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Sustainability in Food Production: A High-Efficiency Offshore Greenhouse

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Abstract: The world's population is expected to increase by nearly two billion in the next 30 years; the population will increase from 8 billion to 9.7 billion by 2050 and could peak at 10.4 billion by the mid-2080s. The extreme weather triggered by global climate change has severely hit crop yields in open-field cultivation and led to an increase in food prices. Furthermore, in the last few years, emergency events such as the COVID-19 pandemic, wars/conflicts, and economic downturns have conditioned agricultural production and food security around the world. Greenhouses could be efficient cultivation systems because they enable food production in a sustainable way, limiting contact between pollutants and plants and optimizing the use of water, energy, and soil. This paper proposes a novel dome-soilless greenhouse concept for tomato cultivation in the Mediterranean area. The proposed greenhouse is fixed on a sea platform to take advantage of the seawater cooling environment and to integrate water consumption into a hydroponic system. In order to evaluate the best covering solution material to adopt, a few thermal and photometric characteristics of greenhouse covering materials were evaluated using a simplified method. A dynamic simulation was carried out to compare the proposed seawater cooling system with a conventional cooling tower in terms of the electric energy spent to maintain the inside temperature range at 13–25 °C across all seasons in the year. The proposed heating, ventilation, and air conditioning (HVAC) system allowed a total annual energy saving of more than 10%. The energy saved was a result of the better cooling performance of the seawater heat exchange that allowed energy saving of about 14% on cooling. The comparison between the model characterised by a 6 mm polycarbonate coupled with UbiGro film and a seawater cooling system, and the model including a 6 mm polycarbonate coupled with a clarix blue film covering and a tower cooling system highlighted energy saving of about 20%. The obtained results indicate possible future directions for offshore greenhouses to carry out independent production together with the integration of photovoltaic modules, water treatment plants, and smart remote-control systems.

Keywords: greenhouse; energy analysis; sustainability; covering materials; seawater cooling; tomato

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1. Introduction

In 2015, all the United Nations member states adopted a plan to build a better world for people and our planet by 2030. The plan defined 17 sustainable development goals (SDGs) to promote prosperity while protecting the environment and ensuring that development balances social and economic interests [1]. The United Nations has committed to fast-track progress for those furthest behind through the pledge to leave no one behind. The keywords in the plan are food, energy, and land. The SDGs have established some policies to guarantee safe food, safe land use, and energy spent on production. On the one hand, it is necessary to adopt specific interventions to limit the current environmental impact, while on the other, it is important to consider the rise in the global population [2]. The influence of climate change on agricultural land production makes this challenge more difficult and complex. Moreover, modern agriculture and food production are more energy-consuming than in the past [3]. Climate change may decrease food production and, at the same time, reduce the amount of space available for energy supply and demand. These events could cause energy and food markets to fluctuate more extensively and increase the energy–food nexus. The extreme weather events triggered by global climate change have hit crop yields severely in open-field cultivation and led to an increase in food prices [4,5]. Such events have unveiled weaknesses in our agricultural system that are threatening the health and livelihoods of people around the world, particularly the most vulnerable and those living in fragile contexts [6]. As urbanization increases, rural and urban areas are becoming more intertwined, and the spatial distinction between them is becoming more fluid. The changing pattern of population agglomerations across this rural–urban continuum is driving changes throughout the agri-food systems. The decrease in agricultural land is creating difficulties in ensuring everyone has access to an affordable healthy diet. In recent years, scientific research and public investments have been directed at developing new technologies and innovations for healthier crop and food production environments [7,8] and for greater availability and affordability of nutritious foods [9,10]. Technology can be particularly important in boosting the capacity of urban and peri-urban agriculture to supply nutritious foods to cities and towns, e.g., to raise the production potential of arable land [11] and develop soilless cultivation systems [12]. More food needs to be produced, but agricultural land is limited to one-quarter of the world's land surface and its availability is decreasing due to nutrient depletion in soils, soil erosion, floods, or drought [13]. It is necessary to adopt suitable strategies to meet future safe and healthy food demand based on projected population growth. Greenhouses could be efficient cultivation systems because they enable food production in a sustainable way, limiting contact between environmental pollutants and plants, and optimizing the use of water, energy, and soil [14,15]. These systems can utilise unusable land to produce high-value crops. It is necessary to adopt sustainable solutions to maintain an optimal temperature range inside the greenhouse in order to enhance crop production. The materials covering greenhouses play an important role in controlling the sun's radiation. Sunlight is fundamental to creating the best conditions for plant growth; however, it should be controlled to limit overheating in the summer. There are several commercial proposals in the market, which, by themselves or together with coating films, can control the sun's radiation and limit the energy required for cooling or heating. Simulating and analysing the greenhouse microclimate is fundamental to guaranteeing optimal operating conditions during the different stages of plant growth. Nowadays, there exist various software simulation programmes for analysing greenhouse energy use based on dynamic thermal analysis, which allows the designer to simulate and assess the behaviour of construction solutions and the heating and cooling greenhouse systems. Even so, it is fundamental to define some important parameters to conduct correct energy analysis, such as the shape and geometry of the greenhouse, the orientation, the local weather, the optimal temperature range for the plants, and the technical equipment needed to control the microclimate inside the greenhouse [16]. The best solution is a compromise between indoor sunlight, yearly temperature range, energy spent, ventilation, and humidity. The computer simulation models allow the designer to analyse different solutions in a limited range of time. In Mediterranean areas, an important challenge is the control of greenhouse indoor temperatures during the hot season [17,18], particularly in recent years, when a rise in atmospheric temperature has been observed. Generally, plants suffer under hot temperatures and struggle to produce crops during the summer because the temperature inside the greenhouse rises above the acceptable range for cultivation. To enable cultivation during the hot season, novel cooling technologies are needed, as conventional cooling technologies show a lot of weaknesses. For example, vapour compression requires large amounts of energy and generally utilises refrigerants that contribute to global warming. Evaporative cooling is efficient under dry weather conditions but produces wet indoor conditions under which plants could develop diseases [19]. In recent years, research has been directed at developing novel advanced cooling systems or incorporating different renewable energy sources into established cooling systems. For example, geothermal cooling systems have shown good performance as sustainable technologies that enable reaching suitable greenhouse temperatures [20]. The principal part of the geothermal cooling system is a pipe placed underground that exploits the cool temperature of the earth's surface and exchanges the warm air inside the greenhouse [21] with the cool air from the earth. The most efficient greenhouse cultivation system is based on hydroponic cultivation. Hydroponics is a soilless cropping method aimed at meeting global food requirements by enhancing food production in a sustainable and efficient way but with low energy use. Hydroponic cropping is a soilless cultivation method that allows the production of fresh and healthy food, in particular for regions with extreme droughts and environmental conditions, thus letting people easily access fresh vegetables [22]. This paper proposes a novel dome, soilless greenhouse concept for tomato cultivation in the Mediterranean area. The proposed greenhouse was fixed on a sea platform to take advantage of seawater cooling. The main aim was to carry out an energy simulation to compare the energy performance of two heating, ventilation, and air conditioning (HVAC) systems for greenhouses. One was equipped with a cooling tower system, while the other had an innovative seawater cooling system. The simulation was conducted in order to evaluate the different greenhouse covering materials. Moreover, a portable measurement method for the performance evaluation of greenhouse covering materials was adopted. The paper is divided as follows: Section 1 is devoted to the problem statement and the aims of the study; Section 2 includes a description of the greenhouse structure, the geometry, the cultivation system, the plant's needs, and the adopted heating and cooling systems. A simplified measurement method for the optical properties of some covering samples and the energy analysis of the greenhouse model are described in Sections 2.2 and 2.3, respectively. Analyses and comments on the results obtained from the comparison of the annual energy analysis for different covering solutions for the proposed greenhouse are shown in Section 3. Finally, Section 4 is devoted to the conclusions and future research outlooks.

2. Materials and Methods

The dome greenhouse analysed has a circular plan with a diameter of 3.50 m, a height of 4.20 m, and an indoor volume of about 190 m^3. The principal dome greenhouse structure is made of 18 radial arrangements of treated cedar wood semiarches that are 5 × 10 cm. A secondary structure with 5 horizontal wood circles is fixed to the semiarches. The sash bars are fixed on the principal and secondary structures to affix the transparent covering material. The dome greenhouse is located on a sea platform close to the coast of Reggio Calabria to take advantage of minimal shading from buildings and infrastructures and seawater cooling [23] (Figure 1). A hydroponic system for cultivation was adopted. Hydroponic cultivation usually utilises a soilless growing medium containing specific nutrients for plant growth. The production is higher than cultivation with soil while consuming less water and using less labour. The development of soilless agriculture provides an alternative to conventional soil-based growing. In this study, a closed hydroponic system technique was proposed. In economic terms, this technique performed better than conventional cultivation. Other studies have shown that the closed hydroponic cultivation system is a sustainable technique for producing food by reducing the number of chemicals utilised to make the soil fertile, minimizing water consumption by 70%, and augmenting yield in a shorter period. The principal benefits of closed systems over open ones are saving water, reducing nutrient loss, and better water productivity. The closed hydroponic cultivation system has water productivity of up to 96% and nutrients of up to 97% compared to the open hydroponic system [24]. Actually, in a closed system, the solution is continually moving and there is very little short-term variation in salinity; for these reasons, it is possible to grow plants in much higher salinity without a decrease in plant quality. The low water quantity needed allows the use of desalinated seawater with a derisory energy cost. This cultivation method uses minimal substrate (whose disposal causes less environmental pollution), and thus provides better contact between the recirculating solution and the air. The oxygen level required by the roots is achieved without additional aeration of the solution. Another advantage of the closed system is that irrigation can be done via gravity and there is no need to use an electric pump [25]. To simplify energy analysis, tomato plants were not taken into consideration in the thermal model. The optimal temperature for tomato cultivation inside the greenhouse was considered to be in the range between 23 °C and 15 °C, while the relative environmental humidity was 70 ± 10% [26].

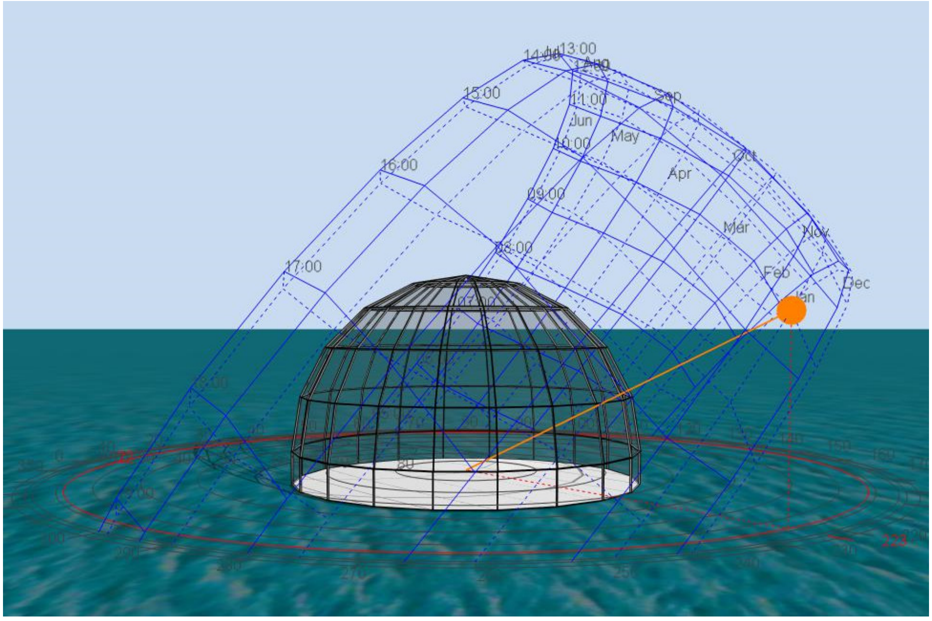


Figure 1. The analysed dome greenhouse model.

2.1. HVAC System

A two-stage HVAC system was used to maintain the indoor greenhouse temperature within the above temperature range. An electric boiler was used in the heating stage while a seawater cooling system (SWAC) was used in the cooling stage. Deep SWAC closed cooling air conditioning systems include three main parts: a closed deep SWAC heat exchange system, a central cooling station, and a chilled water distribution system. The circulating pump provides circulating power, extracts the cooling capacity from the deep SWAC via the SWAC heat exchange system, and transmits this cooling capacity to the chilled water distribution system through the heat exchanger in the central cooling station. In particular, the cooling stage uses a closed heat exchange pipeline to exchange the heat with SWAC [27]. A closed spiral with a 50 cm diameter made of a cooper pipeline [28] with a 5 cm external diameter was used for a total length of 50 m. The water inside the pipeline was moved using a small electric pump that exchanged the heat directly with the seawater. Simultaneously, the thermal fluid exchanged heat with a secondary loop stage using a heat exchanger. Finally, in the secondary stage, a fan system cooled the inside greenhouse air. The greenhouse's indoor environment was heated using a loop with an electric boiler, which heated the pipeline thermal fluid. The HVAC used only electric energy to maintain the inside temperatures within the range of 15–23 °C. It was possible to supply the required energy using a photovoltaic system without a grid connection. The greatest difficulty regarding the HVAC system was the indoor environment cooling because the outdoor temperature in summer can rise above 45 °C.

2.2. Covering Materials

Covering materials are the most important components in a greenhouse. They are the interface layer between the atmosphere and the plants. They have the important task of capturing the sun's rays, keeping the plant safe from external events, and blocking the remission of long infrared rays. Covering materials impact the level and quality of light available to the crop. They should allow maximum illuminance, with high transmission in the photosynthetically active radiation (PAR) bandwidth, but with low transmittance of solar gain to limit excess heat during the hot season and low thermal transmittance to limit heat loss during the cold season [29]. In this study, 4 covering materials were considered and compared; they were also coupled with sun irradiation filter films and analysed (Figure 2). These materials were: 3 mm transparency glass (TG), 4 mm sanitated glass (SG), 4 mm double-layer polycarbonate (P4), and 6 mm double-layer polycarbonate (P6). The technical characteristics are shown in Table 1. Two different films were also used to limit and concentrate the sun's irradiation into a better wavelength range useful for growing tomatoes. The first, (UG), was a luminescent greenhouse film produced by UbiGro® [30], which optimised sunlight within the greenhouse. This layer of light uses clean nanotechnology known as quantum dots to improve the quality of light in the greenhouse. It leverages unused parts of the sun's spectrum—UV and blue photons—and converts them into orange, red, and far-red light, which is particularly helpful for the growth of tomatoes. The second was clarix blue film (CB), a clear film with a specific photo-selective filter effective at equilibrating plant growth and developing more compact plants. It enables a reduction in the solar heat transmitted, thus reducing the shading operations. It is made of ethylene vinyl acetate (EVA) and is produced by Guarniflon Spa. The covering materials were tested and analysed to measure the light, solar power transmission, and the U-value. Each material was analysed on its own and together with the film.

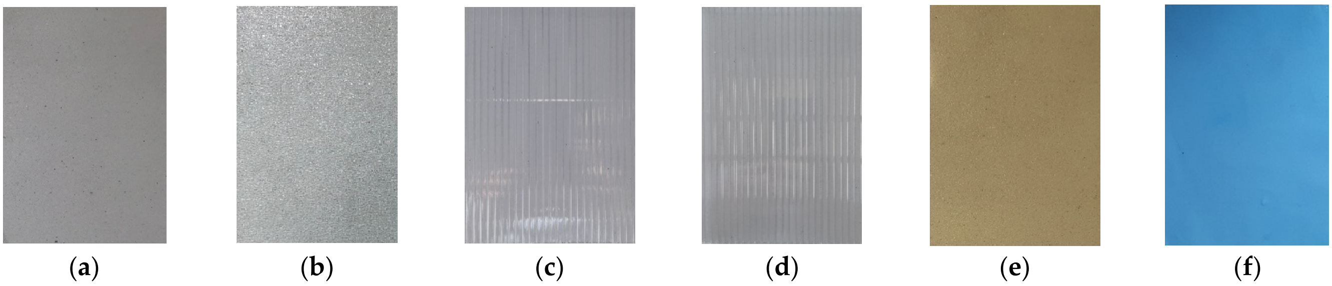


Figure 2. Samples of the analysed covering materials. (**a**) TG; (**b**) SG; (**c**) P4; (**d**) P6; (**e**) UG; (**f**) CB.

Table 1. Measured values of the solar energy transmission coefficient, light transmission, and thermal transmittance for the covering solutions analysed.

Parameters	TG	SG	P4	P6	UG	CB	TGUG	SGUG	P4UG	P6UG	TGCB	SGCB	P4CB	P6CB	IDEAL
g-value (%)	85.35	83.91	77.83	71.11	88.94	69.46	76.69	75.00	68.63	64.46	59.61	55.01	53.02	50.96	50.96
Light transmission (%)	90.66	91.18	73.31	68.26	83.72	60.69	76.50	88.87	62.20	59.21	56.46	53.37	42.52	40.36	91.18
U ($Wm^{-2}K^{-1}$)	5.81	5.79	4.10	3.56	2.15	5.88	2.14	2.14	1.86	1.74	5.81	5.78	4.10	3.56	3.44

Greenhouse Covering Materials Test

In order to evaluate the best covering material, a few thermal and photometric characteristics of the greenhouse covering materials were evaluated. Among them is light transmission, which is the percentage of light that can pass through the covering material and is helpful to the plants. The solar heat gain coefficient (g-value) is another important value that specifies the fraction of the incident solar radiation that has been gained by the indoor environment after passing through the covering material. In warm climates with high cooling needs, covering materials with low g-values are appreciated since they prevent excessive solar heat gain. On the contrary, covering materials with a low U limit energy loss during the cold season [31]. In this work, these three parameters were evaluated, and a multiple attribute decision analysis was carried out to choose the best covering material. To evaluate these parameters, a simplified method was developed and applied. A specific $50 \times 30 \times 16$ cm test box was made; it had polystyrene walls with a thickness of 3 cm. It was coloured green on the inside to simulate the plants' presence, and it was painted black on the outside to eliminate the sun's glare. On top of it was an 18 × 12 cm window with a frame to fix the covering samples for the measurements (Figure 3).

Figure 3. Test box for rapid measurement of optical characteristics of the greenhouse covering. It is portable and enables measurement of the parameters of the greenhouse covering under real conditions.

The measurements were conducted in two steps: the first time without the covering materials and with the sun's rays shining freely inside the box and the second time with the covering material solution in order to analyse it. The measurements were repeated 20 times for each covering solution. The instrument's measurement sensor was positioned inside the box, at a distance of 10 cm from the window opening, while the instrument's data logger was positioned outside the box. The solar energy transmission coefficient (g-value) was measured using SLX-300, a portable power solar metre made by Voltcraft®, with a measurement accuracy of ±10 W/m^2. The value was obtained as a ratio between the solar energy that passed through the covering material fixed on the window box and the solar energy that passed through the uncovered window [1,32].

$$g\text{-}value = E_{in}/E_{ext} \times 100\% \tag{1}$$

where E_{in} [W·m^{-2}] is the solar radiation power passing through the sample of the covering material measured and E_{ext} [W·m^{-2}] is the solar radiation power hitting the sample; both values were measured using SLX-300.

Light transmission was measured using Testo® 545, a portable digital luxmeter with a measurement accuracy of ±3%. The mean light transmission value for each covering solution was obtained as a ratio between the light that passed through the covering material fixed on the window box and the solar light that passed through the uncovered window [2].

$$LT = L_{in}/L_{ext} \times 100\% \tag{2}$$

where L_{in} [lux] is the sunlight passing through the sample of the covering material measured with the luxmeter sensor inside the test box and L_{ext} [lux] is the sunlight hitting the sample; both values were measured using the luxmeter.

The thermal transmittance, U (Wm^{-2}K^{-1}), of the tested material was measured using Testo 635-2, a portable instrument that is based on the thermoflux meter method, with a measurement accuracy of ±0.1 Wm^{-2}K^{-1}. It has two different probes: one to measure the external air temperature and the other to measure the heat flux and surface temperature.

The latter was positioned inside the box in contact with the surface covering material. The data logger calculates the transmittance of the covering material in accordance with ISO 8969 [33] using the formula in [3]. To find a reliable transmittance value, it is mandatory to wait the necessary time to obtain a stable heat flux value.

$$U = \frac{1}{R_{si} + C_t + R_{se}} \tag{3}$$

where:

R_{si} = is the liminar resistances on the inner surface of the covering equal to 0.13 ($m^2 \cdot K \cdot W^{-1}$);
R_{se} = is the liminar resistances on the outer surface of the covering equal to 0.04 ($m^2 \cdot K \cdot W^{-1}$);
and $C_t = \frac{\phi}{T_h - T_c}$
C_t is the thermal conductance of the sample covering ($W \cdot m^{-2} \cdot K^{-1}$);
ϕ is the density of heat flow rate ($W \cdot m^{-2}$);
T_h, T_c are the temperatures on the hot and cold surfaces of the sample at time t (K).

The values of the thermo-optical characteristics of the covering materials are shown in Table 1. Each greenhouse covering solution had different performance values. The best solution does not exist, but each covering material is close to the ideal solution. The ideal solution should allow higher light transmission in order to facilitate the tomato plant's growth, lower g-value to limit summer overheating, and lower U to limit winter heat loss. This is a classic problem of compromise programming, which determines the ranking among the various solutions with reference to their distance from the ideal one. To calculate the distance, the formula in [4] was applied.

$$Euclidian\ distance\ to\ \ ideal\ solution\ D_{j=} \sqrt[2]{\sum_i (d_{i,j})^2} \tag{4}$$

where: $d_{i,j} = \frac{y_i^* - y_{i,j}}{y_i^* - y_i^\#}$

with y_i^* = ideal value of parameter i
$y_i^\#$ = anti-ideal value of parameter i

The best result was the solution composed of a 6 mm double-layer polycarbonate coupled with the UbiGro film (P6UG) (Figure 4).

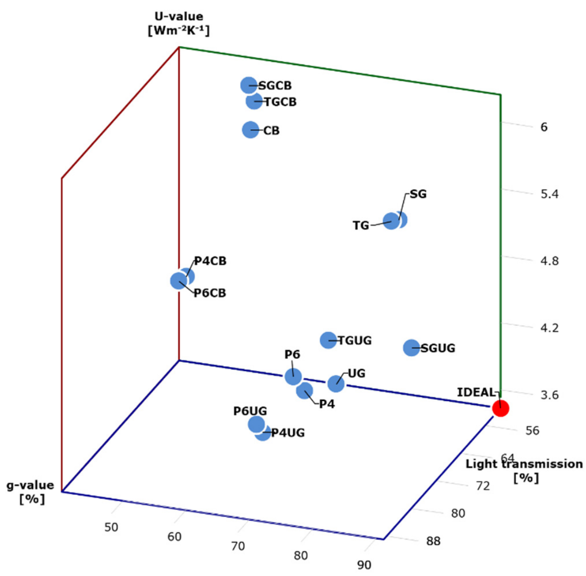


Figure 4. Euclidean distances between the values of the properties of the coverings and the values of the ideal solution.

2.3. Energy Analysis

Energy analysis was carried out using the Design Builder version 6.1 software, which is tightly integrated with EnergyPlus, providing advanced dynamic thermal simulation in sub-hourly time steps [34]. The energy analysis was conducted with reference to the hourly weather data from the international weather for energy calculation for Reggio Calabria (Lat 38.20, Long. 15.55, elev. 51.00 m) (Figure 5). The simulation considered the transmitted solar gains, i.e., short-wave solar radiation transmission through all external coverings. When using a transparent covering, part of the solar radiation passes through the covering while part of it is reflected to the outside. The heating effect of solar radiation on internal opaque components was taken into account in the heat conduction data (greenhouse effect). The covering material consisting of 6 mm double-layer polycarbonate with the UbiGro film was used in the greenhouse energy model. The energy model was developed by integrating a detailed HVAC system. It was composed of three different Loops: the cooling loop that cooled the water using a SWAC heat exchanger, the heating loop that heated the water using an electric boiler, and the zone water-to-air heat pump that used water from its source to thermally condition the air inside the greenhouse using fans (Figure 6a). The cooling loop was based on a deep pond heat exchanger. The condenser loop model represented a deep pond of seawater with submerged hydronic tubes through which the heat transfer fluid circulated. This model was a simplified model of a SWAC heat exchanger in that no attempt was made to model any stratification effects that may be present in the deep sea. The pond may be specified as the only heat exchanger on the condenser loop, or it may be connected in parallel with other condenser loop heat exchangers (such as cooling towers and ground surface heat exchangers). To simulate the "strait of Messina", a stretch of the sea near Reggio Calabria, a pond with a depth of 500 m and an area of 10,000 m^2, and 1 hydronic tubing circuit with a length of 50 m, an inside diameter of 5 cm, a thickness of 2 mm, and tube conductivity of 395 W·m^{-1}·k^{-1} were used. The water was the fluid used in the loop and EnergyPlus accurately modelled the fluid temperature at each time point in the simulation. The temperature setpoint range for the greenhouse air temperature was 15–23 °C, which is the temperature range for optimum tomato growth (Figure 5).

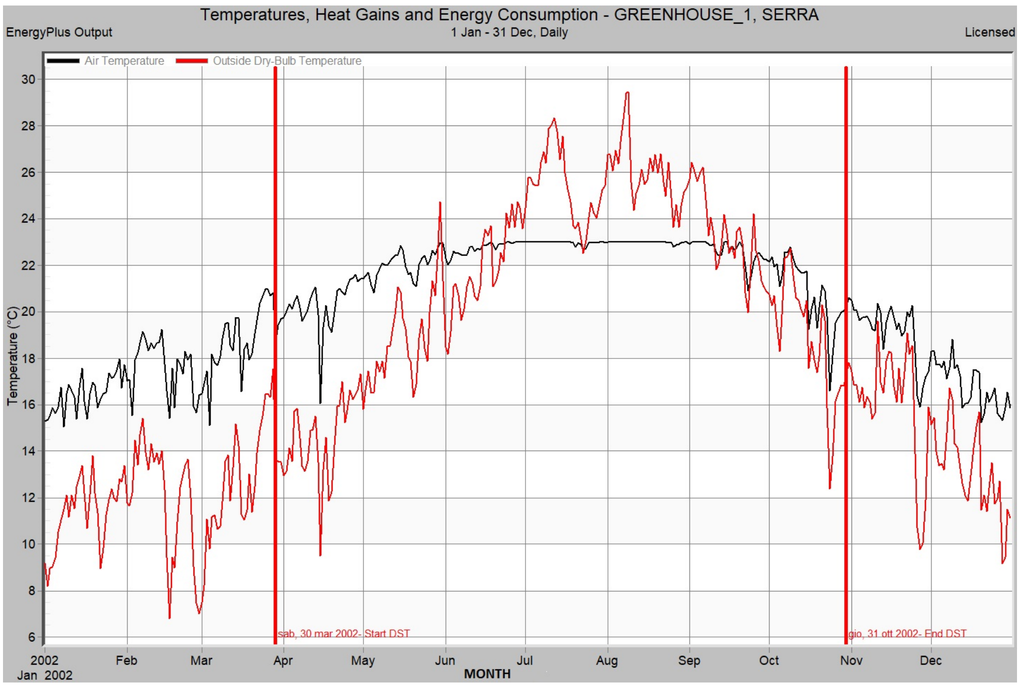
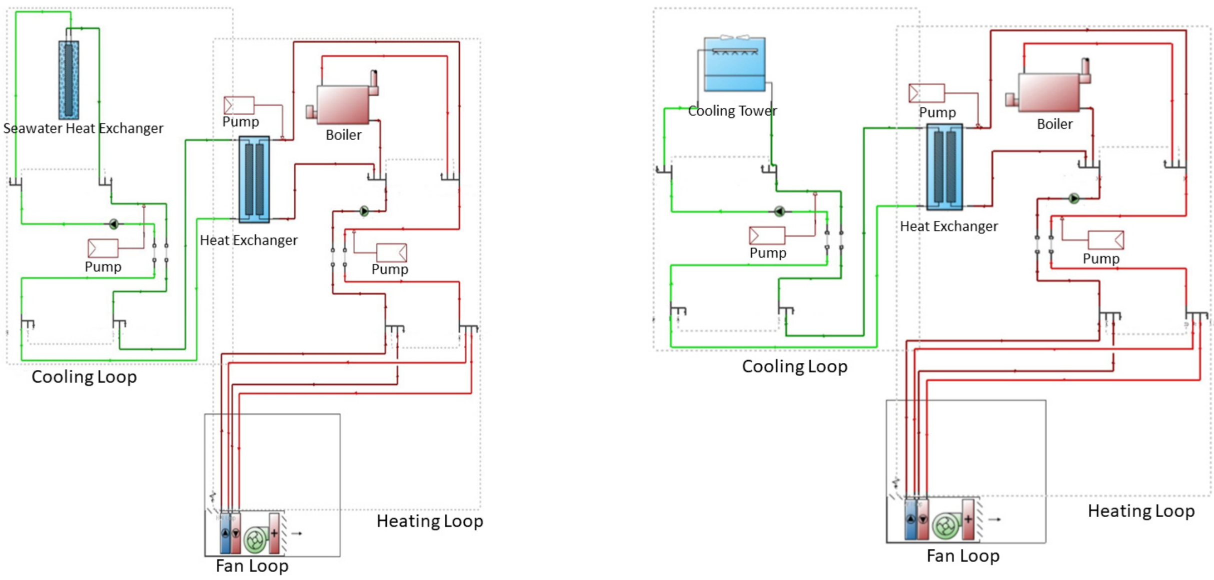


Figure 5. Yearly temperatures (°) outside and inside the greenhouse.



(**a**) (**b**)

Figure 6. Schematics of the HVAC systems. (**a**) cooling using a SWAC exchanger (**b**) conventional HVAC with a cooling tower.

It was assumed that there was no air exchange with the exterior. In order to evaluate the energy performance of the HVAC system proposed, the yearly energy consumption was compared to that of a conventional greenhouse with the same setpoint air temperature range of 15–23 °C. The fuel used to generate cooling energy for the conventional greenhouse was electricity and the capacity of the HVAC system was auto-sized using the cooling design calculations, a specific tool in the Design Builder [35]. In the conventional model, a cooling tower was placed on the supply side of the condenser loops. It was modelled as a counter-flow heat exchanger with a single speed based on Merkel's theory [36]. Tower performance was defined using the heat transfer coefficient-area product (UA) and the water flow rate. The model also considered tower performance in the "free convection" regime, when the tower fan was off but the water pump remained on and heat transfer still occurred (albeit at a low level) (Figure 6b). The energy simulation was run for all 365 days of the year and an hourly output interval was selected for reporting the results. Another specific analysis was carried out on a model with 6 mm polycarbonate coupled with the clarix blue film (P6CB) covering to evaluate the energy-saving effect of the adoption of a low g-value covering. As a matter of fact, among all the examined solutions, P6CB had the lowest g-value. Two HVAC types—one with SWAC and the other with conventional tower cooling—were also considered for this model.

3. Results

The dynamic simulation was carried out in order to evaluate the electric energy spent on maintaining an inside temperature range of 13–25 °C in all the seasons in the year in the greenhouse with the HVAC system proposed and the greenhouse with a conventional cooling tower. The geometric configuration and the building components evaluated were similar for both greenhouses. The P6UG solution had a low solar heat gain coefficient and therefore a low need for cooling energy and a low thermal transmittance. The dynamic energy simulation was able to evaluate the total energy spent on controlling the inside air temperature. It estimated the yearly electric energy needed for the heating and cooling loop, the plant loop hydraulic pumps, and the indoor fan system (Figure 7).

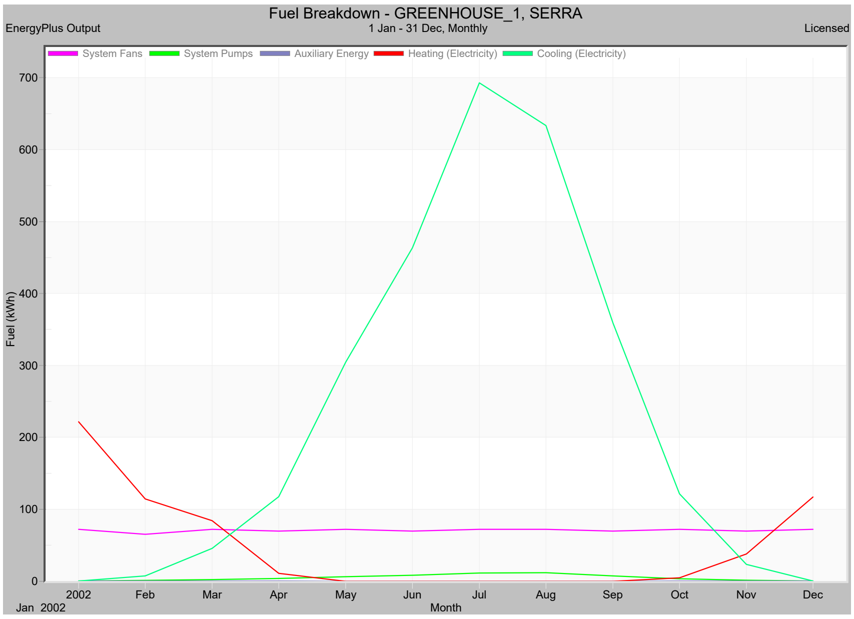


Figure 7. Yearly energy used by the greenhouse with the SWAC system and the P6UG covering.

Analysing Figure 7, it is possible to observe that in the first months of the year, the energy required for heating increases and that required for cooling decreases. On 7 March, the energy used for cooling was equal to the energy required for heating, which continued to decrease. The energy used for cooling increased until 1 July, after which it decreased until October 29, equalling the energy for heating, which increased during the cold season. The results (Table 2) showed that the highest energy was spent on cooling in both the analysed models. It was about 7.12 times the heating energy in the proposed HVAC system and 8.27 times that in the conventional HVAC system. The results highlighted the best energy performance of the proposed system, especially for the cooling loop that had a yearly usage of 3047.00 kWh compared to 3534.00 kWh used by the conventional cooling tower loop. The proposed HVAC method enabled total annual energy saving of more than 10%, with an easier cooling system without complex mechanical parts. This solution also enabled a maintenance cost saving. This result is in accordance with that of [37]. These values were determined by a maximum outside dry-bulb temperature of 29.4 °C, measured on 8 August. The energy saved was a result of the better cooling performance of the SWAC heat exchange allowed an energy saving of about 14% on cooling. Of the two HVAC cooling systems, the yearly energy saving on the energy model with the P6CB covering was slightly lower (about 8%). The comparison between the models with the P6UG covering and the SWAC cooling system and the model with the P6CB covering and the tower cooling system highlighted an energy saving of about 20%, which resulted in controlling the inside temperature. This high value depends on the heating energy spent on maintaining the inside temperature at up to 13 °C during cool periods. P6CB has lower light transmission and higher thermal transmittance compared to P6UG. This difference resulted in a lower increase in the inside temperature due to less irradiation from the sun and higher heat loss due to thermal conduction. It is interesting to note that, with the same SWAC cooling system, the greenhouse with P6UG used more energy for cooling (about 10%) and the hydraulic pumps (about 11%) than the greenhouse with P6CB, which used less energy for heating (about 33%) (Figure 8).

Table 2. Values of the electric energy used by the HVAC system in the greenhouses (for each covering system analysed).

	SWAC COOLING		TOWER COOLING	
	P6UG	**P6CB**	**P6UG**	**P6CB**
Cooling (kWh)	3047.00	2751.00	3534.14	3176.00
Heating (kWh)	428.00	1288.00	427.42	1286.00
System Pumps (kWh)	63.51	57.00	64.00	58.00
System Fans (kWh)	897.48	962.00	897.48	962.42
TOTAL (kWh)	4435.99	5058.00	4923.04	5482.42

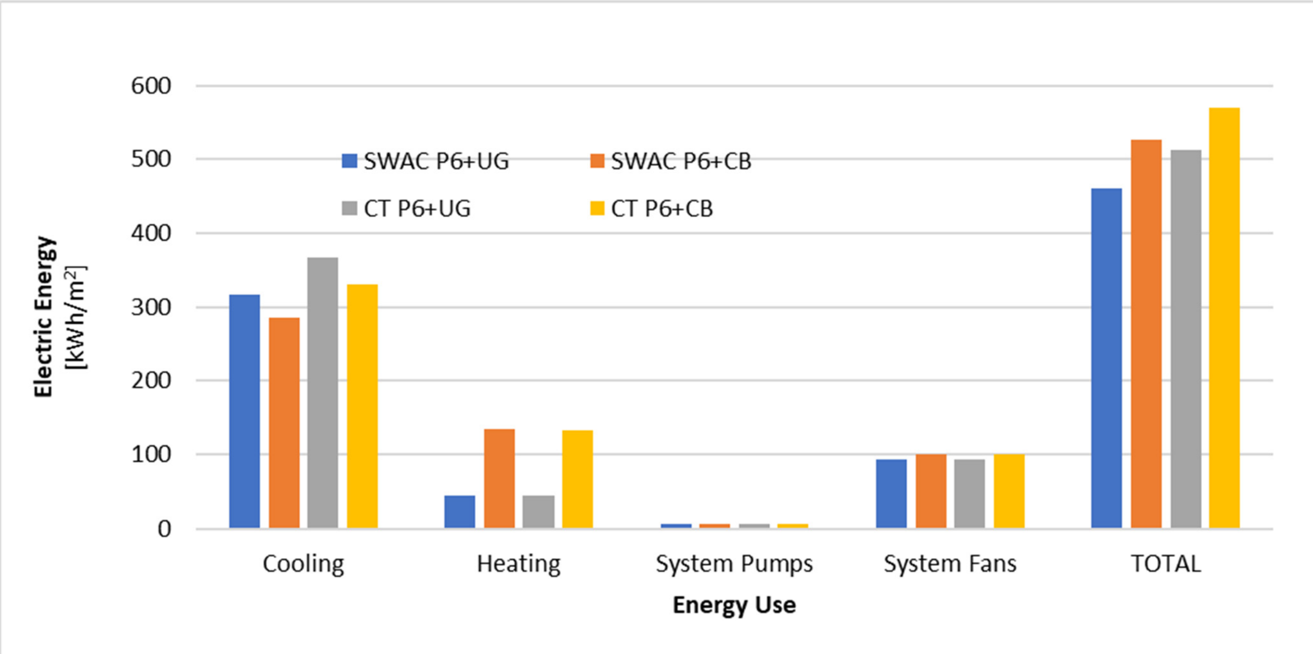


Figure 8. Comparisons of energy per square meter spent by the different greenhouses analysed.

4. Discussion

In this work, different greenhouse covering solutions and the energy performance of an unusual cooling loop system, based on a seawater heat exchanger, were analysed. Energy simulation using Energy Plus, a specialist software programme used for dynamic thermal analysis [38], confirmed the better energy performance of the SWAC cooling system compared to the conventional system (based on the cooling tower). The SWAC cooling system is currently not very common, although it is based on an easier apparatus than the conventional cooling system that is based on a cooling tower with a lot of moving parts (pumps, pulley, fans, fluid pressure, etc.). Undoubtedly, it is essential for the greenhouse to be located near the sea or a lake. For these reasons, a greenhouse on a sea platform could enable easier installation of this efficient cooling system, guaranteeing less management costs. The energy analysis that was carried out using Energyplus highlighted the effect of the covering material on the energy spent on controlling the inside temperature. In fact, materials with lower g-values allow energy saving for cooling. Moreover, less light transmission limits not only light for the plant's photosynthetic activity but also heating through the sun's irradiation. In addition, a material with high thermal transmittance facilitates heat loss through the envelope in cold seasons. The installation of the offshore greenhouses offers some advantages, such as less shade, more sun irradiation, and SWAC for cooling. It is also a good solution to limiting land use. Besides these advantages, it is suitable to analyse some disadvantages, such as the effects of the sea salt aerosol, which affects plant growth but also influences light transmission through the covering, although the sea spray causes the albedo effect. In particular, it is necessary to verify the wind resistance of the structure and the greenhouse covering materials because wind pressure is higher than on land. The energy simulation was carried out with reference to some optical and thermal parameters of some covering materials found on the market. The companies do not often supply technical information and sometimes the methods for measuring the parameters are not comparable. For this reason, a simple and fast method of measuring the g-value, light transmission, and thermal transmittance of the covering materials was proposed. This method allowed us to obtain comparable values because the measurements were taken under the same environmental conditions. The proposed procedure allowed the technicians to use a portable instrument to evaluate the main optical and thermal properties of the greenhouse covering system on site, though it had low measurement accuracy. This was an important opportunity because it allowed the analysis of energy use by the existing greenhouse. Future research will validate the standardization procedure.

5. Conclusions

Conventional agricultural practices will not be able to respond to the rise in the demand for food production, which involves higher energy and water consumption and increases proportionally with the rise in the global population. Population growth calls for a rise in food production to ensure future food security. Furthermore, climate change, which results in environmental degradation, limits food production systems. The global demographic trend highlights the continued concentration of the population in coastal regions, thus predicting that the coastal population will rise by 50 % by 2030 [39]. For these reasons, it is necessary to support food security in coastal communities with sustainable solutions. The main aim of this study was to promote the adoption of new decentralized floating controlled environmental agricultural systems for vegetable production. The greenhouse system proposed in this study allows coastal inhabitants to produce vegetables all year round with minimum utilisation of energy and water resources, making food production flexible and secure. Moreover, a simplified procedure was proposed to evaluate the thermal and photometric characteristics of the covering material. Such parameters are essential for building the correct greenhouse model for accurate energy simulation. The energy values of the analysed greenhouses were obtained using tomato cultivation; different values are likely to be obtained for different vegetable species. Finally, in order to validate the numerical analysis, future research should monitor and analyse the performance of a real greenhouse prototype. The obtained results indicate possible future directions for offshore greenhouses to develop independent production units with integrated photovoltaic modules, a water treatment plant, and smart remote-control systems. It is very important to investigate and search for innovative agricultural systems that enable more sustainable vegetable production to meet the needs of independent food production and small population groups.

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Nomenclature

U	thermal transmittance
g-value	total solar energy transmittance
E_{in}	internal solar radiation power
E_{ext}	external solar radiation power
LT	light transmission
L_{in}	indoor illuminance value
L_{out}	indoor illuminance value
R_{si}	liminar resistances on the inner surface
R_{se}	liminar resistances on the outer surface
C_t	thermal conductance
Φ	density of heat flow rate
T_h, T_c	temperatures on the hot and cold surfaces

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