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# Energy demand hourly simulations and energy saving strategies in greenhouses for the Mediterranean climate

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**Abstract.** This research has been devoted to the selection of the most favourable plant solutions for ventilation, heating and cooling, thermo-hygrometric control of a greenhouse, in the framework of the energy saving and the environmental protection. The identified plant solutions include shading of glazing surfaces, natural ventilation by means of controlled opening windows, forced convection of external air and forced convection of air treated by the HVAC system for both heating and cooling. The selected solution combines HVAC system to a Ground Coupled Heat Pump (GCHP), which is an innovative renewable technology applied to greenhouse buildings. The energy demand and thermal loads of the greenhouse to fulfil the requested internal design conditions have been evaluated through an hourly numerical simulation, using the Energy Plus (E-plus) software. The overall heat balance of the greenhouse also includes the latent heat exchange due to crop evapotranspiration, accounted through an original iterative calculation procedure that combines the E-plus dynamic simulations and the FAO Penman-Monteith method. The obtained hourly thermal loads have been used to size the borehole field for the geothermal heat pump by using a dedicated GCHP hourly simulation tool.

## 1. Introduction

One of the main tasks in greenhouse construction is to optimize the conditions for plant growth, generally during the off-season from normal outside field production. Total energy consumption of greenhouse agriculture is steadily increasing because most of the agriculture companies and growers made a shift from unacclimatized to acclimatized greenhouses in order to satisfy the increasing demand of product quality and vegetable production availability all-year-round, which now characterize the European agro-food industry.

During the last 20 years, countries in the Mediterranean climate area have become increasingly competitive producers of greenhouse vegetables and fruit. The covered area in greenhouses in Italy exceeds 42000 hectares, of which 5000 hectares are devoted to crops of vegetables and more than 37000 hectares to floriculture. The greenhouse cultivation represents for the national agricultural system a productive sector of considerable economic importance.

Greenhouse technologies allow cultivating all horticultural species in any region of the world, provided that the greenhouse is properly designed and equipped to control the indoor climate. Over the past few years, researchers have investigated a large number of energy saving techniques for air conditioning of greenhouses and cropping systems by means of studies, simulations and experimentations. Most of the analysed solutions were developed to reduce inside air temperature without compromising the plant crop production, to improve greenhouse insulation, to optimize shape



and orientation of the greenhouse (Gupta and Chandra [1], Sethi [2]) or to increase the energy efficiency of the heating and cooling.

Moreover, interest in renewable energies for both heating and cooling has become more intense for greenhouse operators to reduce their energy costs and CO<sub>2</sub> emissions. In fact, despite the large presence of renewable energy sources in several European regions with a significant greenhouse production, the renewable technologies have still a limited application for greenhouse air conditioning. Among these renewable technologies one can mention the solar energy exploitation (Abdel-Ghany and Al-Helal [3], Ozgener and Hepbasli [4]), the photovoltaic applications, the use of solid/residues biomass for heating, the latent heat storage for low temperature heating applications (Tuncbilek et al. [5]) and the geothermal contribution to greenhouse conditioning (Adaro et al. [6], Bakos et al., 1999 [7], Santamouris et al. [8]).

Greenhouse heating is important even in countries with temperate climate, like the Mediterranean region, in order to maximize crop production in terms of quantity and quality and thus to increase the overall productivity of greenhouse. Heating costs not only have a critical influence on the profitability, but in the long-term may also determine the survival of the greenhouse industry. In Italy, the cost of heating currently accounts for approximately 30% on the cost of production in the greenhouse. Apart from the costs problems associated with high-energy consumption, heating is associated with environmental problems through the emission of noxious gases.

An extended review about innovative and renewable heating technologies for greenhouse application has been proposed by Sethi and Sharma [9]. They diffusely illustrate several energy saving solutions as thermal storage, ground-to-air heat exchanger systems, movable insulation/thermal screens, optimal use of the north wall, ground air collectors and aquifer coupled cavity flow heat exchanger systems.

Moreover, Jamal [10] and more recently Sethi and Sharma [11] have proposed a comprehensive description of cooling techniques for greenhouses, including renewable technologies as the roof evaporative cooling, the ground-to-air heat exchanger system and the aquifer coupled cavity flow heat exchanger system.

This paper is related to the Liguria Region research program “Smart Agro-Manufacturing Laboratory (SAM-LAB)”. The final goal of the Project was to realize an innovative greenhouse equipped with new materials for the glazed shell and with suitable advanced controls, able to enhance the facility management in the direction of reducing the overall energy needs. The innovative greenhouse has been finally realized at the Regional Agricultural Research Center (Cersaa) located in Albenga (SV). The primary objective of the research was to define solutions for energy efficiency improvement in agriculture and to contribute to the dissemination of methodologies and best practices for the greenhouse sector, even on a large scale and in different territorial and technological contexts.

The present paper illustrates the results of the study with particular attention to the description of the hourly energy demand simulations model built in E-Plus environment and of the sizing method of the BHE (Borehole Heat Exchangers) field coupled to the geothermal heat pump.

## 2. Numerical dynamic analysis and energy demand hourly simulations: the E-plus model

E-Plus (Energy Plus, U.S. Department of Energy) is a worldwide known open-source software for building hourly energy simulations. The basic input of the model are the meteorological *epw* file containing the hourly data of the site of interest and the model data *idf* file with the details about the geometry, the shell, the selected plant solutions and their control systems.

The analysed greenhouse is located in Albenga, Italy (latitude: 44.3 DD, longitude: 8.47 DD, altitude: 3 m, time fuse: +1 CET) and the meteorological data have been obtained from Meteonorm code.

The greenhouse structure consists in a rectangular aluminum frame with pitched roof. The plan dimensions are 15.3 and 9.9 meters, the eave height is 3.50 m while the roof top height is 5.60 m. The material selected for the greenhouse glazed walls is the low emissivity K-glass type N with a thickness of 4 mm, overall heat transfer coefficient 3.3 W/m<sup>2</sup>K, normal emissivity equal to 0.05 and a solar gain (g-value) of 71%.

The air conditioning system of the greenhouse provides shadings applied to the glazing surfaces, natural ventilation by controlled opening windows, forced convection of external air and forced convection of air treated by HVAC unit (reversible heat pumps) for both heating and cooling purposes.

In the model the control of each element of the air conditioning system is realized by means of different Objects available in E-Plus (i.e. *Schedules*) with suitable temporal profiles (monthly, daily, hourly or sub-hourly) or on/off specific set points.

The shading is implemented in the model by means of the object *Window Property: Shading Control* that specifies the type, location and controls. The temperature setpoint that triggers the shading is 24°C for the internal air temperature in the greenhouse, for both winter and summer operating mode.

The controlled natural ventilation operates during both winter and summer and it is modeled by means of two different object: the *Zone Infiltration: Design Flow Rate* and the *Zone Ventilation: Wind and Stack Open Area*. Zone infiltration is specified as a design incoming air rate that is modified by temperature difference and wind speed values. This flow rate also fulfils the minimal air change per hour according to a defined time schedule (0.25 during working period, 0.15 during night and holidays). Zone ventilation represents the natural ventilation of external air driven again by wind and stack effects, only when related window openings are activated by their control. The apertures are located near the ground and at the roof top of the greenhouse. The windows opening is triggered by the internal air temperature of the greenhouse and they allow air circulation when this temperature is higher than 24°C during summer or 26°C during winter. An additional control is related to the minimum external temperature at which the natural ventilation starts: external air temperature has to be higher than 16°C and the wind speed lower than 10 m/s.

The forced convection of external air and the forced convection of air treated by HVAC system (heating and cooling) are all modeled by means of the combination of the objects *HVAC Template/Thermostat*, *HVAC Template/Zone/Ideal Loads Air System*, *Design Specification/Outdoor Air*. In particular, the use of external air is driven by particular settings chosen in the field *Outdoor Air Economized Type* that increases the outdoor air flow rate when a cooling load is requested and the outdoor air temperature is lower than the zone (indoor) exhaust air temperature. To cope with heating or cooling loads, the greenhouse inlet air is pre-treated by the HVAC ideal air system object in order to fulfil the following set-points: the temperature of internal greenhouse air must be not higher than 30°C during summer (cooling mode) and not lower than 16°C during winter (heating mode).

Finally the HVAC system is coupled to a Ground Coupled Heat Pump (GCHP) with vertical ground heat exchangers (BHE field). The ground side of the air conditioning system is simulated and designed according to models developed at the University of Genova.

A very significant contribution in greenhouse energy balance is given by the crop evapotranspiration process. To Authors' knowledge no study related to energy consumption in greenhouses considered this particular contribution for evaluating the greenhouse hourly thermal loads (Fabrizio [12]).

### 3. Evapotranspiration: the model FAO Penman-Monteith

The evapotranspiration consists in the process of transpiration of liquid water through the leaves and underleaf soil. This water contribution to the greenhouse volume is associated with evaporation and hence with a significant latent heat contribution in the energy balance of the greenhouse control volume.

In this study, the FAO Penman-Monteith model is considered in order to evaluate the hourly reference standard evapotranspiration  $ET_0$  from the greenhouse surface occupied by plants. The real evapotranspiration can be estimated by introducing the effect of the crop by the crop coefficient  $K_c$ .

The FAO main correlation is the following one:

$$ET_0 = \frac{0.408 \left( \frac{dp}{dT} \right)_{sat} (G_n - G_g) + \gamma \frac{37}{T + 273} w (p_{sat, T_{hr}} - p_v)}{\left( \frac{dp}{dT} \right)_{sat} + \gamma (1 + 0.34 w)} \quad (1)$$

$ET_0$  standard evapotranspiration [mm/h]

$\left( \frac{dp}{dT} \right)_{sat}$  slope of the saturation curve of vapor [kPa/K]

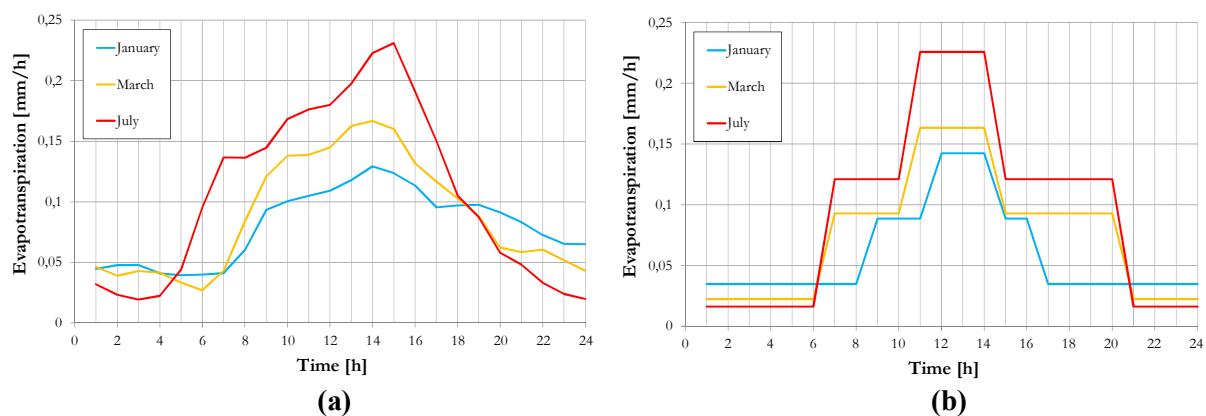
$G_n$	net irradiation on the vegetation [MJ/(m <sup>2</sup> h)]
$G_g$	net irradiation on the ground [MJ/(m <sup>2</sup> h)]
$\gamma$	psychrometric constant [kPa/K]
$w$	hourly mean wind speed [m/s]
$p_{sat,Thr}$	saturation pressure at hourly mean air temperature $T_{hr}$ [kPa]
$p_v$	hourly mean vapor partial pressure [kPa]

The above model has been conceived for estimating the watering needs of outdoor cultivations and it has been here adapted to the greenhouse conditions by referring to the indoor conditions in terms of temperature, humidity and radiation conditions. In particular, the correlation is employed according to the assumptions here below:

- *solar irradiation*: reduced value (with respect to outdoor conditions) of about 30% to take into account the transmissivity of the glazed surfaces of the greenhouse;
- *air temperature*: is iteratively adjusted from E-plus simulations, starting from an initial condition when no evapotranspiration is present;
- *air humidity*: the first guess value is obtained by the starting simulation in E-Plus with no water gain due to evapotranspiration and then the value is adjusted according to the next iterative simulations of combined Penman-Monteith and E-plus models;
- *wind speed*: a minimum value is assigned (0.6 m/s);
- *rain*: no rain;
- *overcast index*: conversion of the meteorological data (clear sky 0, cloudy sky 10) into the Penman-Monteith scale (clear sky 1, cloudy sky 10).

The Penman-Monteith model is implemented in the E-plus model using the object *Water Use Equipment*, which is a generic object for simulating all water end uses and their evaporation fractions into the zone. The mass flow rate of water into the greenhouse is not constant but it follows the variable evapotranspiration activity of the vegetation as described by the Penman-Monteith model. In particular, the evapotranspiration is greatly influenced by the irradiation and it presents a periodical trend during the cycle day-night and according to the seasonal variation of irradiation during the year (figure 1a).

The hourly values of evapotranspiration have been converted into a three-step daily profile (one profile for each month of the year) in order to be easily managed in a suitable Schedule of the E-plus model (figure 1b). For each daily profile, the first step represents the minimal value of evapotranspiration over the night periods and it is calculated as the monthly average of the minimum daily evapotranspiration value among all days of the month under consideration. The higher step represents the maximum value of evapotranspiration corresponding to the hours with the maximum of solar irradiation and it is estimated as the monthly average value of the maximum daily evapotranspiration among all days of that month. The intermediate step characterizes the remaining daily hours and it is calculated as an average between the two previous values.



**Figure 1.** Hourly evapotranspiration values for a representative day of the analysed month, (a) obtained with the Penman-Monteith model and (b) the converted three-step average daily profile.

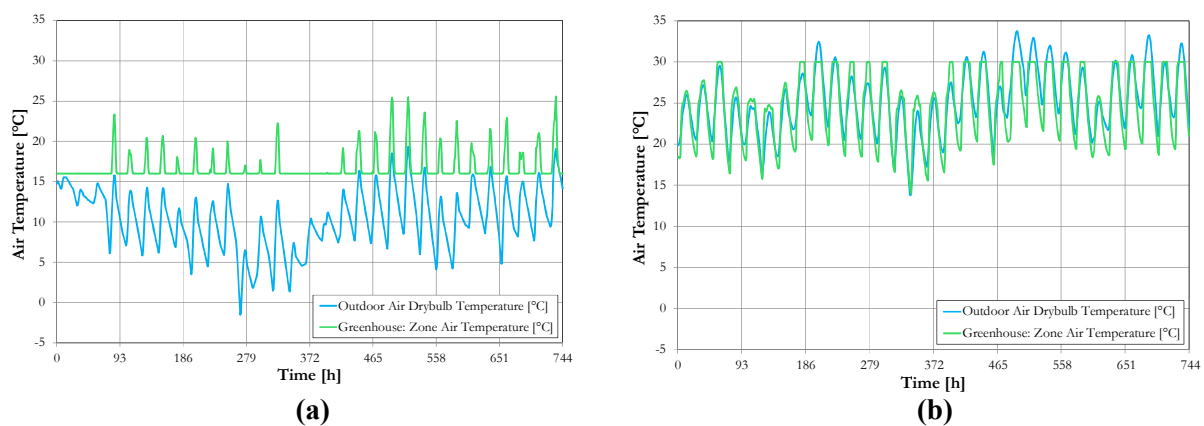
#### 4. Results: the hourly thermal loads

The software E-plus allows to select as hourly output a lot of different parameters.

Among them, the most interesting quantities related to the specific site where the building is built are the *Site Outdoor Air Drybulb Temperature* [°C], the *Site Outdoor Air Relative Humidity* [%] and the *Site Wind Speed* [m/s].

The quantities that evidence the attainment of the design conditions for the zone of interest of the building (in our case a single zone, the greenhouse) are the *Zone Air Temperature* [°C], the *Zone Air Humidity Ratio* [-] and the *Zone Air Relative Humidity* [%].

Figure 2 reports the outdoor and zone temperatures hourly profiles from E-Plus simulations for the month of January and July, respectively. The zone temperatures perfectly fulfil the requested set-points of minimal temperature equal to 16°C during winter and maximal temperature equal to 30°C during summer.



**Figure 2.** External and indoor (Zone) temperatures profiles from E-Plus simulations for the month of January (a) and July (b).

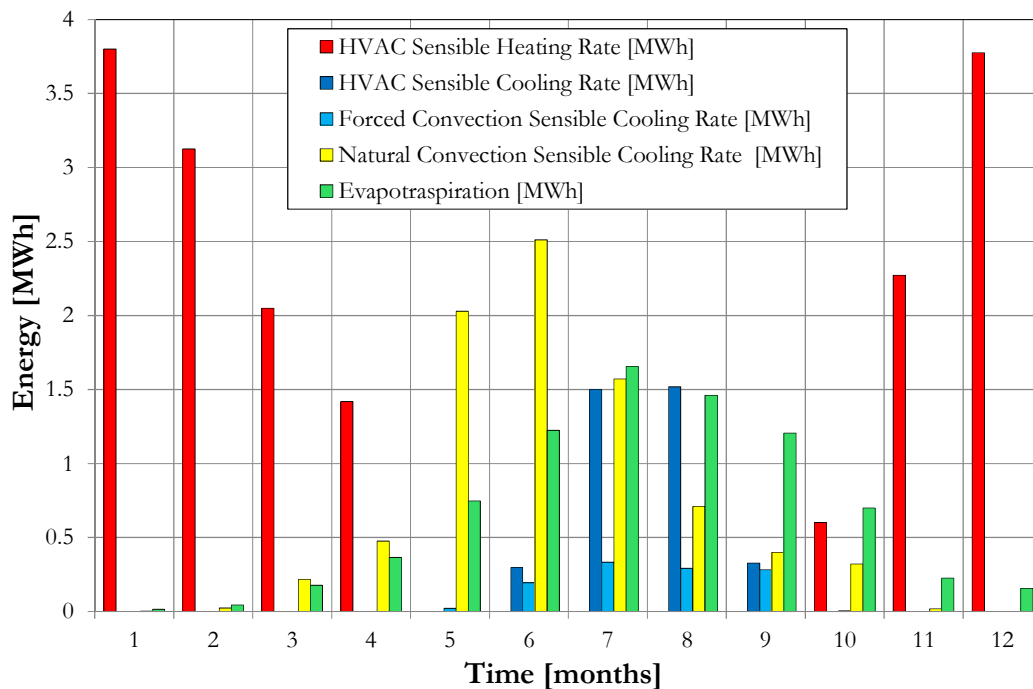
The main outputs of the objects *Zone Infiltration: Design Flow Rate* and *Zone Ventilation: Wind and Stack Open Area* are the *Zone Infiltration Air Change Rate* [ach] and the *Zone Ventilation Air Change Rate* [ach], respectively. From these outputs one can calculate the Natural Convection Sensible Cooling Rate [MWh] (see table 1 and figure 3).

The more relevant outputs of the object *Water Use Equipment*, strictly linked to the effect of evapotranspiration on hourly thermal loads (latent contribution), are the *Water Use Equipment Total Mass Flow Rate* [kg/s], the *Water Use Equipment Zone Latent Gain Rate* [W] and the *Water Use Equipment Zone Moisture Gain Mass Flow Rate* [kg/s]. From these outputs one deduces the Evapotranspiration heat load [MWh] (see table 1 and figure 3).

The sensible loads for both heating and cooling are distinguished between the loads directly provided by the HVAC system (Supply Air) and those entirely delivered to the zone (Zone). The differences between these two different loads, meaningful only in cooling, represent the contribution of the *Outdoor Air Economized*, i.e. the forced convection of external air. In detail, the significant outputs are the *Zone Ideal Loads Supply Air Sensible Heating Rate* [W], the *Zone Ideal Loads Supply Air Sensible Cooling Rate* [W], the *Zone Ideal Loads Zone Sensible Heating Rate* [W] and the *Zone Ideal Loads Zone Sensible Cooling Rate* [W]. From these outputs one can infer the HVAC Sensible Heating and Cooling Rate [MWh] and the Forced Convection Sensible Cooling Rate [MWh] (see table 1 and figure 3).

**Table 1.** Energy contribution [MWh] of different elements of the air conditioning system.

Months	HVAC Sensible Heating Rate [MWh]	HVAC Sensible Cooling Rate [MWh]	Forced Convection Sensible Cooling Rate [MWh]	Natural Convection Sensible Cooling Rate [MWh]	Evapotranspiration [MWh]
1	3.8004	0	0	0.0024	0.0151
2	3.1254	0	0	0.0247	0.0439
3	2.0493	0	0.0011	0.2176	0.1769
4	1.4183	0	0	0.4751	0.3653
5	0	0.0004	0.0216	2.0287	0.7480
6	0	0.2971	0.1946	2.5111	1.2237
7	0	1.5003	0.3335	1.5708	1.6563
8	0	1.5181	0.2927	0.7096	1.4616
9	0	0.3289	0.2822	0.3994	1.2052
10	0.6016	0	0.0058	0.3206	0.6997
11	2.2714	0	0	0.0194	0.2268
12	3.7744	0	0	0	0.1557

**Figure 3.** Energy contribution [MWh] of different processes involved in the greenhouse.

From the analysis of table 1 and figure 3 one can deduce the following outcomes.

During the heating season (winter months), the main load is obviously the sensible heating by the HVAC system, coupled with a feeble evapotranspiration activity. However, during the months of March, April and October, a weak cooling, obtained through natural convection, is required during the days with high outdoor temperature and great solar irradiation.

On the contrary, during the cooling season the air conditioning system starts with the natural ventilation, eventually integrated with forced convection of external air. When these actions are not enough or the temperature of the outdoor air become too high and so unfavorable, the system closes the windows and turns on the forced convection of air treated by the HVAC plant.

Finally, the evapotranspiration activity, greatly influenced by the solar irradiation, presents a trend that follows the seasonal variation of irradiation during the year, with a maximum during the month of

June. Furthermore, the evapotranspiration significantly contributes to the refrigeration of the greenhouse and it allows to reduce of energy consumption during the cooling season.

## 5. Design of the borehole field for geothermal heat pump installation

The exploitation of low enthalpy geothermal resources for air-conditioning represents an important opportunity to reduce the energy consumption and gas emissions even in the air conditioning greenhouse sector. Ground coupled heat pumps (GCHPs) exploit the favourable temperatures of the shallow ground in order to allow high COPs to be obtained. Moreover, in the greenhouse applications the heat pump performance is further enhanced due to the low target temperatures to be pursued at the HP condenser side and to the high target temperatures to be pursued at the evaporator side during the cooling period. In fact, in the current model, the internal greenhouse temperatures to be maintained are 16°C and 30°C during winter and summer, respectively.

Geothermal heat pumps are generally coupled with borehole heat exchangers (BHEs) that play a key role in determining heat pump performance. The borefield design goal is the definition of the best BHE geometry (BHE arrangement, their number and spacing) and the minimum overall length of vertical pipes in order to obtain suitable carrier fluid temperatures from the BHE field able to realize the target seasonal heat pump performance.

Different design criteria are available and all of them rely on a dynamic approach based on the knowledge of the building heat request in time. The simplest and widely employed design method for BHE fields has been developed by Kavanaugh and Rafferty [13], recommended by ASHRAE, and it accounts for three basic heat pulses over 10 years of operations. Monthly time step methods (e.g. EED, Hellström and Sanner [14]) use monthly average heat loads and peak heat loads to model both heating and cooling operations. They are based on the temperature response factor theory (*g*-functions) first introduced by Eskilson [15]. Finally, best analyses are those performed on an hourly time scale: they make use of hourly heat load series to perform a temporal superposition scheme (Bernier et al. [16], Fossa and Paietta [17]).

In the present investigation, the E-plus output data are employed as input for GCHP simulations where the inverse machine COP is iteratively calculated as a function of the variable carrier fluid temperature which in turn depends on the variable temperature of the ground volume surrounding the BHE field.

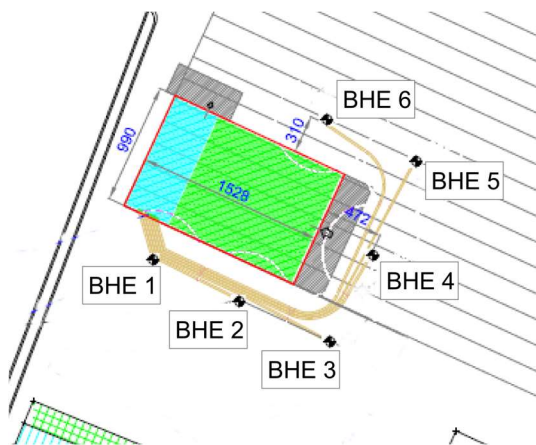
The selected BHE type is a double-U PE100 pipe with external diameter of 32 mm and length of about 100 m. The perforation is filled by grout with nominal thermal conductivity equal to 1.8 W/m K.

The thermal conductivity of the ground has been evaluated according to the new method of enhanced Thermal Response Test described in [18]. It resulted from measurements equal to about 5 W/m K, a very high value, related to the presence of relevant groundwater movements.

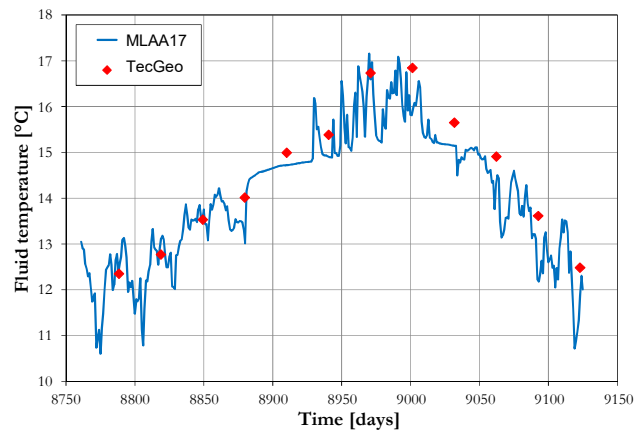
The required length of the BHE field is calculated according to three procedures, namely an hourly and 2 monthly time step calculations that include the use of the EED software (Earth Energy Designer) [14], probably the most widely used design tool for vertical borefield design for GCHP applications. Proprietary code TecGeo (Dalla Pietà and Fossa [19]) is employed to perform monthly simulations with reference to a custom BHE configuration made by 6 BHE arranged in a non-regular U-disposition (see figure 4). Finally the proprietary code MLAA17 [17], which represents a modified version of the Canadian algorithm MLAA [16], is employed for hourly simulations starting from complete E-plus information on greenhouse heating and cooling requirement during the year. The hourly simulation allows the Seasonal Performance Factor (SPF or average COP) to be evaluated and it results, for the given HP taken into consideration, equal to about 5.5. EED is employed to validate and check hourly results and the agreement is very good.

All the simulations are carried out along 25 years. The two different approaches (monthly average, i.e. TecGeo, and hourly, i.e. MLAA17) are in close agreement and both able to describe the time varying behaviour of the ground heat exchanger system when responding to the building heat demand as calculated from E-plus simulations. Figure 5 shows the results of a double simulation made by proprietary codes developed at the University of Genova: the hourly values of the fluid temperature obtained by means of MLAA17 seem in very good agreement with the monthly average values calculated using TecGeo.





**Figure 4.** Greenhouse and BHE field layout.



**Figure 5.** Fluid temperatures from simulations made (25th year) by proprietary codes developed at the University of Genoa, MLAA17 and TecGeo.

## 6. Conclusions

The paper describes the results obtained in the framework of a Liguria Region research program “Smart Agro-Manufacturing Laboratory (SAM-LAB)”. The main goal of the project is to analyse and select air conditioning plant solutions (if possible combined with renewable energies) aimed at improving the energy efficiency in agriculture facilities.

The first part of the study consists in an hourly energy demand simulation of the greenhouse by means of the open-source software Energy Plus (E-plus). The air conditioning system selected for the greenhouse prototype combines shadings applied to the glazing surfaces, natural ventilation through controlled opening windows, forced convection of external air and forced convection of air treated by HVAC unit (reversible heat pumps) for both heating and cooling purposes. In the energy balance of the greenhouse also the crop evapotranspiration is considered as latent heat contribution, and this aspect represents an original contribution of this Research.

From the analysis of the hourly heat loads obtained as outputs of E-plus simulations one can deduce that, during the heating season, the main load is obviously the sensible heating by the HVAC system, coupled with a feeble evapotranspiration activity. During the transitional months (March, April and October) a weak cooling, obtained through the natural convection, is required during the days with high outdoor temperature and great solar irradiation. During the cooling season the system achieves the requested indoor conditions by means of the natural ventilation at the beginning, integrating it with the forced convection of external air or with the forced convection of air treated by the HVAC plant, if necessary.

Finally, the crop evapotranspiration is greatly influenced by the solar irradiation and it presents a trend following its seasonal variation during the year, with a maximum during the month of June. Therefore, the evapotranspiration significantly contributes to the cooling of the greenhouse with a reducing of energy consumption during summer.

The heating and cooling HVAC system couples a reversible heat pump with a borehole heat exchangers (BHEs) field, representing an innovative plant solution when applied to a greenhouse.

To design the Ground Coupled Heat Pump (CGHP), three different design methods are used. Two of them are based on average monthly heat loads combined with seasonal peak (namely EED and TecGeo, the second being a proprietary software developed at Dime, University of Genoa). On the contrary, the third approach uses directly the E-plus hourly heat loads (MLAA17, a proprietary code that represents a modified version of the Canadian algorithm MLAA).

The comparison between results obtained using the different methods reveals a very good agreement and the selected BHE field geometry is composed by 6 BHEs of about 100 m length, arranged in a non-regular U-disposition.

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