Energetic and Ergonomic Aspects in the Photovoltaic Greenhouses

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Abstract
Crops in greenhouses in Italy are made using prefabricated structures, leaving out the preliminary study of optical and thermal exchanges between the external environment and the greenhouse, speaking with heating and cooling for the effects of air conditioning needed for plant growth. This involves operating costs rather significant that directed the interest of designers, builders farmers and to seek constructive solutions to optimize the system such emissions.
Were analyzed aspects of the structural components and their thermal and optical properties to achieve a representation of reality, as well as the microclimatic parameters. In order to estimate the risk for workers, the air temperature, radiative temperature, and air speed were measured using instruments in conformity with ISO 7726.
A model was constructed considering an example of a prefabricated greenhouse located in central Italy and devoted to the nursery: the model provides to simulate electricity production, internal lightness and microclimatic parameters. The data show how the risk of a hot microclimate for the workers (defined with the PHS index) must not be underestimated.

Keywords: renewable energy, heat exchange, microclimate

Introduction

Aim of this study is to test the response of the software TRNSYS simulation of climate parameters in a greenhouse. We want to create a template:
- detailed design of structures,
- to optimize resources,
- to verify the use of new energy systems to agricultural activities.

To simulate the greenhouse have been proposed several studies to obtain values forecasts or simulations of influential variables for protected crops, such as ventilation (Fernandez and Bailey, 1992), the water temperature for hydroponic systems (Zhua, and Deltourb Wang, 1997), the control of CO_2 for Carbon fertilization (Linker, Seginer and Gutman, 1998), the moisture budget (Jolliet, 1994), climate control (Occhipinti and Nunnari, 1996) and heat exchange (Beccali, Giaccone and Panno, 1992). Recently, the thermal behavior of the greenhouses was studied using dynamic thermal simulation tool TRNSYS 15.1. (Pavlou, Sfakianaki, 2007).

Due to the actual strain of researching optimal solutions for the use of resources, is important to create a model that includes all variable influential on greenhouse microclimate. Values of climatic parameters representative of reality are obtained taking an existent photovoltaic greenhouse as reference and creating a simulation project with TRNSYS 16 software.

Another aim of the research is to assess the risk for workers due to microclimate conditions.

Materials and methods

Photovoltaic greenhouse

The photovoltaic greenhouse in this study is located in Rome. It was designed and built through cooperation between Artigianfer and Isofotòn. It has been tested and connected to the grid by engineers Isofoton in May 2009. It consists of a 246.16 kWp photovoltaic system that receives a fee of 0.43 €/kWh for the full architectural integration instead of glass on flap south.

The system consists of 1456 high efficiency modules Isofoton IS-170/24 transparent laminates, unframed, allowing full integration in place of windows. The distance between cells, studied in the design stage, allows the passage of light making possible the operation of nursery underlying coverage. Under the cover are positioned 36 inverter SMA Sunny Mini Central 7000 TL, placed on metal structures to improve the visual impact.

Greenhouse structural description

The greenhouse considered is an Artigianfer type STO construction with steel structure prefabricated, used as a greenhouse for growing flowers and plants. It is covered with glass cover horizontal beam pattern and small flaps with north-south orientation.

Has a width of 25.60 m divided into two spans of 12.80 m. It is 150.107 m long and is divided into 39 sections ranging from 4.035 m. the eaves height is 4.60 m. In terms of structural elements, the greenhouse has cross doors.

Symmetric and transverse frames are stuck at the bottom and top. They are made with tubular columns 120x80x3 mm Fe 360 and horizontal beams lattice currents 80x40x3 mm Fe 430 tubular rods and rod wall. The roof rafters are made from the water canal collector and of pressed sheet metal. The side purlins are made of C-sections from 90x50x1.8 mm made of cool folded sheet. The glazing consists of rods 12 and 14 mm for roofs and walls. The calculation was performed in accordance with the requirements of the UNI-EN 13031-1 for greenhouses with metal structure. The maximum unit stress for steel Fe 360 of 1,600 kg/cm^2 for the first load cases and 1,800 kg/cm^2 for the other; for steel Fe 430 are of 1,900 kg/cm^2 for the first load cases and 2,135 kg/cm^2 for the other. These have a corrosion protection due to the galvanizing bath.

The greenhouse consists of 8 very narrow aisles, each of 3.2 m, characterized by two sloping roof pitches of 22° degrees (40%) and exposed north-south. On south-facing slopes are placed photovoltaic modules, glass is used wholly within the aquifer north. The PV panels near the front side were not fitted for plates of tempered glass for a very specific reason: the force of the wind may be pushing on the end of the greenhouse and could blow up the last panels. For the high cost of a PV module, it seemed appropriate don't install in these areas to avoid the risk of rupture of the modules.

Table 1. Structural specifications

Span width	12.80 m
Span length	150.107 m
Aisle width	3.20 m
Eaves height	4.60 m
Step columns	4.035 m
Ventilation Doors	2.00 m
Between pitch	40% (22°)
Doors	width m 2.50, height m 3.00

The greenhouse is equipped with continuous full-stop in the north stratum (the glass) driven by motors with rack system if the temperature inside the greenhouse exceed a given temperature. This automated system therefore depends on measurement of a temperature sensor located near the slopes. Outside the building is also home to a wind instrument in the case of strong wind forces the system to automatically reclose.

Photovoltaic modules

The PV modules produced by Isofoton, are made with pseudoquadrate monocrystalline silicon cells high efficiency for energy conversion of solar radiation into DC electricity.

The cell circuit is laminated using EVA (Ethylenevinylacetate) as encapsulating a complex of tempered glass on the front and a plastic polymer (TEDLAR) on the back, resistant to environmental agents and provided with electrical insulation.

The variation of electrical modules, depending on the temperature is as follows:

- the voltage decreases at a rate of 2.22 mV / ºC for each cell in series containing the module and for every degree above 25 ºC;
- the current increases at a rate of 17 $\mu A/cm^2$ • ºC area of the cells in parallel and for every degree above 25 °C.

It must be said that the cabinet temperature referred, does not coincide with the temperature, since the cell is heated as a result of sunlight incident. The increase in temperature of the cell, in relation to air temperature, is the characteristics of that building and that of the module.

Depending on the incident radiation, temperature and position of power, a photovoltaic module can operate with different values of voltage and current.

Table 2. Design features

Cell type	Monocrystalline, textured, anti-reflective layer
Dimensions	125 mm x 125 mm
Number of cells per module	72 cells in series
Structure	1) Tempered glass and microstructured high transmissibility 2) Cells laminated with EVA (ethyl-vinyl acetate) 3) Back to back Tedlar / Polyester layers

Table 3. Reference values for system integration

Maximum allowable tension in the system	1,000 V
Reverse current	2 h overloaded to 135% of the maximum security
Upload physical maximum allowable	5,400 Pa
Operating temperature	-40 ºC a 85 ºC
Impact resistance	Hail of 25 mm, 1 m to 23 m/s
Dimensions	1,597 x 800 x 45 mm
Weight	14.6 kg

Table 4. Electrical behaviour at standard conditions and at 800 W/m^2, NOCT, AM 1, 5°

Parameters	Standard	800 W/m^2
Maximum Power	170 W	121.6 W
Open circuit voltage	44.8 V	40.8 V
Voltage at the point of maximum power	36.2 V	32.4 V

Parameters	Standard	800 W/m^2
Short circuit current	5.20 A	4.10 A
Current in maximum power point	4.28 A	3.8 A
Module Efficiency	13.8 %	
Tolerance	± 3 %	± 3 %

Inverter

The efficiency of a PV power plant is directly related to that of his drive. The inverter controls the installation and is therefore a central element in ensuring the energy efficiency.

During the planning commissioners, asked that the 36 inverters installed in the building. This is a fairly high number for this type of PV power plant, for which he usually choose fewer but higher power. This is justified by the fear that the failure or rupture of an inverter lose large amounts of energy, while it would be compromised in this way only one thirty-sixth. The inverter used is the Sunny Mini Central SMC 7000 TL brand SMA (Table 5).

Table 5. Inverter specifications

Input	
Max DC Power	7200 W
Max DC Voltage	700 V
PV-voltage range, MPPT	333 V – 500 V
Input current max	22 A
Number of maximum power point tracker in	1
Maximum number of strings (parallel)	4
Output (AC)	
Rated power AC	7000 W
Max AC Power	7000 W
Output current max	31 A
Rated voltage / range	220 V – 240 V / 180 V – 260 V
Frequency AC (self) / Interval	50 Hz /± 4,5 Hz
Power factor (cos φ)	1
AC connection / power compensation	phase
General Data	
Max Efficiency	98.0 %
EURO-ETA	97.7 %
Dimensions (width x height x depth) in mm	468 /613 / 242
Weight	32 kg
Operational temperature range	–25 °C ... +60°C
Consumption: operating (standby) / night	<10 W / 0,25 W
Typology	transformerless
Cooling technology	OptiCool

Greenhouse modelling

The implementation of the model was carried out by using the program TRNSYS. The model creation was done through the Simulation Studio, starting with the path led to the construction of a "multizone building", which is divided into multiple steps where the user enters the data on the building and its location. After creating a preliminary draft is possible editing the greenhouse description the that those inside the, opening TRNBuild directly from the icon building (Type56) add other components in the project, as the central PV and the inverter.

The greenhouse was modelled using the parameters already described in previous paragraphs, to simulate the heat exchange panels were made of materials not found in libraries provided by the program.

For a correct simulation of humidity inside the greenhouse must consider the input of water due to transpiration of plants. Since the calculation of the transpiration of plants is extremely complex models should be entrusted to a specific Type to run but is not one of those available in the program. To simplify the introduction of these constants of water transpired during the year found in the bibliography. The constancy of these values depends on the type of nursery practice and length of the cycle of the plants.

Upon completion of all changes, the graphical display of the project in Simulation Studio appears in the figure below (Figure 1).

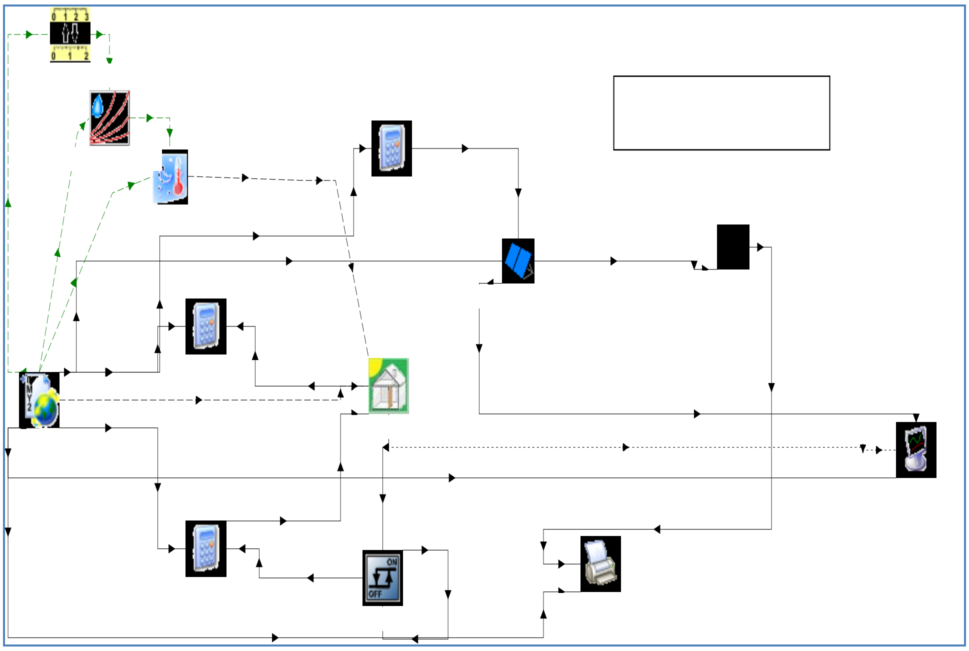

Figure 1. Graphic display of the project in Simulation Studio, where icons represent: Rome: weather data reader; Psychrometrics: psychrometric processor; Sky Temp: CPU sky temperature; Unit change: unit converter; Greenhouse: Greenhouse (Type 56); Nat. Vent.: controllers of natural ventilation; Natural Ventil.: airchanges from natural ventilation; Infiltrations.: airchanges from infiltration; Photovoltaic: photovoltaic array model; Inverter: inverter model; System Printer: data generator; Online Plotter: charts generator.

The PHS method for risk assessment

In order to evaluate the risks for workers operating inside the greenhouse, data such as the air temperature, the average radiative temperature, and the speed of the air were used. These parameters, together with subjective parameters (worker clothing and physical activity) were used to calculate the predicted heat strain (PHS) for the workers in compliance with ISO 7933 (ISO, 2004). European regulation EN ISO 7933 (ISO, 2004) replaces the previous regulation (EN 12515). The new regulation contains a criterion of evaluation of workers' exposure to hot environments that, even though based on references similar to those included in the previous regulation, presents numerous new and different elements. The method has some limitations, in particular the fact that it can only be applied within a defined range of environmental and subjective parameters. Moreover, heart rate is not included in the physiological parameters.

As with all indices that integrate elements of the thermal environment, interpretation of the observed levels of PHS requires careful evaluation of the workers' activity, their clothing, and many other factors, all of which can introduce large errors into any predictions of adverse effects (Budd, 2008).

The PHS method serves to limit duration of work based on two types of risk: (1) core body temperature, and (2) dehydration, due to required sweat loss (Malchaire et al., 2001).

Results

The project carried out with TRNSYS, it allows to extract all variables time-dependent, running simulations for hourly time periods established by the user, from a single hour to one year.

Microclimatic simulations

There were initially simulated climatic parameters inside the greenhouse, with particular reference to the variables that affect plant growth: temperature, humidity, wind speed, solar radiation inside the greenhouse. Were chosen day of the year when temperatures reach the limit values, January 12 for winter and July 20 for the summer. The variables were related to the printer and extrapolated data were processed on Excel and shown in the table below.

Table 6. Microclimatic parameters inside the greenhouse on days considered as resulting from simulations.

hour	air temperature (°C)		relative humidity (%)		air velocity (m/s)		internal radiation (W/m^2)	
	12-gen	20-lug	12-gen	20-lug	12-gen	20-lug	12-gen	20-lug
1	13.53	20.81	59.41	64.45	0.03	0.06	0.00	0.00
2	10.17	21.11	52.26	80.17	0.04	0.06	0.00	0.00
3	11.12	20.69	41.31	87.73	0.05	0.06	0.00	0.00
4	9.80	20.58	41.95	90.14	0.09	0.06	0.00	0.00
5	9.81	20.32	40.72	92.12	0.10	0.04	0.00	0.00
6	9.09	20.52	42.32	91.69	0.11	0.02	0.00	44.20
7	8.80	21.64	43.12	87.92	0.14	0.02	0.00	121.60
8	8.32	23.33	44.72	82.94	0.15	0.02	0.00	221.20
9	8.61	25.17	44.67	78.60	0.13	0.03	44.30	306.30
10	9.41	27.14	44.50	73.13	0.13	0.05	88.20	361.20
11	10.16	28.97	44.94	67.57	0.14	0.07	144.20	421.20
12	10.87	30.66	45.23	62.47	0.12	0.08	170.90	447.80
13	11.62	32.06	45.32	58.35	0.09	0.08	188.90	452.40
14	12.22	33.13	45.60	55.22	0.09	0.07	191.50	441.90
15	12.48	33.80	46.33	53.03	0.08	0.06	146.70	397.80
16	12.30	34.00	47.62	51.92	0.07	0.05	113.80	331.30
17	11.85	33.81	48.84	52.10	0.07	0.06	50.70	254.20
18	11.04	33.44	50.88	52.98	0.08	0.04	0.00	194.70
19	10.49	32.43	52.21	55.71	0.13	0.03	0.00	42.10
20	10.24	31.14	52.57	59.20	0.16	0.02	0.00	5.30
21	9.87	30.37	53.47	61.09	0.12	0.02	0.00	0.00
22	9.57	29.70	54.17	62.52	0.10	0.02	0.00	0.00
23	9.21	29.04	55.01	63.46	0.13	0.02	0.00	0.00
24	9.93	25.77	59.00	62.10	0.12	0.04	0.00	0.00

Temperature simulations

To get a graphical view of temperatures, it is been created a daily simulation comparing inside temperature, outside temperature, photovoltaic panel surface temperature, mean radiative temperature on the inner surface of the walls, operative temperature.

The charts in Figure 2 shows the simulation results on the January 12 and July 20.

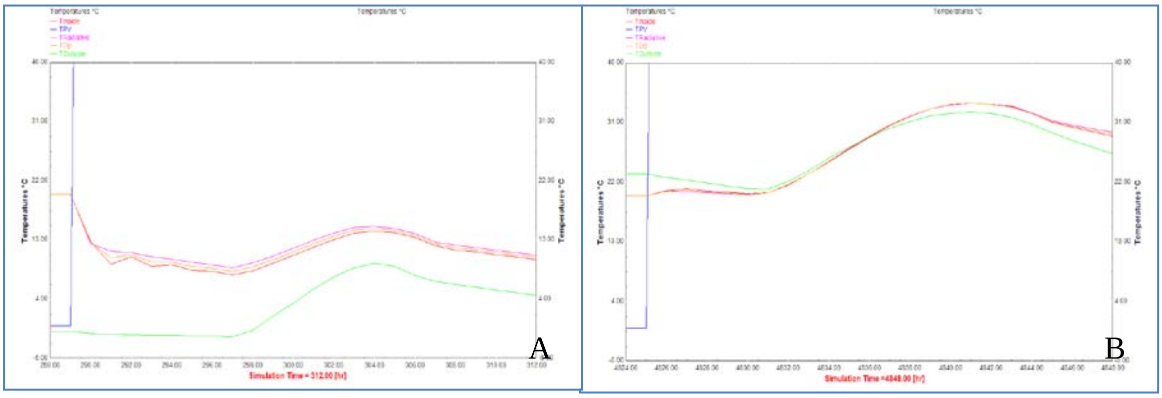

Figure 2. Left. Simulation of temperature on January 12 (A) and July 20 (B) where: Tinside: inside temperature; TPV: temperature of the photovoltaic panel surface; TRadiative: mean radiative temperature on the inner surface of the walls; Top: operative temperature; TOutside: outside temperature

Energy production

The following chart shows the annual simulation of electric power [W/m^2] generated by a m^2 of panels, represented in blue. In red is shown the annual simulation of total solar radiation incident on the panels [W/m^2] with the scale of values on the left axis.

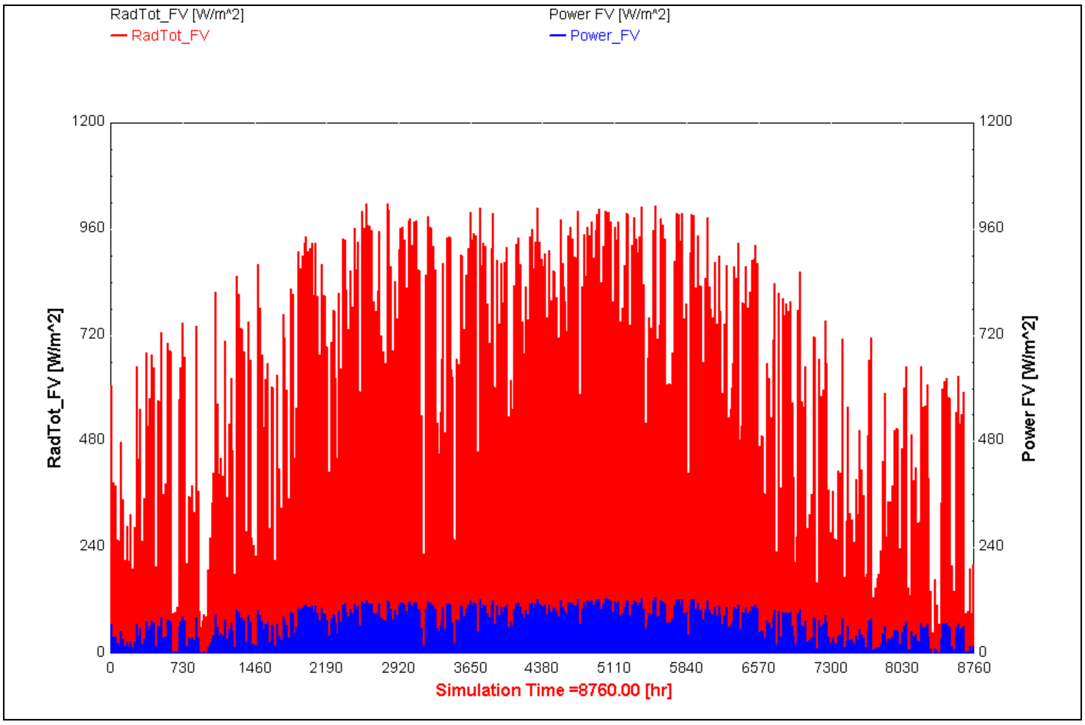

Figure 3. Simulation of the annual electrical power generated and the incident radiation, where: RadTot_FV: total radiation incident on one m^2 of photovoltaic panels; Power_FV: electric power generated by a m^2 of photovoltaic panels.

It was then simulated the annual electricity production of the entire plant, which is about 250 MWh output of the inverter.

<u>*Risk assessment*</u>

The following output values are obtained by applying the PHS model using as input data the values of microclimatic parameters estimated for the date of July 20, obtained as described above and relating to the eight hours between 7.00 am and 3:00 am, and considering a 'moderate' business for the worker (while standing, with continuous use of the arms) (Met = 150 W/m^2) and a clothing consists of shorts, shirt, suit, socks and shoes (Clothing insulation : Icl = 0.8 clo):

- maximum allowable exposure time for heat storage ($D_{lim}\ t_{re}$): 131 min;
- maximum allowable exposure time for water loss, mean subject ($D_{limloss50}$): 480 min;
- maximum allowable exposure time for water loss, 95% of the working population ($D_{limloss95}$): 480 min.

In case of lack of water availability, values $D_{limloss50}$ and $D_{limloss95}$ could lowered to 288 minutes.

Conclusions

TRNSYS software has proven its extreme flexibility to allow development of the project emissions. The construction of the model has been simplified by the procedures explained in a comprehensive manner in the various manuals provided with the software, without showing any particular difficulties in communications between the constituent subprograms.

As for the light component of the simulations, the solution found to allow the passage of long wave radiation through the glass of the greenhouse modelled as "windows", has perhaps shown a critical factor on TRNBuild, not have the optical model for light energy to the walls of buildings, but this did not affect in any way the results. Moreover, this solution has improved the simulation of moisture for the cold bridge effect.

From this model, it might be interesting to continue to work on projects for energy systems applied to agriculture, being able to predict the indoor climatic conditions and from this starting to figure out which crops are actually achievable.

In addition, this program offers many opportunities to improve systems made: will be inserted cooling and heating, dehumidification, the total consumption of electricity and machinery for the exercise of individual farming, the heat emitted by workers, plants and the various electrical components inside the greenhouse and everything else necessary to simulate the reality situations inside a greenhouse. Could be easily build a new components (Type) on variables purely "agricultural" as soil evaporation and plant transpiration of water.

The data concerning work in the greenhouse, analyzed with the PHS model, show a potential health risk for the workers, especially concerning their heat storage. However, we must consider that the data should be confirmed with "in field" measurements. Furthermore, we must remember to put plenty of drinking water at the workers' disposal. In fact, the maximum values of water loss can be easily exceeded.

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