers reported 40 – 50 m^3/m$^2_{,year}$ yearly natural gas consumption [76]. For the Dutch (Groningen) natural gas the HHV value is 35.17 MJ/m^3 [97], and this means 53 m^3/m$^2_{,year}$ greenhouse consumption according to the proposed model. It has to be mentioned that Dutch tomato growers do not use (or just on relatively low level) the heating installations over a certain period because of the plant replacement [78]. Including regular cleaning, this process usually happens in November and takes approximately one month. As a consequence, the heating demand is reduced to 48 m^3/m$^2_{,year}$, which shows a good agreement with the reported figures. For instance, Kwekerij Parasol B.V., a tomato grower working on a total greenhouse area of 45,000 m^2, having a CHP capacity of 2 MW, yearly natural gas consumption of 2,43*10^6 m^3/year), reported an average natural gas consumption of 54 m^3/m$^2_{,year}$ [83].


Distribution of heat losses in a greenhouse from practice

Distribution of heat losses in a greenhouse from the model

Figure 7 Verification of the model according to heat losses for the Netherlands

According to the computational model, the water usage within the greenhouse due to evaporation by the crop was 915 l/m^2,$_{year}$, and the calculated irrigation rate is 1182 l/m^2,$_{year}$, (considering the irrigation factor known from practice). Therefore the calculated drain (extra re-circulated water) is 23 % per year, while it is takes as 20 – 30 % in the practice [91]. The crop uses roughly 7 % of the water uptake for food production, and an additional 10 % is used for building up its dry matter. This results in a crop mass of 70 kg/m^2 [78]. Therefore, the calculated crop yield is 64 kg/m^2,$_{year}$ for 12 months. However, the maximum number of months in a crop cycle is 10 months. This means that, according to the statistics concerning tomato production in high-tech greenhouses in the Netherlands, the computed 53 kg/m^2 food production is correct [78].

6.2. Adjusting the model for China

The results computed for Shanghai are shown in Figure 8. It can be seen that the heat demand for the same greenhouse is lower in this region of China due to the sunny and warm climate. In the case of a 5 hectares Venlo-type greenhouse, a heat demand of 993 MJ/m^2 was calculated for Shanghai, using the 1999 external climate input data. That means a 28

$Q_{rad,tot}$:	4579 MJ/m$^2_{,year}$
$Q_{rad,in,tot}$:	3525 MJ/m$^2_{,year}$
$Q_{heat,tot}$:	**993 MJ/m$^2_{,year}$**
$Q_{gr,tot}$:	4519 MJ/m$^2_{,year}$
CH_4 usage:	**28 m^3/m$^2_{,year}$**

Figure 8 Energy calculations based on the proposed model for China

m^3/m$^2_{,year}$ of natural gas consumption on a yearly basis. It has to be mentioned that these calculations have also been done by assuming a continuous production of 12 months (i.e., without the need for cleaning, and changing the plants when the lifetime is over. However, we may apply the same assumptions as before, namely, (i) growers take out the plants in November, (ii) cleaning and planting of new plants take one month, and (iii) there is no heating in the greenhouse, only thermal screens are used during this period of time. In this case, we obtain 11 % decrease in terms of the heating demand and a 24 m^3/m$^2_{,year}$ yearly usage of natural gas. The calculated need for water due to evaporation by the crop within the greenhouse is 1063 l/m$^2_{,year}$, and the calculated irrigation rate is 1374 l/m$^2_{,year}$ (again, considering the irrigation factor known from practice). Therefore the calculated re-circulated water is 23 %. The calculated crop yield is 74 kg/m$^2_{,year}$ for 12 months. This means that the calculated food production is 62 kg/m^2 if a 10 months long production year is considered.

6.3. Evaluation and sensibility analysis

The heat generation calculated according to the proposed model for a greenhouse in the Netherlands and China is shown in Figure 9. For a more precise and accurate calculation, the heat capacities of the steel frames of the construction materials should have been taken into account. However, in the current model these are ignored. Consideration of the effect of condensation and ventilation control is also a complicated task, though there have efforts been made in this direction [88] [98]. Should the condensation conditions be changed due to a higher temperature in the greenhouse, then the high peaks of the heating demand could be avoid in the summer period. However, it is somewhat difficult to adjust the proposed computational model when the ventilation rate is high, because of the effect of the airflow inside the greenhouse on the condensation rate.

The proposed climate model has undergone an extensive sensibility analysis, which included several checks from multiple aspects. It has been noticed that the condensation factor (f_{condz}) plays an influential role in the results computed by the model. When it is instantiated with a lower value, e.g., 0.6, (meaning that only 60 % of the water vapor condensates), the heat demand increases remarkably. Instead of the previously discussed 53 m^3/m$^2_{,year}$, it entails a 61 m^3/m$^2_{,year}$ heat demand, resulting in a maximum value of 239 W/m^2. On the other hand, when it is

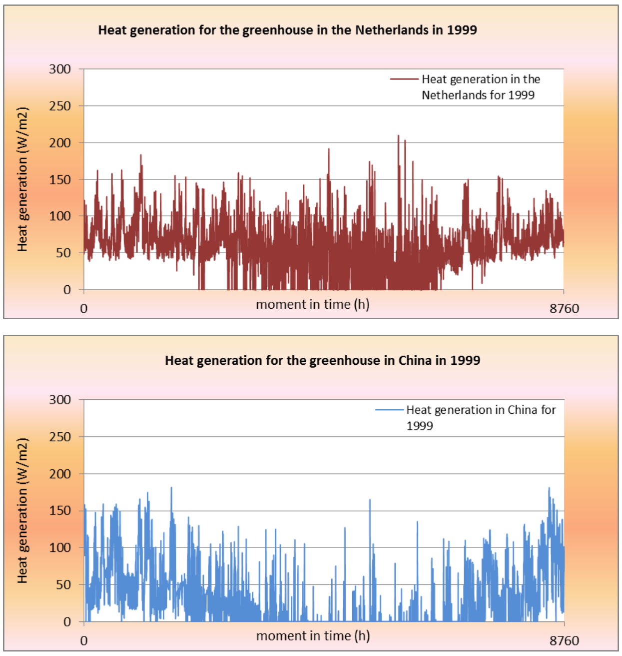


Figure 9 Heat generation in the Netherlands (upper diagram) and China (lower diagram) ($f_{condz} = 0{,}8$, $f_{screen,night} = 0{,}5$)

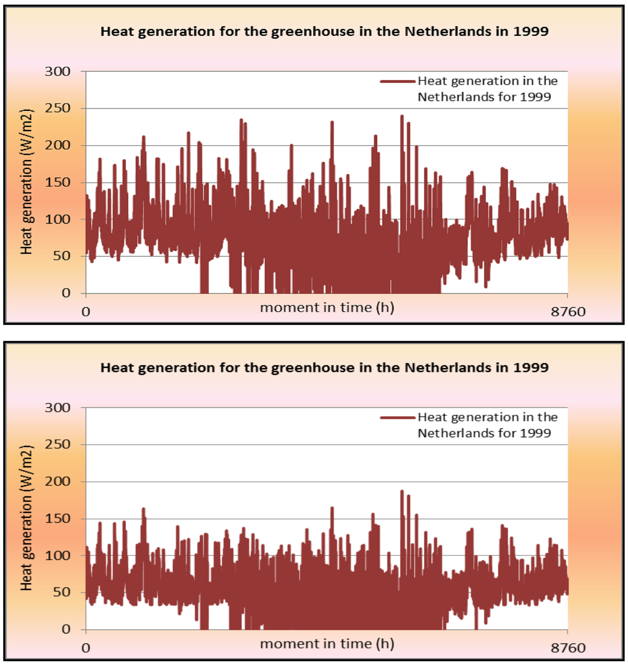


Figure 10 Heat generation in the Netherlands (upper: $f_{condz} = 0{,}6$; lower: $f_{condz} = 1{,}0$)

instantiated with the highest possible value, i.e., 100% condensation, (meaning that 100% of the water vapor condensates and there is no re-evaporation), the heating demand becomes low. That implies some 45 $m^3/m^2_{,year}$ gas consumption, with a maximum value of 187 W/m^2 (Figure 10).

The thermal screen factor is important from the aspect of heat losses. Few percent of change in the $f_{screen,night}$ causes relatively large changes in heat demand. As stated by growers, greenhouses without thermal screens may end up with a 50 $m^3/m^2_{,year,}$ or more gas consumption in a year. Other growers argued that owing to proper vertical and horizontal thermal screens and good insulation they could reduce gas consumption to 40 $m^3/m^2_{,year}$. We applied the proposed model to investigate the effects of using thermal screen during night. The results are shown in Figure 11. Thermal screen influences both the heat demand and natural gas consumption. The upper part shows 50 % heat loss reduction ($f_{screen,night}$ = 0.5), while the lower part shows 70 % heat loss reduction ($f_{screen,night}$ = 0,3).

$Q_{rad,tot}$:	3941 $MJ/m^2_{,year}$
$Q_{rad,in,tot}$:	3034 $MJ/m^2_{,year}$
$Q_{heat,tot}$:	**1852 $MJ/m^2_{,year}$**
$Q_{gr,tot}$:	4887 $MJ/m^2_{,year}$
CH_4 usage:	**53 $m^3/m^2_{,year}$**

$Q_{rad,tot}$:	3941 $MJ/m^2_{,year}$
$Q_{rad,in,tot}$:	3034 $MJ/m^2_{,year}$
$Q_{heat,tot}$:	**1729 $MJ/m^2_{,year}$**
$Q_{gr,tot}$:	4763 $MJ/m^2_{,year}$
CH_4 usage:	**49 $m^3/m^2_{,year}$**

Figure 11 Effects of using thermal screen during night

Obviously, the dimensions of the greenhouse largely influence the heating demand. We set the height of the walls of the greenhouse in the proposed climate model to 6 meter [91]. If the wall height is changed to 4.5 m, then the heat demand drops down to 1770 $MJ/m^2_{,year}$. It means that 4.5 % of the needed energy (i.e., 85 MJ/m^2) can be saved on a yearly basis. This can be explained by the fact that the surface area of the greenhouse is reduced so as less amount of inside air should be heated up. In addition, the smaller surface areas (radiation, convection, leakage, etc.) result in less heat losses. In real life, the use of thermal screens depends on the growers' decision. They typically use thermal screens during winter and spring. During the summer, i.e., from June until October, thermal screens are typically not used [89] [91]. During the winter, they are usually used for more than 12 hours per day (often for more than 20 hours on cold cloudy days). These have also been considered in the development of the computational model as assumptions. Our experiments imply however, that the model needs to be adjusted in order to provide more articulated and accurate results concerning these factors. It also entails that additional research is needed in terms of the mathematical representation of the effects and usage of thermal screens and the influence of the condensation factor with regards to the basic equations of energy balance calculation.

The heat demand is less sensitive to factors such as the soil and the construction materials. There are multiple reasons of it. For instance, the soil has a high heat capacity, its temperature is close to the air temperature of the greenhouse, and, in the case of certain crops (e.g., tomato) only a low amount of radiation reaches the soil. The effect of construction materials is also limited, as shown by the calculations in which the condensation effect was neglected and the temperature of the glass of the greenhouse was approximated [88]. Based on various calculations, the caused maximum temperature difference is less than 6 °K, but it is influenced by condensation that depends on the temperature of the construction and the dew point temperature of the air within the greenhouse [93].

7. DISCUSSION AND CONCLUSIONS

The overall objective of our research was to investigate the possibilities of integration of renewable energy systems in the climate system of a cyber-physical greenhouse. Our concrete goals were

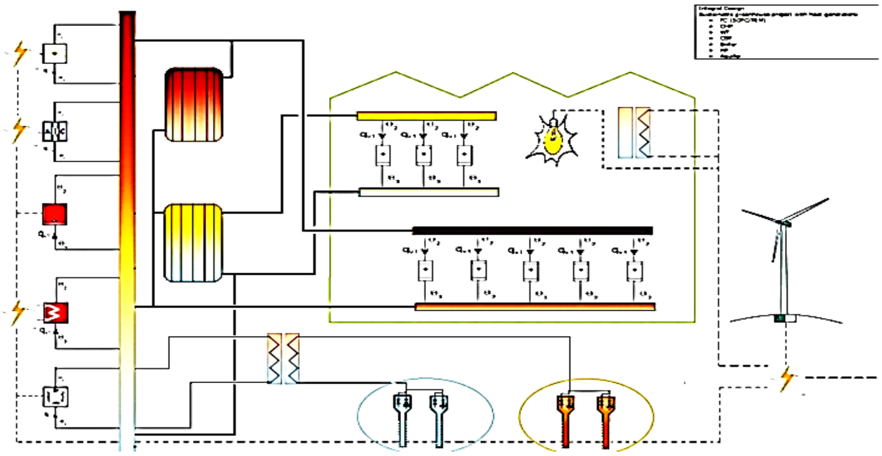
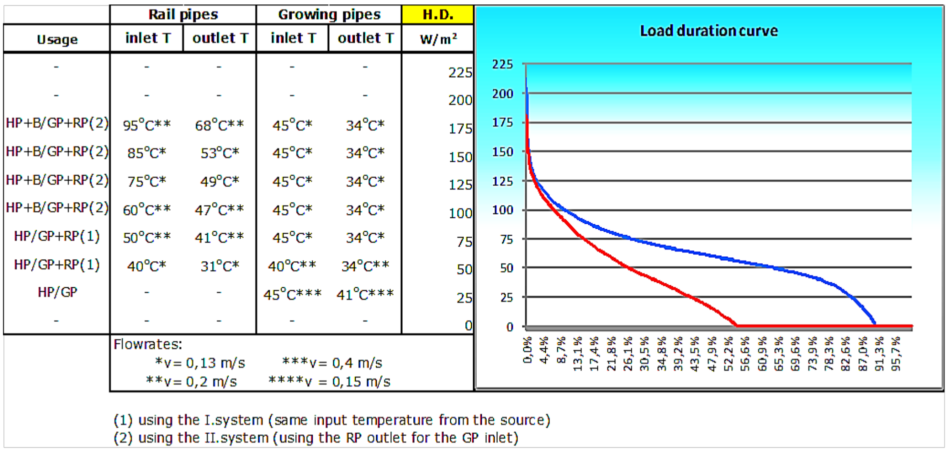


Figure 12 Integral design of the greenhouse heating system



	Rail pipes		Growing pipes		H.D.
Usage	inlet T	outlet T	inlet T	outlet T	W/m²
-	-	-	-	-	225
-	-	-	-	-	200
HP+B/GP+RP(2)	95°C**	68°C**	45°C*	34°C*	175
HP+B/GP+RP(2)	85°C*	53°C*	45°C*	34°C*	150
HP+B/GP+RP(2)	75°C*	49°C*	45°C*	34°C*	125
HP+B/GP+RP(2)	60°C**	47°C**	45°C*	34°C*	100
HP/GP+RP(1)	50°C**	41°C**	45°C*	34°C*	75
HP/GP+RP(1)	40°C*	31°C*	40°C**	34°C**	50
HP/GP	-	-	45°C***	41°C***	25
-	-	-	-	-	0

Flowrates:
*v= 0,13 m/s ***v= 0,4 m/s
**v= 0,2 m/s ****v = 0,15 m/s

(1) using the I.system (same input temperature from the source)
(2) using the II.system (using the RP outlet for the GP inlet)

Figure 13 Combined usage of heat generation units and transportation lines

to look into the current academic and industrial state of the art, to aggregate knowledge for a mathematical climate model that can be used to forecast the effects and usability of various sustainable energy sources in cyber-physical greenhouses. The thermal balance of a greenhouse is a complex matter, which is influenced by a large number of functional parameters, as well as by internal and external factors. In this paper we presented the synthesized knowledge, and focused on both the development and the validation of the proposed forecasting model. This computational model uses external climate data as input and heat demand with losses as output. The latter information is used to support the selection of appropriate renewable energy options for a greenhouse climate system. However, we concentrated of the issues of the actual integration, rather than on the pre-selection of the combinable renewable energy options in this paper.

The proposed forecasting model facilitates integral design of the heating systems and the flow distribution systems of greenhouses, as demonstrated in Figure 12. This figure shows the main heat generation units, the transportation lines with the distribution system (rail and growing pipes). A pre-selection is applied, that plays an important role in the case of cyber-physical greenhouses, in which renewable energy sources are used not only for powering the plant growing functions of the greenhouse, but also for providing the requested additional energy for computation, control, and communication. Relying on the outcome of the pre-selection, integral design combines all appropriate renewable energy systems and heat generation units into the functional framework of the designed greenhouse. Contrary to their advantages (which are comprehensively discussed in the literature), solar PV systems could not be considered as renewable energy sources in the proposed computational model because of the caused light shading. Further renewable options, such as CSP (concentrated solar power), fuel cell (SOFC, PEMFC), WT (wind turbine), HP (heat pump) with aquifers and CHP (combined heat and power), or boilers have only been considered as backup systems.

Figure 13 shows the calculated heat demand with controlled temperature and flow rates. This scheme supports the analysis of combinations of pre-selected heat generation units. The load duration curves show the distribution of the yearly heat demands for the Netherlands and China, respectively. They support the reasoning about the final selection of the renewable energy system of appropriate heating capacity. As shown, the heat demand in China is under 75 W/m^2 in 85 % of the year, while the same energy need exists in 72 % of the year in the Netherlands under the same conditions. In combination with these energy demands, the highest temperatures are 45 - 95 ^{o}C for the growing pipes and

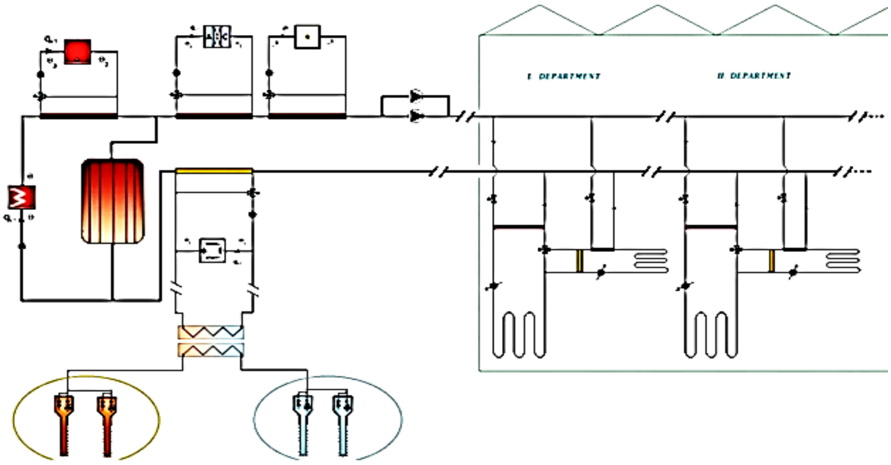


Figure 14 Integral design of the distribution systems

the rail pipes, respectively. It means that heat pumps with aquifers could cover some 72 – 85 % of the heating demand for both countries in a year. For the rest of the year (i.e., 15 -28 %, and in the case of high peaks, a boiler or CHP is necessary to cover the actual heat demand.

The highlights of our work can be summarized as follows. We extensively investigated the characteristics and applicability of renewable energy systems as part of greenhouses' energy system. We found that their application is actually in a premature stage and more knowledge was needed about how they can be integrated into the energy flows of greenhouses, considering all factors, which determine and influence the energy balance of a greenhouse. We developed a comprehensive climate model, which considers both external and internal conditions, and is able to forecast the share of the renewable energy systems in the energy balance. The model is based on a large number of assumptions and specifications, but has been validated for two geographical regions based on averaged empirical data. The integratability of renewable energy systems plays an important role in the climate system of cyber-physical greenhouses. The integral design pursues the integration of the renewable energy systems and the hydraulic design. Figure 14 shows the detailed distribution systems with all the appropriate heat generation units. Our future research will focus on the exploration and development of design principles for energy provisioning for cyber-physical greenhouses including multiple renewable energy sources.

LEGEND

$c_{air,gr}$	specific heat of air inside greenhouse	J/kgK
cc	cloud coverage	(-
c_{const}	specific heat of the construction materials	J/kgK
c_{crop}	specific heat of the crop	J/kgK
$c_{p,air}$	specific heat of air	J/kgK
c_{soil}	specific heat of air inside greenhouse	J/kgK
e_{crop}	absorption coefficient of the crop	-
e_{glass}	absorption coefficient of glass	-
e_{soil}	absorption coefficient of soil surface	-
f_{condz}	condensation factor	-
f_{ratio}	plant energy absorption and control factor	-
f_{screen}	thermal screen factor	-
$f_{solar,air}$	solar factor for radiation for the inside air	-
$f_{solar,const}$	solar factor for radiation for construction materials (absorption)	-
$f_{solar,crop}$	solar factor for radiation for the crop	-
$f_{solar,in}$	solar factor for radiation going in the greenhouse	-
$f_{solar,soil}$	solar factor for radiation going to soil	-
f_{vent}	ventilation factor	-
$k_{air,gr-soil}$	heat resistance for greenhouse air/soil	W/m^{2}K
$k_{const,air}$	heat resistance for const/air outside	W/m^{2}K
$k_{const,air,gr}$	heat resistance for const/air of greenhouse	W/m^{2}K
$k_{crop,air,gr}$	heat resistance for crop/air of greenhouse	W/m^{2}K
k_{leak}	leakage factor	W/m^{2}K
$m_{air,gr}$	mass of air per m^2 greenhouse	kg/m^2
m_{const}	mass of construction material per m^2 greenhouse	kg/m^2
m_{crop}	mass of crop per m^2 greenhouse	kg/m^2
$m_{gr,evap}$	evaporation flow of crop in greenhouse	kg/sm^2
m_{soil}	mass of soil per m^2 greenhouse	kg/m^2
$Q_{conv,loss}$	heat loss due to convection	W/m^2
Q_{heat}	heat generated from machinery	W/m^2
Q_{leak}	leakage	W/m^2
Q_{rad}	incoming solar radiation	W/m^2
$Q_{rad,crop}$	solar radiation for crop	W/m^2
$Q_{rad,gr,air}$	solar radiation for greenhouse air	W/m^2
$Q_{rad,in}$	solar radiation through the greenhouse	W/m^2
$Q_{rad,totloss}$	overall heat loss due to radiation	W/m^2
Q_{vent}	heat loss due to ventilation	W/m^2
$T_{air,gr}$	inside air temperature of the greenhouse	K
T_{const}	temperature of construction materials	K
T_{crop}	temperature of the crop	K
T_o	outside temperature	K
T_{soil}	temperature of soil	K
δ	Stefan-Boltzmann constant	W/m^{2}K^{-4}
Δh_{evap}	vaporization heat of water (T=20^{o}C, p=1bar)	J/kg

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