Dynamic Simulation and Energy, Economic and Environmental Analysis of a Greenhouse Supplied by Renewable Energy Sources

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Abstract: This paper presents the design and dynamic modelling of a greenhouse coupled with renewable energy technologies, such as PV panels, solar thermal collectors, biomass auxiliary heater. The system is also coupled with a pyrogasifier, supplied by wood and agricultural wastes in the framework of a biocircular economic approach. In order to match the real load of power and heat of the investigated user, a "green farm" located in Naples (South of Italy) reducing the energy consumption and operating cost, all the main components of the plant were suitably designed. The operation of the designed components was simulated by a dynamic simulation model developed in TRNSYS environment and validated by means literature results. A comprehensive energy, economic and environmental analysis of the greenhouse was presented. Main results suggest that the proposed renewable system is able to reduce the total equivalent CO_2 emissions of 148,66 t/y. Considering the high current increase of the energy prices due to energy crisis due to the war, the system shows a very significant profitability with a simple payback of only 1.7 years.

1 INTRODUCTION

Renewable energy sources (RES) (Rahman, 2022) can be integrated into several energy systems to provide the energy required for the process and significantly reduce the primary energy demand of the systems itself. In particular, solar technologies - such as solar thermal collectors (Chantasiriwan, 2022), photovoltaic (PV) panels (Xue, 2017) or photovoltaic/thermal (PVT) collectors (Calise, Cappiello et al. 2021) - can be easily integrated in greenhouses (Azam, 2020). Such option seems very attractive, to avoid or reduce the use of natural gas boilers and power from the grid. For example, it is possible to install a PV field to produce electricity (Okakwu, 2022) as an alternative energy source of water pumping for irrigation farming, or a solar thermal collector field to supply the thermal energy needed to the greenhouse heating system in order to obtain the greenhouse operating temperature within the designed temperature range (Xu, 2022). Several authors investigated this issue. For example, a nonlinear integrated controlled environment agriculture model is developed to correlate the impact of weather disturbances, temperature and humidity control, fertilization, and irrigation, on the crop growing conditions. Results of the simulation of a renewable energy-powered semi-closed greenhouse growing tomatoes located in Ithaca, New York were presented. The integrated controlled environment agriculture model can help in increasing renewable energy usage efficiency from 4.7% to 127.5%. In the work of (Singh, 2006) a mathematical model to simulate a greenhouse was developed and validated vs experimental data. The equations were written for four components of the greenhouse, i.e. cover, inside air, canopy surface and bare soil surface. The model was applied to the Research Farm of the Punjab Agricultural University, Ludhiana. The model solved using Gauss–Seidel Iteration method, confirms a good agreement with measured data related to the winter operation for a tomato crop. A dynamic greenhouse environment simulator was developed in ref. (Fitz-Rodríguez, Kubota et al. 2010) to predict the

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dynamic behavior of greenhouse environments with different configurations. The model was implemented in a web-based interactive application that allowed for the selection of the greenhouse design, operational strategies, and weather conditions (four seasons of four geographical locations). In order to predict the hourly heating requirements of conventional greenhouses a time-dependent, quasi-steady state thermal model based on the lumped estimation of heat transfer parameters of greenhouses was developed (Ahamed, 2018). The model considers greenhouse indoor environmental control parameters, physical and thermal properties of crops and construction materials, and hourly weather data including temperature, relative humidity, wind speed, and cloud cover. The model also includes the heat loss for plant evapotranspiration, and the heat gain from environmental control systems. Thermal analysis indicates environmental control systems could reduce 13–56% of the total heating requirements over the year. A comprehensive TRNSYS model for predicting the transient heating requirement of a Chinese-style solar greenhouse for Canadian Prairies, was presented in ref. (Ahamed, 2020). The model in TRNSYS environment was also validated by a new heating simulation model. The same model developed in ref. (Ahamed, 2020) was improved in ref. (Dong, 2021) and validated using the field data collected from a solar greenhouse in Manitoba, Canada. The annual simulation indicates that the daily average heating in the coldest month (January) could be two times higher (6.3 MJ/m2·day) compared with March (3.4 MJ/m^2·day). Comparing this solar greenhouse with a traditional local one, the heating cost is about 55% lower.

1.1 Aim of the Work

This work aims at increasing the renewable energy technologies usage in the agricultural sector. In particular, in this work, the development of a greenhouse dynamic simulation model in TRNSYS environment and the related validation by the literature values is presented. Then, the greenhouse model is integrated into a comprehensive dynamic simulation model, including several renewable technologies based on the use of biomass and solar source in order to evaluate the energy, economic and environmental performance. With respect to the literature review the work aims at showing how hybrid renewable energy plants can be an optimal solution in the framework of the green farm and biocircular economy approach. In addition, the whole system is dynamically simulated considering both the dynamic demand of the greenhouse and user and the dynamic power and heat production

2 METHOD

In this section the method adopted to develop this work will be described. Here the greenhouse model and its validation vs literature data will be reported. Then, this model will be integrated into a comprehensive simulation model including the investigated renewable technologies according to the investigated layout (Figure 1). The section also includes some details of the modelling of the main components, such as the solar thermal collector and PV panel fields and the main economic and energy indexes evaluated to perform the technoeconomic analysis.

2.1 Layout

The layout investigated in this paper is represented in Figure 1.

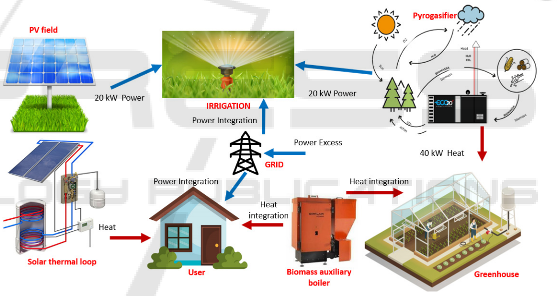

Figure 1: Layout.

It includes:

- solar PV panels producing electricity to supply the user and irrigation pumps.
- solar thermal collectors to supply the thermal energy demand of the greenhouse, corn drying and the domestic hot water and heating energy demand of the user.
- a biomass auxiliary boiler in case of scarce irradiation, during the night hours or switching off of pyrogasifier, to match the global thermal energy demand.
- a water tank to store the produced thermal energy by the solar field.
- a pyrogasifier supplied by wood and agricultural wastes to produce both thermal and electric energy.

The plant is connected to the grid in order to match the electricity of the user if the production of the included technologies is not enough.

2.2 Model

The simulation model of this system is developed using the well-known dynamic simulation tool TRNSYS. The tool includes a large library of components, which are able to accurately simulate the energy performance of the components included in the investigated system. The types included in TRNSYS environment are considered reliable and validated (Klein SA, 2006). For sake of brevity, the components used to model the whole plant are summarized in Table 1.

Table 1: TRNSYS Types.

Type 1b	Solar thermal collectors
Type 94	PhotoVoltaic panels
Type 109	Weather conditions
Type 48	Inverter regulator
Type 4c	Thermal storage tank
Type 114	Circulation pump
Type 6	Biomass auxiliary boiler
Type 641	Humidification system
Type 77	Ground modelling

TRNSYS software is very reliable and accurate for the evaluation of building energy demand (Calise, 2020) and it is considered by the scientific community as a benchmark tool to validate the in-house building simulation models (Buonomano and Palombo, 2014, Calise, 2016, Buonomano, 2019). However, its application can be suitable also for the simulation of greenhouses as reported in ref. (Ahamed, 2020). The next subsection includes the description of greenhouse model and validation.

2.2.1 Greenhouse Model

Type 56 was selected to model the greenhouse. This component calculates the dynamic energy demand, by considering its 3D geometry (defined in the Google SketchUp TRNSYS3d plug-in (Murray, Finlayson et al. 2009)), the effects of the environmental conditions (i.e. ambient temperature and humidity, solar radiation, etc.) on the greenhouse and the envelope thermophysical proprieties, as well as the ventilation and infiltration rate. gain. The greenhouse geometry analyzed in this work is represented in Figure 2. The validation of the whole Type 56 is presented in reference (Voit, 1994). It is also worth noting that Type 56 considers a detailed model for the calculation of radiation in the greenhouse, considering a complex model for the calculation of view factors and considering the radiative properties of the surfaces as a function of the wavelength.

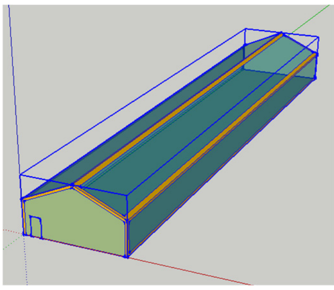

Figure 2: Geometric model of the investigated greenhouse.

As a consequence, the model returns the surface temperatures and the radiate flows emitted by the surfaces and transmitted by the glazing surfaces. The validation of the model of greenhouse was carried out considering the greenhouse model developed in TRNSYS according to the ref. (Ahamed, 2020), where all the assumptions to redevelop the model were reported.

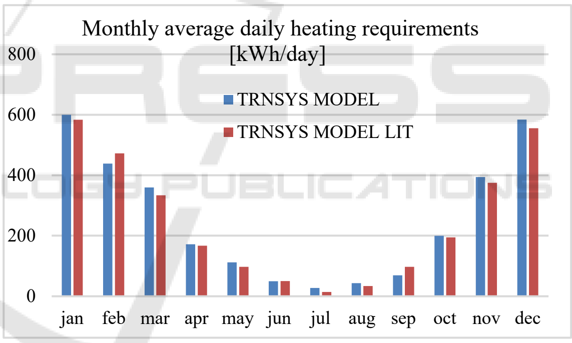

Figure 3: Model Validation.

In Figure 3, the monthly average daily heating requirement obtained both by ref. (Ahamed, 2020) and our model were summarised.

2.2.2 Energy, Economic and Environmental Model

A detailed thermo-economic model was also developed in order to assess the energy and economic profitability of the system under investigation. The primary energy saving (*PES*) was evaluated considering a reference system (RS) supplied by the national grid for the electric energy demand and a conventional gas boiler for the thermal energy demand, featured by an efficiency of 46% and 90% ($\eta_{el,GRID}$, $\eta_{NGboiler}$), respectively.

$$PES=\frac{PE_{RS}-PE_{PS}}{PE_{RS}}=\left(\frac{E_{th,NGboiler}}{\eta_{NGboiler}}+\frac{E_{el,fromGRID}}{\eta_{el,Grid}}\right)_{RS}-\left[\frac{E_{el,fromGRID}-E_{el,toGRID}}{\eta_{el,Grid}}\right]_{PS} \quad (1)$$

The yearly operating cost saving *ΔC* of the proposed system (PS) with respect to the RS considers the purchasing of the electricity from the grid at unit cost $c_{el,fromGrid}$ and of natural gas at unit cost c_{NG}, for RS and the purchasing/selling of the electricity from/to the grid for PS. $c_{el,toGrid}$ is the selling unit cost in PS. In PS, the biomass for the wood-chip auxiliary boiler is purchased at unit cost $c_{bio.boiler}$; the biomass for the pyrogasifier supplied by wood and agricultural wastes is purchased at unit cost $c_{bio,pyr.}$ The maintenance *Mn* of all the components were considered.

$$\Delta C=\left(E_{el,fromGRID}c_{el,fromGrid}+V_{NG}c_{NG}\right)_{RS}-\left(+Mn+M_{bio,pyr}c_{bio,pyr}+M_{bio,boiler}c_{bio,boiler}\right)_{PS} \quad (2)$$
$$-\left(E_{el,fromGRID}c_{el,fromGrid}-E_{el,toGRID}c_{el,toGrid}\right)_{PS}$$

The equivalent CO_2 emissions difference are evaluated as follows:

$$\Delta CO_2=\left(E_{el,fromGRID}F_{el}+\frac{E_{th,NGboiler}}{\eta_{NGboiler}}F_{NG}\right)_{RS}-\left[\left(E_{el,fromGRID}-E_{el,toGRID}\right)F_{el}\right]_{PS} \quad (3)$$

All the capital costs of the included technologies as well as the main parameters for the thermoeconomic analysis were reported in the case study section.

2.3 Case Study

The model of the greenhouse was applied to a suitable case study located in Castelvolturno (Naples, South of Italy). The main features of the greenhouse were reported in Table 2. In Table 3, the design data of proposed plant were also summarised. The plant is designed to produce the electricity for the buildings close to the greenhouse and the related irrigation pumps, and to produce the thermal energy both for the greenhouse heating and the domestic hot water and space heating energy demand of the user. The thermoeconomic and environmental assumptions for the analysis of the PS with respect to RS were summarised in Table 4. Figure 4 reports the thermal energy demand of the greenhouse; Figure 5 reports the power and heat load of the user.

Table 2: Greenhouse features.

Area	450 m^2 (9 m x 50m)
Max height	5 m
Slope of the roof	30 °
Air change infiltration	0.5 1/h
Ventilation	0.1 m/s
Artificial Lightning	30 W/m^2
Day/nigh humidification rate for evapotranspiration	21.5/3.6 g/h
Heating temperature	20 °C
Materials	Plastic cover, steel structure, chalk/clay floor

Table 3: Design data of proposed plant.

Rated power PV field A	15 kW
Rated power PV field B	5 kW
Slope PV field A	0°
Slope solar thermal field/PV field B	30°
Area solar thermal field	28 m^2
Rated power pyrogasifier	20 kW
Rated thermal flow rate pyrogasifier	40 kW
Equivalent oper. hours pyrogasifier	7500 h/y
Efficiency curve coeff. solar collector	
a_0	0.785
a_1	1,03 W/m^2K
a_2	0.0033 W/m^2K^2

Table 4: Thermoeconomic and environmental parameters.

Data	**Value**
Pyrogasifier cost	150 k€
Biomass auxiliary boiler cost	10 k€
Ordinary Maint. Pyrogasifier	3%/y
Extraordinary Maint. Pyrogasifier	5 k€/2y
Maint. biomass auxiliary boiler	2,50%
Unit cost of purchased biomass	0,12 €/kg
Unit cost of self-produced biomass	0,07 €/kg
Lower heating value of wood-chip	4 €/kg
Unit cost of PV field	1800 €/kW
Maint. PV field	2%
Unit cost solar thermal field	400 €/m
Maint. solar thermal field	2,5%
Lifetime proposed system	20 y
Discount rate	5%
CO_2 emission factor for electricity	0.48 $kgCO_2/kWh$
CO_2 emission factor for primary energy	0.20 $kgCO_2/kWh$

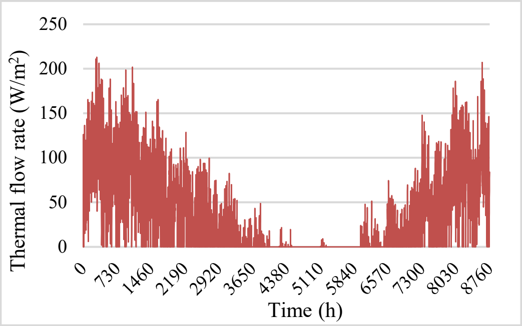

Figure 4: Thermal energy demand of the greenhouse.

It is clearly shown how the thermal energy demand is very high during the winter months due to the cold temperatures. Over 50% of all yearly heating demand is concentrated in the coldest winter months.

The power load is mainly due to the irrigation pumps (with a rated power of 55 kW). Note the high peak value during the summer day, considering that the irrigation time range is wider in the summer days. In addition, the electric consumption due to technologies and offices is negligible with respect to the irrigation. The thermal flow rate during the winter day reaches the peak value of 14 kW at 8 am, higher than summer one, considering that the winter thermal flow rate is due to the space heating and DHW purposes and corn drying.

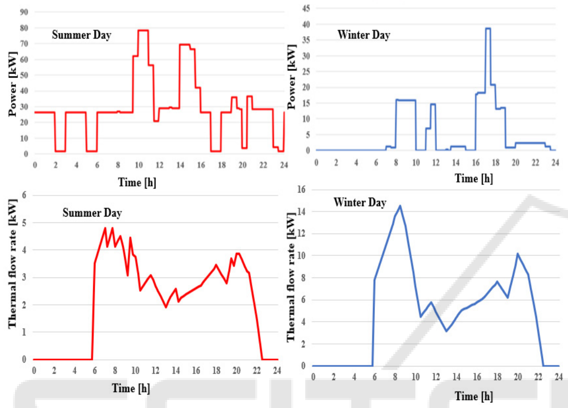

Figure 5: Heat (space heating and DHW) and power demand of user (irrigation and offices demand).

3 RESULTS

In this section the results of the dynamic simulations performed for one year of operation will be presented according to different time basis: hourly, and yearly basis. In particular, the results of the energy, economic and environmental analysis will be also reported when PS is compared with RS. In addition, the economic analysis will be presented considering the purchasing costs before and after the energy crisis.

Figure 6 shows the trends of temperature of greenhouse and outdoor air without the heating system. Note that the heating of greenhouse quickly occurs during the central hours of the day and that the greenhouse temperature follows the same trend of the ambient temperature.

The heating of the greenhouse occurs because the rays of the sun enter through the glass of the greenhouse featured by particularly high absorption coefficients. However, the infrared radiation emitted by the ground cannot be transmitted through some materials, such as glass, guaranteeing a higher temperature than the outdoor air temperature.

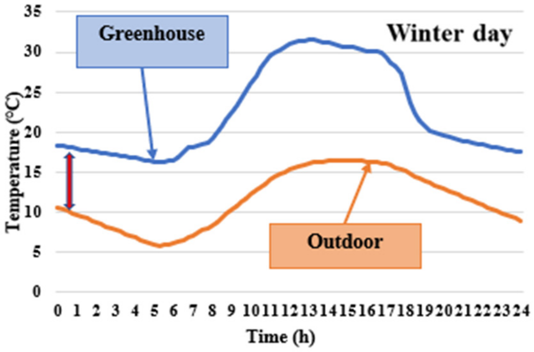

Figure 6: Temperature difference between greenhouse and outdoor air.

A heated greenhouse allows an increase in the yield of the crop, so that some crops can be cultivated even in the winter months. Conversely, in case of greenhouse with heating system, the trend of the thermal flow rates represented in Figure 7 can be observed.

The heating demand of greenhouse by the heating system occurs only if the greenhouse temperature is lower than 20°C, mainly when the radiation is absent or for cold ambient temperature. During these hours, the thermal losses by the construction materials are high. Due to the transmitted solar radiation, the thermal energy demand is null from 11 am to 16 pm because the greenhouse temperature is higher than 20°C, although this is a winter day.

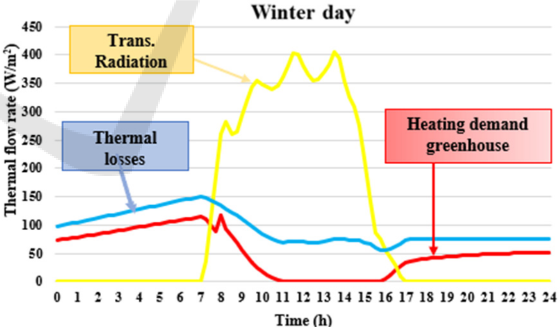

Figure 7: Transmitted solar radiation, thermal losses, and heating demand of greenhouse.

Figure 8 reports the powers of the electric loop. The power production of pyrogasifier is not dependent on the weather conditions and it is constant and very significant. Both the systems, pyrogasifier and PV panels, are able to reduce the integrations of electricity from the grid, although the higher power demand of summer season due to the irrigation pumps than the winter season one. Note that during the central hours of the day, the pyrogasifier is switched off to carry out the ordinary maintenance of the unit and the electricity is only provided by the PV panels. Note that the electricity is delivered to the grid mainly during the night and late afternoon hours. This mainly occurs because the irrigation pumps operate during the central hours, doubling the power consumption.

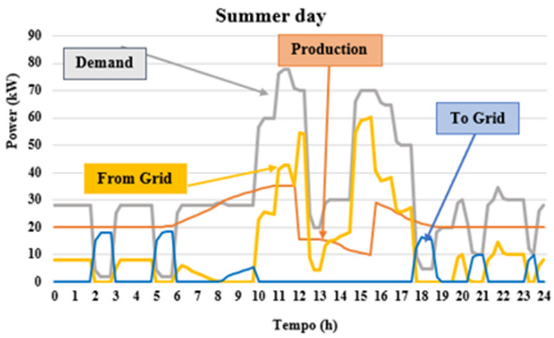

Figure 8: Total power production of PV panels and pyrogasifier, total power demand, power from/to grid (space heating and DHW).

The yearly results of energy analysis were summarised in Table 5 and 6. The electricity integration from the grid is about 35% of the total electric energy demand, whereas the thermal self-consumption is 63% of the total thermal energy demand. The electric self-consumption is 65% of the total electric energy demand. The electric production of the solar field covers only 17% of the total electric energy production, result that confirm the small size of PV field with respect to the pyrogasifier.

Table 5: Yearly energy results.

Energy Analysis			
Energy [MWh/y]	Value	Energy [MWh/y]	Value
User thermal demand	44	Electric integration	108
Greenhouse thermal demand	246	Thermal self-consumption	182
Total heat demand	290	Thermal excess	136
Total electric demand	122	Thermal production solar field	22,7
Elec.production (PV+pyrog)	179	Thermal production pyrogasifier	296
Electric integration	42,3	Thermal product. (solar field+pyrog)	318
Electric excess	99,7	Electric production pyrogasifier	149
Electric self-consumption	79,7	Electric production PV field	30,6

The proposed system is able to obtain a reduction of 149 t/y (Table 6). The primary energy saving of 121% is due to the high amount of the electric energy delivered to the grid, equal to 55% of the total electricity production. During the winter months, due to the lower electric energy demand when the irrigation pumps operate for only few hours per day, the electric-self consumption with respect to the demand reaches high value, also 90%. Therefore, the excess of electricity reduces during the summer months, although the higher PV production.

Table 6: Yearly energy and environmental results.

Primary energy RS	587,04 MWh/y
Primary energy PS	-124,67 MWh/y
PES (Primary Energy Saving)	121%
CO_2 emissions RS	122,93 t/y
CO_2 emissions PS	-25,73
Avoided CO_2 emissions	121%

Considering the increase of the purchasing costs before and after the energy crisis, 0.70 vs 1.58 €/Sm^3 for natural gas, and 0.19 vs 0.66 €/kWh, the economic indexes, reported in Table 7, clearly improve, with a simple payback period, decreasing from 6.7 to 1.7 years.

Table 7: Economic results.

Adopted purchasing costs	Post crisis	Pre crisis
ΔC	122 k€/y	31 k€/y
SPB	1,7 y	6,7 y
DPB	1,8 y	8,4 y
NPV	1317 k€	177 k€
PI	6,4	0,86

4 CONCLUSIONS

In this work the modelling and the energy, economic and environmental analysis of a renewable plant based on PV panels, solar thermal collectors and a pyrogasifier was presented. The plant is designed to satisfy the main energy demands of a farm, including a greenhouse. The modelling was developed in TRNSYS environent and the types of the software were adopted, except for the greenhouse. For the greenhouse a suitable model, validated by a literature research work, was presented, allowing to evalute the thermal energy demand for heating of greenhouse. Subsequently, the validated model was adapted for a case study related to the Castelvolturno greenhouse

(Naples, South of Italy) with a total heating demand of 246 MWh/year. Considering the total thermal and electrical energy demand of the farm, equal to 289 MWh/year and 122 MWh/year, coupling the mix of renewable plants, the following results can be summarized. The electric production covers more than 65% of electric consumption (79 MWh/year). The integration of thermal energy provided by the biomass boiler is 108 MWh/year. The economic analysis was performed considering the purchasing energy costs before and after the energy crisis. Significant differences were detected, with simple payback values decreasing from 6.7 to 1.7 years. Finally, the energy and environmental analysis showed how much the implementation of green systems connected to a circular economy can positively affect the reduction of emissions (-148.66 tons of CO2/year) and the exploitation of fossil fuels (-711 .7 MWh/year of primary energy).

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