Mathematical Modeling and GIS Applications for

Greenhouse Energy Planning in Italy

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Abstract

The analysis of the energy requirements carried out using simple algorithms and historical air temperature series allows to obtain a classification of the territory, identifying those areas where the demand for artificial energy for heating a greenhouse is limited, resulting in reduced costs management and greenhouse gas emissions. In this work were determined the annual requirements of artificial energy to heat a greenhouse (MJ m$^{-2}$ year$^{-1}$) covered with polyethylene film for the whole Italian territory at a predetermined internal thermal threshold. The results show that through the analysis of energy requirements has been possible to obtain a classification of the Italian territory by identifying areas that are most appropriate to the greenhouse activity for the high availability of natural energy.

Keywords: energy requirements, greenhouse, energy planning
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;

\(i\) = internal;

\(ri\) = reflected internal;

\(ap\) = absorbed by the plants;

\(rg\) = reflected from the ground;

\(ag\) = absorbed by the ground;

\(ac\) = absorbed by the cover;

\(p\) = plants;

\(G\) = ground;

\(ia\) = indoor air;

\(atm\) = atmosphere;

\(sky\) = vault of heaven.
1 Introduction

In the last years the issue of the use of energy has aroused great interest at both European and national level through the enactment of a series of regulations and directives. In 2000, the European Commission has stimulated a debate on the security of energy supply in the European borders through the publication of the Green Paper “Towards a European strategy for the security of energy supply” which is still the reference document at Community level.

The agricultural sector contributes, albeit in a less significant than in other sectors, at the consumption of energy especially for the energy requirements intended for greenhouse structures.

The greenhouses activity has played and continues to play an important role in Italian agriculture in terms of quality of production and technology development. In Italy, the development of this activity is mainly due to favorable climatic conditions that facilitate the settlement of these structures on the territory.

The distribution of greenhouses affects almost all the national territory except for some mountain areas (ISTAT data) (Fig.1). It's understandable that farmers have tried to exploit those portions of land that could provide certain natural energy resources and those close to major national and international markets.

![Density of installations for protected crops in relation to the U.A.A.](image)

One of the greatest needs of this activity is related to energy availability, that is, to have natural energy to create microclimatic conditions inside the greenhouse to encourage the growth of plants at different times and at latitudes less than ideal. Not all Italian places have favorable climatic conditions (air temperature and humidity, solar radiation, etc.) for the establishment and the conduct of green-
house activity. Where these conditions are not met it is necessary to produce artificial energy through the burning of fossil fuels. As a result, a high emission of greenhouse gases and an equally high production of combustion residues that create environmental impact. Only in recent years has been attempted to generate electricity for agricultural activities from renewable energy sources (Moreton et al. 2012, Marucci et al. 2012, Marucci et al. 2013a) in order to reduce this environmental impact and try to create a closed system greenhouses.

To face with foreign competition is not enough to resort only to natural resources because not offer guarantee on the quality but especially on the timing of production. For this reason it is necessary to use artificial energy for heating and cooling the environment inside the greenhouse, but trying to limit this need.

The artificial energy needed for heating a greenhouse can be described through the energy balance equation (1), that is the difference between the input of global solar radiation that enters inside the environment and the energy output due to losses for transmission, ventilation and radiation (Campiglia et al. 2007, Marucci et al. 2013b, Marucci et al. 2011a, Marucci et al. 2011b).

\[ R_i = RT_{g,sky} + RT_{g,atm} + RT_{p,sky} + RT_{p,atm} + RT_{ia,sky} + RT_{ia,atm} + T + V + \Delta E_g + S_g \] (1)

Where:

The global solar radiation (direct and diffuse) inside the greenhouse in clear sky conditions was calculated using the equation (2):

\[ R_i = R_i [r_g (1 + C_d) + r_d] \cos \theta_z \cdot \tau_z \] (2)

Where:

\[ R_i = 1367 \left[ 1 + 0.033 \cos \left( \frac{360 \cdot n}{365} \right) \right] \] (Wm\(^{-2}\));

\( n = \) julian day;

\[ \cos \theta_z = \sin \lambda \sin \delta \cos \theta_z - \cos \lambda \sin \delta \sin \theta_z \cos \psi + \cos \lambda \cos \delta \cos \omega \cos \theta_z \cos \psi + \sin \lambda \cos \delta \cos \omega \sin \theta_z \cos \psi + \cos \delta \sin \omega \sin \theta_z \sin \psi \]

\[ \cos \theta_z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega; \]

\( \phi = \) latitude (°);

\[ \delta = 23.45 \cdot \sin \left[ \frac{360}{365} \cdot (284 + n) \right] \] (°);
\( \omega = \text{hour angle} = \frac{360}{24} \cdot (12 - h) \) (°);

\( \psi = \text{angle between the horizontal projection of the surface normal and the direction south} \) (°);

\( h = \text{hour days} \) (h);

\( A = \text{altitude} \) (km);

\( \tau_b = \text{transmissivity of the atmosphere to the direct radiation} = A_0 + A_1 \times e^{-\frac{k}{\cos \theta}}; \)

\( \tau_d = \text{transmissivity of the atmosphere to the diffuse radiation} = 0.271 - 0.294 \tau_b; \)

\( A_0 = [0.4237-0.00821 \cdot (6 - A)^2] \cdot [1+0.03 \cdot \sin \left( \frac{\pi}{91+n} \right)]; \)

\( A_1 = [0.5055+0.00595 \cdot (6.5 - A)^2] \cdot [1+0.01 \cdot \sin \left( \frac{\pi}{91+n} \right)]; \)

\( K = [0.2711+0.01858 \cdot (2.5 - A)^2] \cdot [1.01 - 0.01 \cdot \sin \left( \frac{\pi}{91+n} \right)]; \)

\( C_d = \text{Diffusivity coefficient of the plastic film cover} \) (indicates the direct radiation that is converted into diffuse in the internal environment from the cover).

Trasmissivity (\( \tau_c \)) of the cover and the walls to solar radiation was determined using the model described by Marucci et al. 2013b.

The energy lost by transmission from walls and the cover was calculated with the relation (3):

\[ T = K \cdot S \cdot (T_i - T_e) \] (3)

\( K = \text{thermal transmittance} \) (W m\(^{-2}\) K\(^{-1}\));

\( S = \text{surface} \) (m\(^2\));

\( T_i = \text{internal temperature} \) (K);

\( T_e = \text{external temperature} \) (K).

The energy lost by ventilation was calculated with the relation (4):
\[ E_v = V \ (H_i - H_e) \]  

(4)

\( E_v \) = energy lost by ventilation (KJ h\(^{-1}\));

\( V \) = flow rate of ventilation (Kg Dry Air h\(^{-1}\));

\( H_i \) = internal air enthalpy (KJ Kg Dry Air\(^{-1}\));

\( H_e \) = external air enthalpy (KJ Kg Dry Air\(^{-1}\)).

The enthalpy \( H \) (KJ Kg Dry Air\(^{-1}\)) of a Kg of air, at temperature \( T \) (°C) and with a water content, in the form of water, equal to \( x \) (Kg Kg Dry Air\(^{-1}\)) is obtained from (5):

\[ H = 1.005 \ t + x \ (2499.5 + 2.005 \ t) \]  

(5)

\( x \) (Kg Kg Dry Air\(^{-1}\)) represents the water vapor contained in the air and can be determined through the psychrometric diagram or with the following formula (6):

\[ x = 0.6215 \ \frac{P_{H,0}}{P - P_{H,0}} \]  

(6)

\( P = 1.013 \) (Kg cm\(^{-2}\)) atmospheric pressure;

\( P_{H,0} \) = vapor pressure of the air, expressed in Kg cm\(^{-2}\) at the temperature \( T \) (K) and at relative humidity \( UR \) (%) (7);

\[ P_{H,0} = 1.41 \times 10^{10} \ \text{e}^{\left(\frac{-3928.5}{T-41.5}\right)} \times UR \]  

(7)

The energy lost by radiation was calculated with the relation (8):

\[ RT_{12} = \sigma \ \varepsilon_{1,2} F(T_i^{4} - T_{12}^{4}) \]  

(8)

\( RT_{12} \) = Energy lost by radiation (W m\(^{-2}\));

\( \sigma \) = Stefan–Boltzmann constant (W m\(^{-2}\) K\(^{-4}\));

\( \varepsilon_{1,2} \) = emissivity;

\( F \) = view factor;
$T =$ absolute temperature (K).

In a planning where the availability of meteorological data is always complicated and is often used approximations and interpretations of data from surrounding areas not make much sense to use complicated methods. For this reason it is considered rather the adoption of a method which takes into account an overall heat transfer coefficient $K_t$ (W m$^{-2}$ °C$^{-1}$) that takes into account of losses due to conduction, convection and radiation. For the polyethylene film was assumed a value of 7 W m$^{-2}$ °C$^{-1}$.

Spatially representations of climate data called "climate surfaces" are usually used in applications, both theoretical and practical, that relate to the environmental sciences, agricultural and biological (Hijmans et al 2005, New et al. 2002). Some examples include models ranging from hydrology (Grimaldi et al. 2013, Shen et al. 2013) at climate changes (Matouq et al. 2013, Ferrer et al. 2012) from the study of renewable energy resources (Sánchez-Lozano et al. 2013, Arnette et al. 2011) at agricultural science (Korthals Altes et al. 2013, Gatrell et al. 2013, Kroschel et al. 2013).

The goal of this work is to determine through a spatial representation of the annual requirements of artificial energy for heating in the greenhouses (MJ m$^{-2}$ year$^{-1}$) covered with polyethylene film for the whole Italian territory and at a predetermined the threshold internal heat.

Through the results obtained were drawn up thematic maps for the temperature thresholds of 10, 12 and 14 °C in QuantumGIS.

2 Materials and method

The method was developed using the experimental data of some research carried out in two greenhouses, located in Viterbo at the didactic-experimental farm "N. Lupori ", Faculty of Agriculture, on the energy behavior of cold greenhouses that is without heating fixed or rescue.

Through statistical regression coefficients (9,10,11,12) were calculated in order to estimate the time $T_{slc}$ (h month$^{-1}$) of which the temperature inside the greenhouse falls below a certain threshold $t_c$.

\[
K_1 = 5114 \times 10^{-6} \times t_c^2 + 1.3 \times 10^{-4} \times t_c + 1.82 \times 10^{-5}; \quad (9)
\]

\[
K_2 = -0.05593 \times t_c^2 + 1.663625 \times t_c - 11.7179; \quad (10)
\]

\[
K_3 = 0.003575 \times t_c - 0.0674; \quad (11)
\]

\[
K_4 = -0.10907 \times t_c^2 + 3.390788 \times t_c + 11.6433; \quad (12)
\]

\[
T_{slc} = K_1 \times (n-180)^2 + K_2 \times t_{mme} + K_3 \times t_{mme}^2 + K_4 \quad (13)
\]
where:

\[ n = \text{julian day}; \]

\[ t_{\text{mm}} = \text{mean monthly minimum external air temperature (°C)}; \]

To choose the thermal threshold as to maintain inside the greenhouse were analyzed optimum minimum temperatures of the major horticultural crops and it was noted that the majority of these crops admits a biological threshold between 10 and 14 °C.

Mean monthly minimum temperature Italians values were used those supplied by Worldclim (Fig.2). Worldclim is the most popular global bioclimatic dataset (Hijmans et al., 2005), is widely being used because it is easily available and offers high resolution (~1 km) for all land areas globally (Bedia et al. 2013)

**Fig. 2: Mean monthly minimum temperature in January**

Subsequently steps were taken to calculate the amount of monthly energy per unit area required to maintain the minimum temperature to a certain level \( t_c \) (kJ m\(^{-2}\) month\(^{-1}\))(14):
\[ E_{(\text{tc})} = K_t * (t_c - t_{\text{nume}}) * T_{\text{tc}} * d_m * 3.6 \] (14)

Where:

- \( K_t \) = overall heat transfer coefficient (W m\(^{-2}\) °C\(^{-1}\));
- \( T_{\text{tc}} \) = Estimated time during which the internal temperature of the greenhouse is fallen below the threshold (h month\(^{-1}\));
- \( d_m \) = days of month.

Were considered the months from October to May and was therefore calculated the annual artificial energy demand for the heating per unit area (MJ m\(^{-2}\) year\(^{-1}\)) to avoid that the internal air temperature falls below the predetermined thermal threshold. Subsequently thematic maps were prepared in QuantumGIS (QGIS) concerning to the annual energy requirements for heating a greenhouses for the Italian territory considering the temperature thresholds of 10, 12 and 14 °C.

### 3 Results and discussions

Figure 3 shows the annual energy requirements for heating a greenhouses per unit area (MJ m\(^{-2}\) year\(^{-1}\)) in relation to a predetermined air temperature threshold of 10 °C.

![Figure 3: Energy requirements to internal thermal threshold of 10 °C](image)

At the threshold of 10 °C thermal energy demand for heating a greenhouses in the
country appears to be homogeneous. The energy requirements for heating are almost always less than 200 MJ m\(^{-2}\) year\(^{-1}\) with the exception of mountain areas and high hills areas where the energy demand increases significantly. This is mainly due to a lower value of minimum mean external air temperature that exists at these altitudes resulting in increased thermal excursion between the inside greenhouse and the outside with an increase of energy demand.

Increasing the internal thermal threshold at 12 °C (Fig. 4) result a certain lack of uniformity in demand of artificial energy to maintain a certain temperature levels (\(t_e\)) greenhouses on the Italian territory. In mountain areas and in the high hills areas the energy requirements for this thermal threshold are almost double those the lower thermal threshold of 10 °C by passing from 300-400 MJ m\(^{-2}\) year\(^{-1}\) to values of 600-700 MJ m\(^{-2}\) year\(^{-1}\). Also in coastal areas of north-central Italy the energy requirements are doubled compared to the thermal threshold of 10 °C by passing a range of 0-100 MJ m\(^{-2}\) year\(^{-1}\) at an interval of 100-200 MJ m\(^{-2}\) year\(^{-1}\).

In the southern coastal areas and islands the energy requirements were unchanged compared to the thermal threshold of 10 °C for highlighting that in these areas the need to heat the greenhouse appears to be very limited.

![Fig. 4: Energy requirements to threshold of 12°C](image)

Figure 5 shows the annual energy requirements for heating a greenhouses per unit area (MJ m\(^{-2}\) year\(^{-1}\)) in relation to a predetermined internal thermal threshold of 14 °C.
Areas where you cannot resort to artificial energy in the colder months are very limited. These areas correspond to the island regions and the coasts of Calabria.

**Fig. 5: Energy requirements to internal thermal threshold of 14°C**

The comparison between the maps for the three temperature thresholds shows that the increase of the value of the thermal threshold, the higher energy range (> 800 MJ m² year⁻¹) tends to go down towards the south of the peninsula for the northern regions. In the central and southern Italy this range tends to extend to the coastal in a fairly limited area.

This analysis also revealed that there are areas that have so far been little affected by the development of greenhouses farms although you have a natural energy source that would limit the use of artificial energy with a consequent reduction in operating costs. In our opinion this is due to the lack of tradition in these areas for the greenhouses activity, to a lack of water resources and above all to a difficult connection to the major national and international markets, but careful planning could make the development of these areas of the country.

**3 Conclusion**

The results show that through the analysis of energy requirements performed with
the use of simple algorithms and historical series of air temperature values it was possible to obtain a classification of the Italian territory by identifying areas that best lend themselves to the greenhouses activity thanks to a high available natural energy.

In some areas, the energy requirements gradient is very broad therefore minimum displacements on the territory involve an increase significantly of energy demand. So it not correct to say that in a region exist outstanding climatic qualities to encourage or discourage greenhouses activity but this statement should be limited to small areas of territory.

References


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