Research Article

Energy Efficiency of a Greenhouse for the Conservation of Forestry Biodiversity

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Forest biodiversity conservation is one of the most interesting and crucial problems in forestry world. Currently, the conservation methods are based on two phases: the conservation of seeds at low temperatures and the multiplication of vegetable material. This latter operation can be successfully developed in properly designed greenhouses. The aim of this paper is to define a type of greenhouse which is particularly suitable for plant material propagation in order to preserve forest biodiversity in the area of the Central Italy. Some general parameters were first defined for a correct planning of the structure, such as: the shape of the section, volume, cover material, systems for heating and cooling, and those for the control of the internal microclimate parameters (light, air temperature, and relative humidity). Considering the construction characteristics and the climatic conditions of the place, the internal microclimatic conditions have been later determined by the useful implementation in TRNSYS in order to analyse the energy efficiency of the greenhouse.

1. Introduction

Greenhouses crops in Italy are made by using prefabricated structures, leaving out the preliminary study of optical and thermal exchanges between the external environment and the greenhouse, dealing with heating and cooling and the effects of air conditioning needed for plant growth [1].

The design and implementation of greenhouses is done without the study of energy exchanges between the external environment inside the greenhouse. Climatic conditions are evaluated only on the plant species planted without verifying the construction parameters of the greenhouse or efficiency of air conditioning systems [2].

As a result of human actions many forest species have become extinct and many more are at risk of extinction. To oppose this loss of forest biodiversity one of the operations most widely used—especially in those areas where the climatic conditions are not optimal—is the multiplication of plant material.

Conservation strategies currently used are in situ and ex situ [3].

The in situ technique requires that the species are preserved in their natural environment, encouraging natural regeneration of wild species or acting through artificial regeneration from seed or transplant in the same area where the seed was taken [3, 4].

On the contrary, ex situ conservation takes place outside the natural habitat and is practiced where risk of species' extinction occurs because of events difficult to control, such as climate change or natural disasters [5]. This practice necessarily requires human intervention for collection, storage, and reproduction of different vegetative materials.

The production process of plants is an important step for the conservation of forest species; the seeds are put down in the most suitable conditions in order to promote germination and to protect young plants against biotic and abiotic agents. These conditions can be obtained in greenhouses where it is possible to control solar radiation, temperature, and relative

humidity of the air and to adapt these parameters to the specific needs of various plant species [6, 7].

Greenhouse cover, structural elements, soil, and crop contribute to the solar radiation absorption, and consequently, to the generation of sensible or latent heat [8].

Inside a greenhouse are many interactions that can occur between crop species, climate conditions, and design characteristics of the greenhouse itself. During the design phase, it is necessary to verify the climatic conditions that are found inside the greenhouse as a function of climate zone in which they are installed. This verification is required to ensure a correct design of the greenhouse and also a reduction in energy consumption.

Approximately 20–30% of the greenhouse on the Italian territory are equipped with heating and cooling. Has been calculated that the energy consumption on the conditioning of greenhouses is about 140,000 TOE (tons of oil equivalent), approximately 90–95% of global energy demand for the production [9].

From these data it is essential to a detailed study of the energy consumption of the greenhouse. This can be done through the use of TRNSYS 17 dynamic simulator that allows you to verify the energy consumption related to the cultivation of a particular plant species and therefore allows you to change the design of the greenhouse.

The aim of this paper is to identify the most suitable type of greenhouse for the multiplication of plant material in order to preserve forest biodiversity in relation to the specific needs of forest species and climatic conditions in Central Italy. In particular, in this study we created a greenhouse model which allows to check, with TRNSYS, correct climatic conditions inside and the energy consumption related to the cultivation of forest species.

2. Materials and Methods

The study was carried out with considering the type “multi-span greenhouse” and located in Central Italy.

After the definition of construction parameters, equipments and climatic conditions of the site, microclimatic conditions inside the greenhouse were determined by simulation software TRNSYS 17. As regards the determination of the thermal needs of each species forestry, the phytoclimatic classification of Pavari was considered: according to it, the Italian territory is divided into five climatic zones, characterized by a Latin name—*Lauretum*, *Castanetum*, *Fagetum*, *Picetum* e *Alpinetum*—and by an altitudinal and thermal interval. The Latin name refers to the cenosis or species, wild or cultivated by man, which characterizes that specific area [10].

2.1. Greenhouse Structural Description. Considering the large size of forest species, the type “multispan greenhouse”—with high height to eaves—was chosen (Figures 1 and 2).

The main dimensional characteristics are the following: length 100 m, width 12.25 m, height to eaves 4.5 m, ridge height 6 m, slope of the roof pitches 22° (slope = 40%), and orientation with the long axis north-south. The cover material

FIGURE 1: Steel and glass greenhouse: SECTION.

FIGURE 2: Steel and glass greenhouse: AXONOMETRIC VIEW.

is glass since it is the best material for the greenhouse effect and is strong and durable over time.

In order to allow the multiplication of forest species with very different microclimatic needs, particular attention has been paid to the monitoring and control of the inside microclimate.

Greenhouse is equipped with a system of artificial heating to provide energy in winter. Nevertheless, it is more important, in Central Italy, to contain the excess energy in summer because most forest species are sensitive to high temperatures.

Cooling is ensured by natural and mechanical ventilation. The greenhouse is equipped with large openings on the slopes and on the longitudinal walls and axial ventilators placed at the head of it.

The greenhouse is equipped by a system for automatic regulation and control whose aim is to ensure a correct management of the microclimatic conditions. More precisely, it consists of a series of sensors that detect microclimatic internal and external parameters, and of a control unit that processes the data and transmits the changes to the control system.

2.2. Greenhouse Model. The thermal behavior of the greenhouses was studied using dynamic thermal simulation tool, TRNSYS 17. A model, which includes all greenhouse influential variables on microclimate, has been created.

This model includes

- (i) detailed design of structures,
- (ii) optimizing resources, and
- (iii) verification of climatic parameters in greenhouse.

The simulation of climate parameters of the greenhouse is carried out with a model that calculates the thermal exchanges in nonstationary conditions [11]. Depending on the parameter, one can highlight energy waste and improve the design of the greenhouse. The created model can be applied in any type of greenhouse changing design parameters in the TYPE 56.

The model was built using the simulation program TRNSYS Studio. The first step concerns the construction of a building multizone, which is divided into multiple steps in which the user enters the data relating to the building and its location in space [12]. TRNSYS provides a daily evaluation on the air conditioning system in the greenhouse in response to the climatic conditions of the area in which greenhouse is located.

The climatic parameters affecting the growth of greenhouse plants are [13]

- (i) radiation entering the greenhouse in the ultraviolet band (290 to 380 nm), visible (380 to 760 nm) and near infrared (760–3000 nm),
- (ii) air, soil and plants temperature,
- (iii) air humidity, and
- (iv) air composition (particularly the concentration of CO_2).

Solar radiation inside the greenhouse is less than the outer coating material which reflects and absorbs solar radiation; one also needs a ventilation system that ensures the air movement between the plants and facilitates the transpiration; the lower is the air movement, and the smaller is the concentration gradient of CO_2 .

It is necessary to assess the detailed exchange of energy between internal and external part to have accurate values of climatic parameters in the greenhouse and to study the temperatures that influence the thermal freight exchange [14–17]:

- (i) air temperature,
- (ii) soil temperature (or substrate for soilless),
- (iii) plants temperature, and
- (iv) temperature of the greenhouse cover.

In order to calculate the heat balance in emissions, it is fundamental to examine the individual energy input (Figure 3).

Energy balance equation:

$$R_i + R_{ac} = RT_{g,sky} + RT_{g,atm} + RT_{p,sky} + RT_{p,atm} + RT_{c,sky} + RT_{c,atm} + T_c + V + \Delta E_g + S_g, \quad (1)$$

where

$$T = KS(T_i - T_e), \quad (2)$$

K is thermal transmittance ($\text{W m}^{-2} \text{K}^{-1}$); S is wall surface (m^2); T_i is internal temperature ($^{\circ}\text{C}$); and T_e is external temperature ($^{\circ}\text{C}$).

$$E_v = V(H_i - H_e), \quad (3)$$

E_v = energy lost for ventilation (KJ h^{-1}); V = flow rate of ventilation (Kg DryAir h^{-1}); H_i = internal air enthalpy (KJ Kg DryAir^{-1}); H_e = external air enthalpy (KJ Kg DryAir^{-1}).

The enthalpy H (KJ Kg DryAir^{-1}) of a Kg of air, at temperature t ($^{\circ}\text{C}$) and with a water content, in the form of water, equal to x (Kg Kg DryAir^{-1}) is obtained from

$$H = 1.005t + x(2499.5 + 2.005t), \quad (4)$$

x (Kg Kg DryAir^{-1}) represents the water vapor contained in the air and can be determined through the psychrometric diagram or with the following formula:

$$x = 0.6215 \frac{P_{\text{H}_2\text{O}}}{P - P_{\text{H}_2\text{O}}}, \quad (5)$$

$P = 1.013$ (Kg cm^{-2}) atmospheric pressure; $P_{\text{H}_2\text{O}}$ = vapor pressure of the air, expressed in Kg cm^{-2} at the temperature T (K) and at relative humidity UR (%);

$$P_{\text{H}_2\text{O}} = 1.41 \times 10^{10} e^{(-3928.5/(T-41.5))} \times \text{UR}, (\text{Pa}), \quad (6)$$

$$RT_{12} = \sum_{\lambda=2.5\mu\text{m}}^{\lambda=20\mu\text{m}} \varepsilon_{12}(\lambda) \times \tau_a(\lambda) \times \frac{C_1}{\lambda^5} \times \left[\frac{1}{e^{C_2/\lambda \times T_1} - 1} - \frac{1}{e^{C_2/\lambda \times T_2} - 1} \right] \times \Delta\lambda \quad (7)$$

RT_{12} = radiated radiation (W m^{-2}); λ = wavelength (μm); T = absolute temperature (K); $C_1 = 3.74 \cdot 10^8$ ($\text{W } \mu\text{m}^4 \text{ m}^{-2}$); $C_2 = 14385$ ($\text{K } \mu\text{m}$); $\tau_a(\lambda)$ = transmittance of the atmosphere at the wavelength λ ; $\varepsilon_{(\lambda)}$ = monochromatic emissivity of the object at the wavelength λ .

The TRNSYS is commonly used to simulate transient heat transfer for design and control of power systems exploiting renewable energy sources. Another frequent use of software is now on the energy certification for homes, offices, shops, restaurants, and industries. In this sense the present work is an example of using the software for agricultural systems [18]. The structure is a multispans greenhouse with high height to eaves, used as a greenhouse for growing flowers and plants. It is covered with glass cover horizontal beam pattern and small flat foot north-south. The approach of the model was carried out by using the program TRNSYS Simulation Studio. The first step concerns the construction of a building multizone, which is divided into multiple steps in which the user enters the data relating to the building and its location in space [12]. The data required by the software at this stage will be used for the automatic construction of the project and its connections between the components.

During construction of the project there is also the source of meteorological data that will be used in the simulation. This is indeed a link with the Type 109 (Weather Data Processor) and in the present study, the meteorological station of Rome Fiumicino (Airport) was selected. The outline of the project is in (Figure 4), where

FIGURE 3: Heat balance in a greenhouse.

weather date: weather generator
 psychrometrics: processor psychrometric
 sky Temp: CPU temperature sky
 radiation: radiation converter
 greenhouse: Greenhouse (Type 56)
 nat. Vent. 1 and 2: controllers of ventilation
 turn: unit converters
 charts: Online Plotter.

3. Results

3.1. Simulation Results. The purpose of the simulation is to check the temperatures inside the greenhouse related to external climatic parameters and the type of construction of the greenhouse itself. The required energy for optimal climate conditioning is based on such calculation. These values in fact are calculated in order to maintain a steady temperature of 20 degrees which is considered suitable for the cultivation of a wide range of plant species. The results are shown in the chart (Figures 5, 6, 7, 8 and 9):

The solar radiation arrives in the greenhouse and affects the inside temperature. In particular the characteristic constructive of the greenhouse is 97% of the radiation incident, reaches the ground, and increases on the internal temperature (Figure 7).

In Figure 6 the solar radiation inside the greenhouse is compared with the incident one. It can be seen that the low resistance of the structure results to be an advantage in winter, even if energy consumption for cooling is higher.

During cold months the internal radiation is almost equal to the outside, while in summer transmission of solar radiation falls on the most important reflection of the glass. This is due to the increased presence of direct radiation and different angles of incidence.

During the winter months the trend of the indoor temperature is almost identical to that of the external solar radiation and the structure has a low thermal capacity (infiltration losses of 1/h) (Figure 9), where

$T_{\text{Greenhouse}}$: inside room temperature

Q_{Heat} : required heating, the rate at which energy must be supplied to the device in order to heat the air to its outlet temperature, including the effects of losses and conversion inefficiencies.

Q_{Cool} : rate of energy removed with the cooling system.

Moreover, the amount of heat to be provided or removed by heating and cooling was connected to the printer to obtain the annual energy needs for heating and cooling:

$$\begin{aligned}
 Q_{\text{Heat}} &= 1,44E + 23 \text{ kJ h}^{-1}, \\
 Q_{\text{Cool}} &= 2,25E + 23 \text{ kJ h}^{-1}.
 \end{aligned}
 \tag{8}$$

It can be seen that the energy demand for cooling is higher than that for heating [14]. This is due to the latitude where the greenhouse is located, characterized by very rigid winters and hot summers. The technology normally used in greenhouses for cooling, as shown in the chart above, is from an energy point of view very expensive. The graphic represents a

FIGURE 4: Air conditioning system diagram with TRNSYS.

FIGURE 5: Simulation of annual solar radiation inside the greenhouse (W/m^2). FIGURE 6: Simulation of annual solar radiation inside the greenhouse (W/m^2) in blue and external red.

constant value of Q_{Cool} for the period July-August, even if the temperature inside the greenhouse undergoes changes.

An analysis of the chart is highlighting the need to rationalize the climate inside the greenhouse. This can be achieved

- (i) either through the use of a more precise control systems, such as PID;
- (ii) through more sustainable air conditioning systems. The latter using heating and cooling floor system powered by a geothermal heat pump or conventional pump;
- (iii) or improving the greenhouse insulation and ventilation systems.

FIGURE 7: Simulation of annual temperatures.

FIGURE 8: Simulation of annual relative humidity (%).

FIGURE 9: Chart of greenhouse climate simulation.

4. Conclusions

In this research the most suitable type of greenhouse was identified in order to multiply forest plants for biodiversity conservation. It is a multispan greenhouse covered with glass and high height to the eaves. The Energy balance, between the input and output of energy, was carried out for this specific type of greenhouse. This goal was reached by the simulation in TRNSYS and with specific regard to locations in Central Italy. The results obtained in the simulation show the following values for the principal microclimatic parameters:

- (i) solar radiation: 300–600 W/m² in winter months and 600–800 W/m² in summer months;
- (ii) air temperature: 10–20°C in winter months and 20–34°C in summer months;
- (iii) relative humidity: 85–95% in winter months and 75–85% in summer months.

Furthermore, energy needs in winter (heating) and in summer (cooling) were calculated in order to reduce seasonal fluctuations in the air temperature.

These values are compatible with the needs of forest plants included in the range of phytoclimatic *Lauretum* classification of Pavari.

It has to be underlined that the control systems for heating and cooling should be used—to a greater extent—for other forest species.

The greenhouse model created with the TRNSYS allows use for various applications, that is small changes of parameters allow you to use it for the simulation of different tree species and climatic zones. Turns out to be an important tool for the design of greenhouses. The model created ensures, in fact, a sustainable building, from the point of view of energy, while minimizing energy consumption.

Thanks to a prior verification of heat exchanges achievable between the inside and the outside of the greenhouse is possible to intervene in the construction phase through the modification of the constructive aspects.

Nomenclature

Alphabetic Symbols

- R : Global solar radiation [MJ m⁻² d⁻¹]
 RT : Energy lost by radiation [MJ m⁻² d⁻¹]
 C : Energy exchanged by convection [MJ m⁻² d⁻¹]
 T : Energy lost by transmission [MJ m⁻² d⁻¹]
 V : Energy lost by ventilation [MJ m⁻² d⁻¹]
 TR : Plant transpiration [MJ m⁻² d⁻¹]
 S : Energy transferred by conduction in the deep layers [MJ m⁻² d⁻¹]
 E : Thermal storage [MJ m⁻² d⁻¹].

Subscripts

- e: External
re: Reflected external
ac: Absorbed by the cover
i: Internal
ri: Reflected internal
ap: Absorbed by the plants
rg: Reflected from the ground
ag: Absorbed by the ground
c: Cover film
p: Plants
G: Ground
ia: Indoor air
oa: Outdoor air
atm: Atmosphere
sky: Vault of heaven.

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