Greenhouse localized heating powered by a polygeneration system

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Abstract

Energy consumption in greenhouse heating could reach up to 90% of the total energy requirement depending on the type of greenhouse, environmental control equipment and location of the greenhouse. The use of climate conditioning technologies that exploit renewable energy and the application of passive systems to improve the energy efficiency and the sustainability of the greenhouse sector are recommended. During winter 2020-2021, an experimental test was carried out at the University of Bari in a Mediterranean greenhouse heated by a polygeneration system, composed of a solar system and an air-water heat pump. Three localized heating systems were tested to transfer thermal energy close to plants of Roman lettuce. Heating pipes were placed inside the cultivation substrate in the underground pipe system and on the cultivation substrate in the laid pipe system. The third system consists of metal plates heated by steel tubes and placed in the aerial area of plants. A weather climatic station and a sensor system interfaced with a data logger for continuous data acquisition and storage were used. The plate system was the best for air temperature rising, as it allowed an increase of 3.6% compared to the set-up without any localised heating system. The underground pipe system was the best for the soil heating, as it achieved a temperature increase of 92%. Localized soil heating systems contributed significantly to an earlier harvest by almost 2 weeks.

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Introduction

Following the growing demand for high quality horticultural products, the greenhouse sector is interested in technologies and systems aimed to obtain an accurate microclimate control at every crop stage. The adequate microclimate for plant growth depends on the climate of the geographical area, the covering material, the growing season, and the cultivated species. Greenhouse covering materials are chosen mainly to maximise the penetration of solar radiation with little attention to thermal insulation (Fabrizio, 2012). Growers typically use fossil-fuelled air conditioning systems with a high environmental burden as well as high costs. Bibbiani *et al.* (2016) reported a consumption of fossil fuels for maintaining optimal greenhouse air temperature equal to about 5-6 kg m^{-2} yr^{-1} in Southern Europe and to 60-80 kg m^{-2} yr^{-1} in Central-Northern Europe. The yearly energy demand for greenhouse production is estimated at 220-320 MJm^{-2} in Southern Europe and up to 3600 MJm^{-2} in Northern Europe (Gorjian *et al*., 2021).

Costs for greenhouse climate control represent approximately 70-85% of the total cost, excluding labour costs. Energy consumption in greenhouse heating could reach up to 90% of the total energy requirement depending on the type of greenhouse, environmental control equipment and greenhouse location (Ahamed *et al*., 2019). Sethi and Sharma (2008) reviewed the heating technologies used in greenhouse production by discussing the main applications of each technology. Water storage, rock bed storage, phase change material storage, thermal screens, ground air collector and north wall storage can be used to increase greenhouse sustainability (Sethi and Sharma, 2008).

Technological solutions are advocated to reduce energy consumption and use of fossil fuels, so as to lower their associated environmental impacts (Hernández *et al*., 2017; Gorjian *et al*., 2021). The use of climate control technologies that exploit renewable energy sources (RES) and the application of passive systems for improving energy efficiency are key factors (Vox *et al*., 2008; Fabrizio, 2012; Vox *et al*., 2014; Cuce *et al*., 2016). RES and passive systems reduce both energy costs and CO_2 emissions in the greenhouse sector (Barbaresi *et al*., 2020). Applicable renewable energy sources for greenhouse cultivation purposes are solar, wind, biomass, and geothermal heat. Gorjian *et al*. (2021) reported that several studies investigated the integration of agricultural greenhouses with individual renewable energy sources, even though additional studies are necessary on polygeneration systems powering greenhouse equipment.

The use of the solar thermal energy for greenhouse heating in southern Mediterranean countries was evaluated by several researchers (Bazgaou *et al*., 2021). The integration of a renewable energy source technology into a heating system which is not powered by renewable energy could overcome the intermittent supply of the renewable sources.

The greenhouse volume to be conditioned can be reduced using localized conditioning systems, but these techniques must be perfected and adapted to the different types of cultivation (Puglisi *et al*., 2019, 2020). The use of localized conditioning systems may require the introduction of thermal energy transmission methods, which have never been used in agriculture, as, for example, in the case of radiative surface systems. The aim of our research was to heat a greenhouse cultivation by means of a polygeneration system composed of a solar system and an air-water heat pump. Therefore, our research is intended to achieve a progress in the field of the exploitation of polygeneration systems to power greenhouse equipment. An innovative aspect of our study is the use of thermal energy distributed to the plants by three different localized systems. The experimental tests have shown that the volume to be conditioned can be reduced to less than 20% of the initial one with the use of the localized systems.

Materials and methods

Experimental greenhouse

The research activity was carried out at the experimental centre "P. Martucci" of the University of Bari. The centre is in Valenzano (Bari, Italy), latitude 41°01' N, longitude 16°54' E, altitude 85 m a.s.l. During winter 2020–2021, the greenhouse was heated by means of the polygeneration system composed of a solar system and an air-water heat pump (Figure 1). The arch-roofed experimental greenhouse was characterized by a galvanized steel supporting structure and a plastic covering film in ethylene-vinyl-acetate (EVA). The greenhouse had a length of 30.00 m, a width of 10.00 m, a ridge height of 4.45 m and a gutter height of 2.45 m. Its longitudinal axis had a north-south orientation. There were openings along the side walls and at the ridge to allow natural ventilation.

The EVA covering film [Patilite E, P.A.T.I., San Zenone degli Ezzelini (TV), Italy] had a thickness of 0.21 mm. Its radiometric characteristics were: solar total transmissivity equal to 74.9% and solar direct transmissivity equal to 40.7% in the wavelength range from 300 to 2500 nm and Long Wave Infrared (LWIR) greenhouse effect equal to 89.4% in the wavelength range from 7500 to 12,500 nm. Plants in greenhouse were grown in rectangular pots (1.00×0.40×0.40 m) arranged transversely to greenhouse longitudinal axis (Figure 1). There were 8 rows with 6 pots each. The growing substrate was made of a mixture of soil and peat. Irrigation was provided to the plants by means of a drip irrigation system.

Polygeneration heating system

The polygeneration heating system tested was made up of a solar system and an air-water heat pump. The solar system was composed of solar field, hot water tank, dry cooler, pump, valves and piping. The solar field consists of 15 stationary solar collectors (model Sky PRO CPC 58-1800-20, Kloben, Verona, Italy) placed on the ground and south-facing. The collectors were installed with a tilt angle of 40° to maximize the harnessing of the solar radiation. Each solar collector had 20 evacuated-tube pipes, with a gross area of 4.28 m^2, an opening area of 3.81 m^2 and an absorption area of 5.17 m^2. A 2000-L. tank (model PVR-15/742, Pacetti, Ferrara, Italy) stored the hot water provided by the solar collectors. The dry cooler (Thermocold, Bari, Italy) was an emergency device used when the temperature of the water delivered by the solar field was higher than 95°C.

The air-water heat pump [model ANLI 101 HX, AERMEC SpA, Bevilacqua (VR), Italy] was a reversible outdoor inverter. The heat pump had a cooling capacity of 28.9 kW and a thermal power of 31.5 kW. It produced both hot water and cold water that could be used for greenhouse heating and cooling. During the summer season the heat pump could work at full load up to an external air temperature of 42°C.

Inside the greenhouse another 1000-L. tank (Cordivari srl, Teramo, Italy) was used to store hot water for greenhouse heating.

The solar collectors supplied hot water to the 2000-L. thermal storage tank. When the solar radiation was higher than 300 Wm^{-2}, the hot water flowed from the external tank to the tank located into the greenhouse. The water flow rate from the 2000-L. tank to the 1000-L. greenhouse tank was equal to 0.0003 m^3 s^{-1}. The same water flow value was used to deliver thermal energy to the distribution pipes inside the greenhouse. These were galvanized insulated steel pipes with a diameter of 32.0 mm.

The air-water heat pump worked automatically and continuously by integrating the hot water tank inside the greenhouse to keep the water in this tank at a temperature of 40°C.

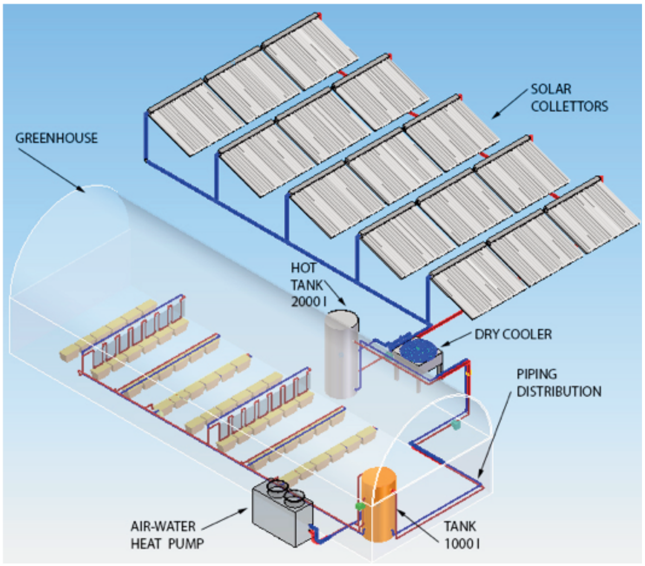

Figure 1. Polygeneration system with solar collectors and air-water heat pump at the University of Bari.

Heat localized distribution system

The heating distribution system branched off from the hot water tank located inside the greenhouse to the plants. Hot water began to circulate in the pipes for localized heating, when the greenhouse air temperature was below 15°C. The heat distribution system near the plants was made of galvanized steel pipes with a diameter of 12.7 mm.

The water passed through the growing area and returned to the tank inside the greenhouse and from here to the external thermal storage tank and towards the air-water heat pump.

The use of localized heating system may require the introduction of thermal energy distribution systems, which have not yet been tested in agriculture. During winter 2020–2021, three different heat distribution systems close to plants were tested (Figure 2). The plant, with its growth and productivity, represents a bio-sensor able to record the performance of the climate conditioning system.

The first localized heat distribution system, coded as *underground pipe*, was made of polyethylene (PE) pipes, with a diameter of 16.0 mm, and was placed inside the cultivation substrate. The pipes were placed 15 cm below the soil surface.

The second system, coded as *laid pipe*, was made of PE pipes, with a diameter of 16.0 mm, and was located on the surface of the cultivation substrate.

The third system, coded as *plate*, consisted of metal plates heated by steel tubes, and was placed in the aerial area of the plants. The steel pipes, with a diameter of 12.7 mm, were placed vertically above the cultivation pots near one of the longitudinal edges and in contact with the 0.5-mm thick aluminium plates. There were also 3-cm thick polystyrene panels for the rear insulation of the plates.

Underground pipes and laid pipes heated the growing medium. The plate system heated the air close to plants, while the presence of radiative surfaces influenced plant growth. Plants are certainly sensitive to the heat exchange, when exposed to high temperature radiant surfaces.

Radiometric tests were performed on the aluminium plate at the University of Bari. Tests were carried out by a FT-IR spectrophotometer (1760 X, Perkin Elmer Instruments, Norwalk, CT, USA), with a step of 4 cm^{-1}, in the LWIR range between 2500 and 25,000 nm. The emissivity coefficient in the LWIR range was calculated as the average value of the spectral emissivity in the wavelength range from 7500 to 12,500 nm (Vox *et al*., 2005; Schettini and Vox, 2012). This range corresponds to the wavelengths with the maximum emission of bodies at ambient temperature and is an indicator of the material ability to release and receive radiation and therefore disperse heat. The emissivity coefficient of the aluminium plate, evaluated as an average between 7500 and 12,500 nm, was equal to 0.234.

Data acquisition and storage

The experimental farm was equipped with a weather climatic station and a sensor system interfaced with a data logger for continuous data acquisition and storage. Data were measured at a frequency of 60 s and the average was calculated every 15 min; data was stored in a data logger (CR10X, Campbell, Logan, USA).

The parameters measured were: i) external solar radiation, temperature and relative humidity of the external air, the air inside the greenhouse and the air near the plants; ii) temperature of the growing substrate; iii) flow and return temperature and volumetric flow rate of the heated water from the external tank to the internal tank; iv) flow and return temperature of the heating water over the rows of pots.

The temperature and relative humidity of the external air, the air inside the greenhouse and the air near the plants was measured using thermistors [Tecno.el srl, Formello (RM), Italy]. The soil temperature was also detected using thermistors (Tecno.el s.r.l.).

Solar radiation was measured using a pyranometer (model 8-48, Eppley Laboratory, Newport, RI, USA) in the 0.3-3 mm wavelength range.

The temperature of the water flowing inside the pipes was measured by means of PT100 (Tecno.el s.r.l., Formello, Rome, Italy). The volumetric flow rate at which water flowed through a pipe was detected by a volume measuring meter (model MTH3, GWF MessSysteme AG, Lucerne, Switzerland). Balancing valves [Caleffi S.p.A., Fontaneto d'Agogna (NO), Italy] adjusted the flow rate of fluid flowing into the pipes in the cultivation area to ensure the operation of the system in the optimal design conditions.

Experimental test

In winter 2020-2021 an experimental test was performed to compare the growth of plants cultivated using three different localized heat distribution systems. Plants cultivated without any localized heating system were used as control. The test was carried out on Roman lettuce from December 17, 2020 to March 2, 2021.

An experimental block scheme was used for the agronomic tests, with 12 replications. The growth of the plants, by evaluating height and number of leaves per plant, was periodically monitored from transplanting to the beginning of the harvest. All the plants were grown with the same agronomic techniques.

Results

Solar energy gathered during daytime was collected in both tanks, for a total of 3000 L. During the night, the stored thermal energy was used for plant heating. Weather conditions strongly affected thermal storage. Figure 3 shows the energy captured by the solar collectors and stored in the 1000-L. tank on 1st February 2021. The solar energy collected during the entire day was equal to 37.2 MJ, while the energy delivered to the plants from one line with the plate system was 134.4 MJ and from one line of underground pipes was 168.7 MJ. The remaining energy necessary for

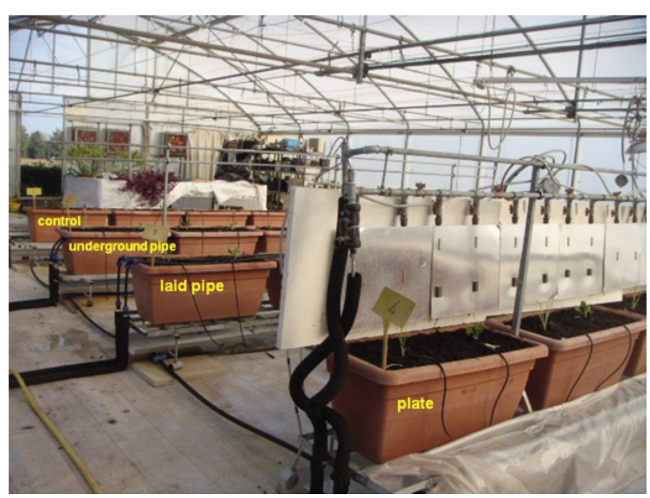

Figure 2. Heat distribution systems near the plants tested during 2020 inside the greenhouse at the University of Bari.

plant heating over all the lines was provided by the heat pump. As expected, the heat pump compensated for the intermittent supply of the renewable sources.

The use of a heat localized distribution system ensures lower dispersion of the produced energy. The values of air and soil temperature in the three heat distribution systems and in the control were analysed. Figures 4 and 5 show air and soil temperature recorded when greenhouse air temperature was lower than 15°C, for three days (16-18 January 2021). This period was particularly cold with a mean external air temperature of 3.9°C and a mean greenhouse air temperature equal to 9.0°C. Air and soil temperature differences between the three localised heating systems and the control were evaluated. Regarding the air temperature (Figure 4), it was found that the highest heating (0.3°C) was obtained by using the plate system, while the temperature was 0.5°C lower than that of the control system for the underground pipe system. Air temperature increases equal to 3.6% and to 3.5% were found for the plate and laid pipe systems, respectively, while a decrease of 6.7% was recorded for the underground pipe system.

With regard to the soil temperature (Figure 5), the highest increase (8.0°C) was recorded for the underground pipe system, lower increases for the laid pipe system (2.2°C) and the plate system (0.3°C). In percentage terms, the underground pipe allowed to reach a soil temperature increase of 92.0%, the laid pipe and the plate increases of 25.2% and 3.9%, respectively.

Overall, it can be observed that the laid pipe system was an intermediate solution between the three systems both for air and soil heating. The plate system was the best for air temperature increasing, while the underground pipe system was the best for soil heating. The choice of one localized distribution system over another can also be depend by the cultivated crop species.

Table 1 reports data concerning harvest and the increase in the height and number of leaves of lettuce plants compared to the initial values recorded at transplanting. The increase in the height and number of leaves was assessed over the 55 days following the transplant up to the day of the first harvest. Three harvests were performed at 55, 68 and 75 days after transplanting. The values at harvest were evaluated as the average of all measurements carried out during the three harvests.

In the first 55 days after transplanting, the underground pipe heat distribution system had always allowed lettuces to grow more, while the lowest growth rate was recorded with no local heating (control). This behaviour can be explained by the fact that the heating of the soil, compared to the heating of the air, influenced plant growth more. The heat distribution system with a laid pipe heated both the growing substrate and the air near the plant itself, while the plate localized system heated the plants by radiative surfaces. After 55 days after transplanting, the first harvest accounted for 85% of lettuce heated with the underground tube and only 19% of the lettuce grown without any local heating (control). Localized soil heating systems contributed significantly to an earlier harvest by almost 2 weeks. The anticipation of the harvest is related to the highest increase of soil temperature recorded for the underground pipe.

To the authors' knowledge, there are no studies in literature which analyse a similar greenhouse polygeneration heating system, so the results obtained could not be compared to the results obtained by other researchers. Our research work was focused on greenhouse heating, but the described methodology and approach can be extended to smart communities, energy districts, industrial areas, *etc*. The results obtained using the polygeneration system could provide a decision support tool and different technical options to energy planners and operators. The use of a polygener-

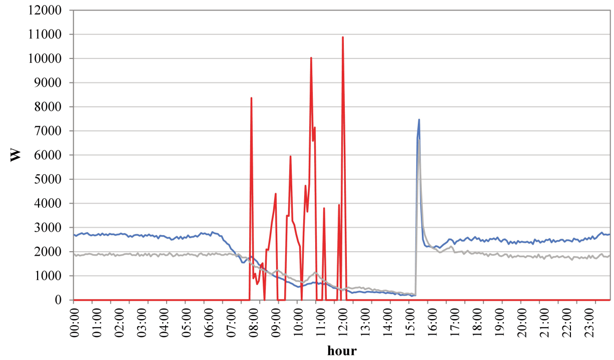

Figure 3. Thermal energy gathered by the solar collectors and stored in the 1000-L. tank (solar collectors, red line), heating energy delivered to the cultivation area from one line of the plates system (plate, grey line) and from one line of the underground pipes (underground pipe, blue line).

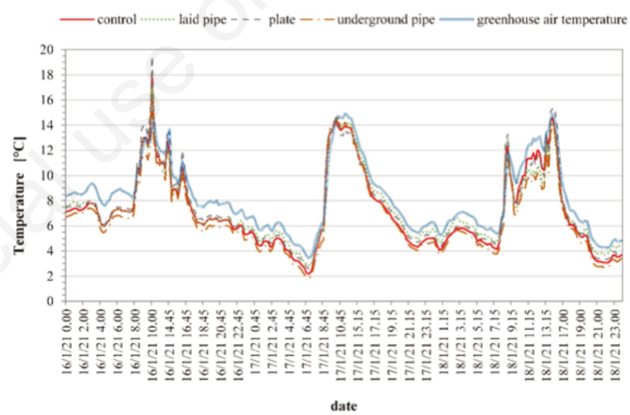

Figure 4. Air temperature in the four systems and greenhouse air temperature, 16-18 January 2021.

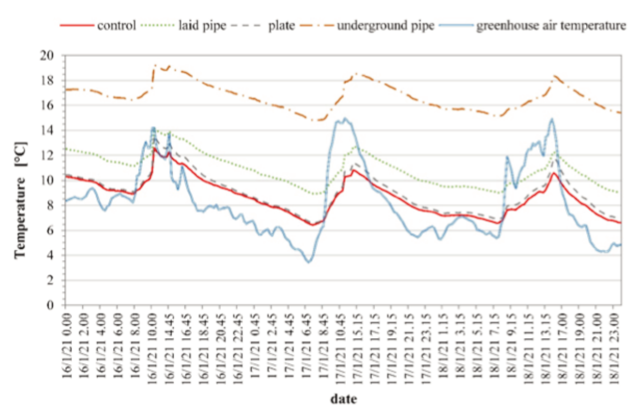

Figure 5. Soil temperature in the four systems and greenhouse air temperature, 16-18 January 2021.

Table 1. Winter lettuce: height increase; leaves increase; average weight and cumulated harvest.

	Control	Plate	Underground pipe	Laid pipe
Initial height (cm)	9.25^{a}	9.04^{a}	8.75^{a}	8.83^{a}
Height increase at 28/12/2020 (cm)	0.33^{b}	0.58^{ab}	1.04^{a}	0.50^{b}
Height increase at 13/1/2021 (cm)	1.16^{c}	2.91^{b}	4.70^{a}	2.70^{b}
Height increase at 04/02/2021 (cm)	7.16^{c}	10.08^{b}	11.79^{a}	9.45^{b}
Height increase at 10/02/2021 (cm)	9.54^{b}	11.95^{a}	12.91^{a}	11.66^{a}
Height increase at harvest (cm)	11.79^{a}	12.83^{a}	13.29^{a}	12.29^{a}
Initial number of leaves	4.83^{b}	5.5^{a}	5.33^{ab}	4.75^{b}
Leave increase at 28/12/2020	1.00^{b}	1.16^{ab}	1.58^{a}	1.33^{ab}
Leave increase at 13/1/2021	4.16^{c}	4.58^{bc}	6.08^{a}	5.75^{ab}
Leave increase at 04/02/2021	10.25^{c}	11.25^{bc}	13.58^{a}	12.50^{ab}
Leave increase at 10/02/2021	12.66^{c}	14.16^{bc}	17.58^{a}	15.08^{b}
Leave increase at harvest	17.41^{ab}	14.66^{c}	18.16^{a}	15.66^{bc}
Average lettuce weight at harvest (g)	234.58^{ab}	198.5^{b}	275.33^{a}	193.41^{b}
Yield at 10/02/2021 (g)	536	1407	2813	1884
% of yield harvested on the total yield	19%	59%	85%	81%
Cumulated yield at 23/02/2021 (g)	2523	2085	3014	2111
% of yield harvested on the total yield	90%	88%	91%	91%
Cumulated yield at 02/03/2021 (g)	2815	2382	3304	2321

$^{a-c}$Mean values in a row with a different superscript letter statistically differ at $P<0.05$ using Tukey-Kramer test.

ation system could improve the global energy and environmental performance in the short and long term.

Conclusions

The choice of an appropriate heating system for a greenhouse is influenced by several parameters such as type of climate, crop to be grown, investment-related costs, installation, operation and maintenance, ease of operation, reliability, equipment lifetime, electricity consumption, and so on. The polygeneration system, composed of a solar system and an air-water heat pump, described in this paper, was designed to increase the air temperature inside a greenhouse in wintertime. The integration of the solar heating technology with an air-water heat pump could maximize the utilization of solar energy by overcoming the irregular intensity of solar irradiance. This experimental study focused on three different localised heating systems (laid pipe, underground pipe and plate) to find out the most appropriate technology. The plate system was the best for air temperature increasing, while the underground pipe system was the best for soil heating. The highest increase of soil temperature (8.0°C) recorded with the underground pipe was decisive for the anticipation of the harvest by almost 2 weeks. Our work showed the effectiveness of localized energy distribution in greenhouses, which is a novelty that can be further explored in future research.

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