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Assessment of the energy consumption of indoor farming for different climates and lighting system intensity

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Abstract. Nowadays, due to the energy, water, and arable land crises, as well as the constant global population growth and urbanization, water, energy, and food sources are strongly linked to each other, and a comprehensive analysis including all the influencing factors has to be carried out. In this context, the need to improve the energy performance of traditional cultivation systems, as well as to develop alternative and innovative ones, is causing a shift in interest from greenhouses to indoor farming methods (such as vertical farms) in the agricultural sector. In fact, they allow for completely controlled crop production without the use of chemical pesticides. Moreover, their productivity is independent of external conditions and improved compared to traditional systems. However, their energy consumption is larger than that of greenhouses. To evaluate the techno-economic feasibility of such systems, a comprehensive model of a vertical farm, including air conditioning, lighting systems, and plant evapotranspiration, has been developed to quantify the energy share for the different elements of the system (air conditioning and lighting) and to relate the energy consumption to the kilogram of produced crop, analysing exclusively the growth phase. The analysis is carried out for different cities and considers different scenarios in terms of lighting and electricity costs.

1. Introduction

Nowadays, more than 795 million people in the world are malnourished, and 1.4 billion people cannot access electricity. Furthermore, the increasingly reduced variety of crops in the agricultural sector (since 1990 it has lost 75% of crop varieties) [1] represents a serious problem that needs to be addressed. To mitigate the catastrophic effects of the aforementioned issues, the United Nations has set several goals to be achieved by 2030: to end hunger, poverty, and malnutrition, and to ensure sustainable and healthy food production in the agricultural sector, increasing productivity while limiting environmental impact. It is well-known that in recent decades, due to constant global population growth, urbanization, pest use, climate change, degradation and scarcity of the resources, the agricultural sector has been heavily stressed. In detail, it is the largest user of water, accounting for 70% of total global freshwater withdrawals [2], with a projected increase of about 55% by 2050 [3]. Moreover, energy consumption in the agricultural sector represents 3% and 2% in the European and Italian scenarios, respectively [4] and it is expected to globally increase about threefold by 2050 [5]. Additionally, the global population is projected to reach 9.8 billion by 2050 and 11.2 billion by 2100, with intense urbanization affecting more than 70% of the world's population [6].

All these aspects will contribute to a 60% intensification in energy consumption in the food production sector by 2050 (already accounting for 30% when considering the cold chain and the transport sector as well) [7][8]. This scenario is exacerbated by the scarcity of arable land and the extensive use of pesticides and chemical substances. In fact, approximately 1.9 million tons of them were employed in the agricultural sector in the EU context during 2019 [9][10]. The objectives set by the United Nations are to improve the energy performance of traditional agricultural methods and to develop alternative and innovative ones, considering the ongoing energy transition, such as indoor farming methods. Traditional farming methods are affected by several issues, including production uncertainty and high-water consumption, which is significantly higher compared to vertical farms [11][12][13]. Vertical farms (VFs) consist of completely controlled environments where optimum conditions for crop growth in terms of temperature, relative humidity, and lighting are achieved using air conditioning systems and artificial lighting, while constantly monitoring CO_2 levels [14]. VFs are becoming increasingly popular in very cold climate regions with low solar radiation and arid regions with water scarcity. However, the main drawbacks are the high investment costs and energy consumption, which are significantly higher compared to traditional greenhouse systems [15][16]. Several studies in the literature analyse the techno-economic feasibility of vertical farms from different perspectives. Kozai et al. [14] conducted a comparison between VFs and greenhouses in terms of water use, CO_2 use, electricity use, and inorganic fertilizer use efficiency. Similar analyses were carried out by Harbrick et al. [13] and Graamans et al. [11], considering four different climates in the US and EU, comparing them in terms of energy use and environmental impact. Finally, Avgoustaki [17] compared vertical farms and greenhouses for basil production, evaluating their productivity, energy consumption, and resource use efficiency. Since one of the main drawbacks of th VF systems is the higher energy consumption due to the lighting system, different studies addressed the possibility to integrate renewable energy sources such as PV panels in order to reduce their energy consumption. Cossu et al [18] integrated a VF system with a pre-existing photovoltaic greenhouse for the growth of baby-leaf lettuce in order to maximize the system productivity and minimize the CO_2 emissions, while taking advantage in the use of PV panels combined with VF system. Yalcin et al [19] studied a novel lighting system to be employed in vertical farms which consists of parabolic collector which collects the sunlight and splitters and optical fibres which transmit it to the internal ambient of crop growth. Finally, Teo et al [20] simulated the energy and environmental performances of a vertical farm system integrated with solar panels, founding a reduction in the energy consumption up to 12%. For the best of authors' knowledge, no studies in literature propose a thermo-economic analysis of VFs in which their productivity is correlated to the annual energy consumption with reference to the geographical location and to the specific cost for electricity. To achieve this aim, a thermo-economic model of a VFs has been developed, taking into account each component of the system (air conditioning, lighting system and plant evapotranspiration) to attribute the cost of energy expenditure to kg of harvest.

2. Method

To assess the energy consumption of a vertical farm and its relationship to the kilogram of harvested product in different climate regions, the following methodology has been implemented. In Figure 1 the schematization of the considered vertical farm system with all the potentially energetic loads is shown:

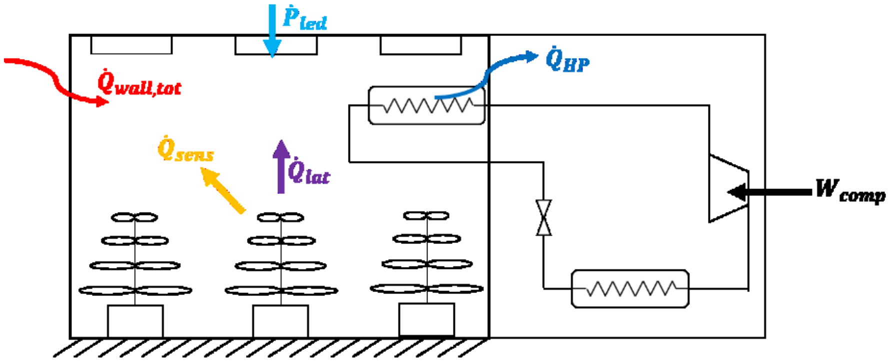

Figure 1 - Vertical farm schematization with the potentially energetic loads.

In the above schematization, $\dot{Q}_{wall,tot}$ is the incoming/outgoing thermal load exchanged with the external ambient through the walls and the roof of the plant, $\dot{P}_{led}$ is the power of the installed LEDs, $\dot{Q}_{sens}$ is the sensible thermal load of the plants, $\dot{Q}_{lat}$ is the latent thermal load caused by the canopy evapotranspiration process and $\dot{Q}_{led}$ is the thermal load caused by the lighting system. Finally, $\dot{Q}_{HP}$ is the thermal load of the installed chiller/heat pump that keeps constant the temperature level within the growth cell, depending on the photo/dark period during the growth cycle. All the thermal loads are evaluated in kW.

2.1. Crop transpiration and energy balance

The net thermal load intercepted by the crops is a rate of $\dot{P}_{led}$ and is given by the following equation:

$$\dot{I}_{net,canopy} = \dot{P}_{led} \cdot \eta_{led} \cdot CAC \cdot (1 - \rho_R) \tag{1}$$

In Equation (1) η_{led} is the LEDs efficiency, CAC is the cultivation area cover factor and ρ_R is the reflection coefficient. Only a rate of $\dot{I}_{net,canopy}$ [kW] contributes to the growth of the crops and it is indicated as $PPFD$ [μmol·m^{-2}s^{-1}], evaluated by Equation (2):

$$PPFD = \dot{I}_{net,canopy} \cdot \eta_{led,PAR} \tag{2}$$

In the Equation (2), the term $PPFD$ represents the photosynthetic photon flux density and $\eta_{led,PAR}$ is a conversion factor [μmol·J^{-1}] that takes into account that only a rate of the net radiation intercepted by the crops for their growth. The latent thermal load caused by the evapotranspiration process of the canopy $\dot{Q}_{lat}$ is evaluated through the following equations implementing the model of Graamans et al [21]:

$$\dot{Q}_{lat} = LH \cdot A_{grow} \tag{3}$$

$$LH = LAI \cdot \lambda \cdot \frac{VCD}{r_s + r_a} \tag{4}$$

$$r_a = 350 \cdot \left(\frac{l}{u_\infty}\right)^{0.5} \cdot LAI^{-1} \tag{5}$$

$$r_s = 60 \cdot \frac{1500 + PPFD}{200 + PPFD} \tag{6}$$

In the Equations (3-6) LH is the latent heat caused by the evapotranspiration of the crops [kW·m^{-2}], A_{grow} [m^2] is the growth surface of the crops, LAI is the leaf area index and can be assumed as a constant value as all the stages of the growth process are considered to be present during the cultivation period of the crops as stated in [22]. The VCD [kg·m^{-3}] term is the vapour concentration deficit between the leaf and the air, u_∞ is the uninhibited velocity of the air [m·s^{-1}] and λ [kJ·kg^{-1}] is the latent heat of vaporization. Finally, r_s and r_a are the leaf surface resistance to the vapour transfer and the aerodynamic one, respectively [m·s^{-1}]. The sensible thermal load exchanged by the plants $\dot{Q}_{sens}$ is evaluated through an energy balance applied to the leaf surface of the crops by Equation (7):

$$\dot{Q}_{sens} = \dot{I}_{net,canopy} - \dot{Q}_{lat} \tag{7}$$

Then, the sensible heat exchanged by the plants (SH) is evaluated by dividing the sensible thermal load by the crop's growing surface. It is well-known that the sensible heat depends on the temperature difference between the transpiring surface and the surrounding air. Therefore, it is possible to calculate the air temperature of the growth cell T_a [°C], required to guarantee the desired leaf temperature of the crops, namely T_s, which in the present study is fixed to a constant value of $24°C$ in order to ensure proper crop growth [23]:

$$T_a = T_s - \frac{SH \cdot r_a}{\rho_a \cdot c_{p,a} \cdot LAI} \tag{8}$$

2.2. Energy model for the wall losses

Once the air temperature is evaluated through equations (3-8), the thermal load of the cell through the walls and the roof $\dot{Q}_{wall,tot}$ can be calculated as the sum of the thermal load of the walls and roof of the plant $\dot{Q}_{wall,j}$:

$$\dot{Q}_{wall,tot} = \sum_{j=1}^{M} \dot{Q}_{wall,j} \tag{9}$$

The thermal load exchanged with the external ambient of the generic j-th wall is evaluated by taking into account the radiative, convective and conductive contributions to the heat transfer mechanism as reported in Equations (10-12):

$$\dot{Q}_{wall,j} = UA_j \cdot (T_{ext} - T_a) + \dot{Q}_{solar,j} \tag{10}$$

$$\dot{Q}_{solar,j} = G \cdot A_j \cdot \alpha \cdot cos(\vartheta) \tag{11}$$

$$U_j = \frac{1}{\left(\frac{1}{h_{ext}} + \frac{s}{k} + \frac{1}{h_{int}}\right)} \tag{12}$$

In Equations (10-12) T_{ext} [°C] is the external ambient temperature during the whole year, G is the solar radiation [W·m^{-2}], ϑ is the angle of incidence of the solar radiation, h_{ext} and h_{int} [W·m^{-2}· K] are the external and internal convective heat transfer coefficients, respectively, α is the absorption coefficient, A_j [m^2] is the surface of the generic j-th wall, s [m] and k [W·m^{-1}·K^{-1}] are the thickness of the walls and the insulating material's conductivity, respectively. The analysis was carried out by considering the hourly temperature profile of different climate regions during the whole year.

2.3. Vertical farm energetic model

Once the thermal load $\dot{Q}_{wall,tot}$ is evaluated during the whole year, it is possible to calculate the thermal load of the installed chiller/heat pump $\dot{Q}_{HP}$ by considering the energy balance reported in Equation (13):

$$\dot{Q}_{wall,tot} + \dot{P}_{led} = \dot{Q}_{HP} \tag{13}$$

2.4. Vertical farm thermo-economic model

In order to relate the energy consumption [kWh·kg^{-1}] of the growth cell to the kilogram of crop produced, the following methodology has been implemented. By knowing the quantity of lettuce m_p and the time interval $\Delta\vartheta$ in which the analysis is carried out –assumed as 1h – the energy consumption is evaluated as reported in Equation (14):

$$E_{lettuce} = \left(\frac{\dot{Q}_{HP}}{COP} + \dot{P}_{led}\right) \cdot \Delta\vartheta \cdot \frac{1}{m_p} \tag{14}$$

The quantity of lettuce grown in the cell, namely m_p, is evaluated by considering a production cycle of 29 days and assuming a reference yield, Y_{ref}, of 6.25 kg·m^{-2} as indicated in the reference [22]. The number of cycles during the year is assumed to be 12 [22]. Furthermore, the productivity of the system is strongly dependent on the lighting system radiation, which linear dependency is evaluated with the term F_{PPFD}, calculated in Equation (15):

$$F_{PPFD} = \left(\frac{PPFD_{actual}}{PPFD_{target}} - 1\right) \cdot 0.74 + 1 \tag{15}$$

$PPFD_{actual}$ is the actual $PPFD$ supplied by LEDs whereas $PPFD_{target}$ is the target of $PPFD$ used in the manuscript [22]. For each cycle of production, it can be assumed that the yield of the system is equal to:

$$Y = F_{PPFD} \cdot Y_{ref} \cdot A_{grow} \tag{16}$$

The yield dependency on the crop surface temperature is neglected since, as specified before, a constant temperature is ensured. Since the vertical farms is a completely-controlled ambient in terms of temperature and relative humidity, the yearly dynamic simulation are carried out in quasi-steady state conditions. The coefficient of performance of the chiller/heat pump serving the plant is hourly evaluated by simulating a standard vapor compression cycle, using R134a as refrigerant (whose transport and thermodynamic properties are calculated by using Refprop 9.1 [24] software), and assuming that the system always counterbalances the total thermal load of the plant and guarantees the desired internal conditions within the cell. The coefficient of performance COP is:

$$COP = \frac{\dot{Q}_{HP}}{\dot{W}_{comp}} \tag{17}$$

Finally, the rate of cost for energy – named RCE [€·kg^{-1}] – for the kilogram of grown product is evaluated by multiplying the total energy consumption during the year and the specific cost for electricity:

$$RCE = \sum_{i=1}^{N_{step}} \left(E_{lettuce,i}\right) \cdot specific\ cost\ of\ electricity \tag{18}$$

3. Results and discussion

3.1. Case study description

The model described in the previous section has been executed in Matlab [25] to carry out an assessment of both energy consumption and costs for a vertical farm producing lettuce, by considering different climate conditions in the cities of Naples, Milan, Helsinki and Dubai and various levels of $PPFD$ on the plant. In Figure 2 is reported the external thermal load ($\dot{Q}_{wall,tot}$) profile for each city during the year whereas the parameters adopted in the simulations are shown in Table 1:

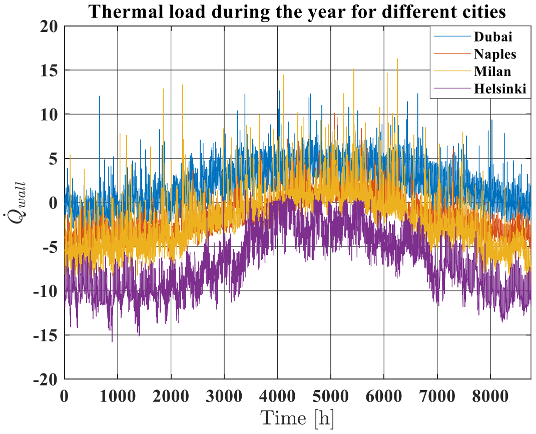

Figure 2 - Yearly external thermal load profile through the walls and the roof of the cell for each considered climate.

Table 1 - Parameters for the simulation of the vertical farm.

Quantity	Value	Quantity	Value	Quantity	Value
Climate zone	Naples, Milan, Helsinki, Dubai	$PPFD$	250 – 375 – 500	s	0.01
Leaf temperature	24/18	Growth cycle duration [day]	29	k	0.023
Photoperiod [h]	16	Number of cycles during the year	12	ρ_R	0.05
Number of growth cells	5	$PPFD_{target}$	250	h_{int}	7.7
Dimension of growth cell [m]	48x7.2x6.5	LAI	2.1	λ	2260
Y_{ref}	6.25	CAC	0.95	VCD	5·10-3
η_{led}	0.52	$\eta_{led,PAR}$	2.3		

3.2. Energetic analysis

In Figure 3a, the total energy required for each city is shown with respect to the different levels of PPFD. It is evident that increasing the PPFD, and therefore the power required from the LEDs, the total energy demand of the vertical farm increases significantly, regardless of the climate. However, also the productivity increase with the lighting, passing from 1170 ton·year^{-1} with a PPFD of 250 µmol·m^{-2} ·s^{-1} to 2060 ton·year^{-1} with a PPFD of 500 µmol·m^{-2}·s^{-1}. When comparing the different analysed climates, it can be observed that the total energy demand decreases in colder climates. This is due to the fact that in warmer climates, for a fixed PPFD level and LED consumption, there is a higher energy demand for cooling purposes, as the external load ($\dot{Q}_{wall,tot}$) is higher. On the other hand, in colder climates, the remarkable heat emission from the LEDs leads to a decrease in the heat required from the heat pumps to maintain the appropriate temperature in the growth chamber. As a result, in Dubai, the energy demand is approximately 15% higher than in Helsinki. This observation is supported by Figure 3b, which demonstrates that, despite the total energy required by the LEDs being the same for each city at a fixed PPFD, it represents nearly 80% of the total energy demand in Dubai, while in Helsinki, it exceeds 90%. This indicates that in the latter case, the energy consumption of the air conditioning system is reduced. From Figure 4, it is evident that for a given PPFD and productivity, the yearly specific energy consumption (kWh·m^{-2}year^{-1}) is significantly higher in warmer climates. Moreover, it is worth noting that the increase in $PPFD$ brings to higher productivity, passing from 75 kg m^{-2}·year^{-1} with a $PPFD$ of 250 µmol·m^{-2}·s^{-1} to 130.5 kg·m^{-2}·year^{-1} with a $PPFD$ of 500 µmol·m^{-2}·s^{-1}.

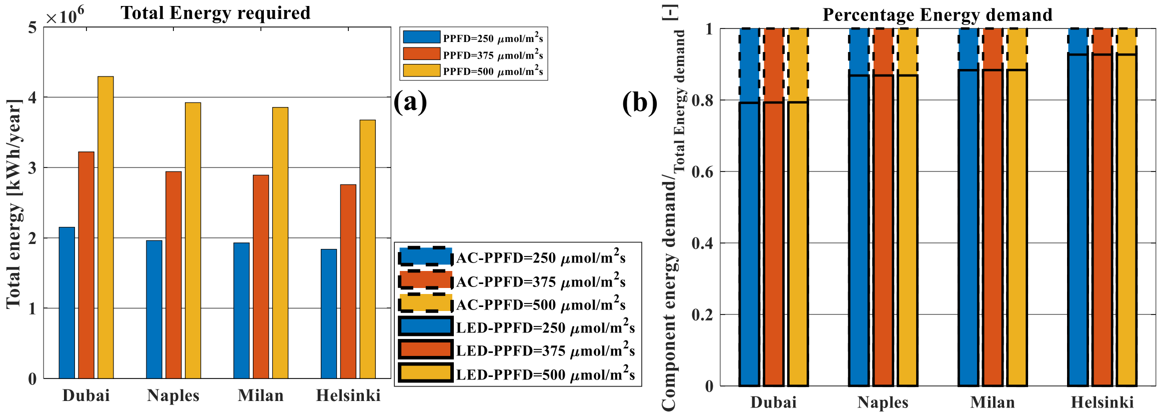

Figure 3 – For different climate regions and PPFD levels (250, 375 and 500 $\mu mol/m^2 s$):(a) Total energy required with respect of three PPFD levels.(b) Percentage energy demand for Air conditioning (AC) and lighting (LED) for different PPFD levels.

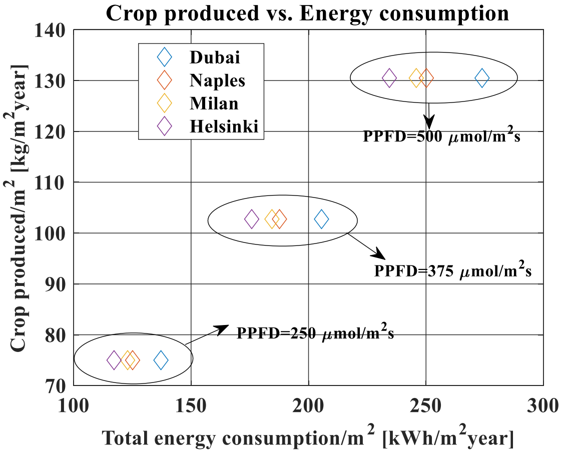

Figure 4 - Crop produced per m^2 with respect to the total energy consumption per $m^2$for different climate regions for three different PPFD.

3.3. Economic analysis

The economic analysis is conducted by considering different specific costs for electricity (0.05, 0.1, 0.2 and 0.3 €·kWh^{-1}), to account for variations due to market conditions in each city and country analysed. As depicted in Figure 5a, for each city, considering a $PPFD$ of 250 µmol·m^{-2}·s^{-1}, the RCE of the product is highly affected by the electricity costs. As a matter of fact, considering Dubai, for the electricity cost of 0.05 €·kWh^{-1}, RCE is lower than 1 €·kg^{-1}, while it becomes higher than 5.3 €·kg^{-1} when the electric kWh electric 0.3 €.

In Figure 5b is shown the RCE for an electricity cost of 0.05 €·kWh^{-1} and different values of the $PPFD$. It is evident that the RCE slightly enhance due to the higher energy consumption. Nevertheless, also the productivity rises, thus the profitability of the choice to increase the $PPFD$ depends also on other factors, such as costs for sanitization of structure, workforce and maintenance services. However, comparing Figure 5a and Figure 5b, it is worth nothing that the price of electricity has a higher impact on RCE compared to lighting intensity.

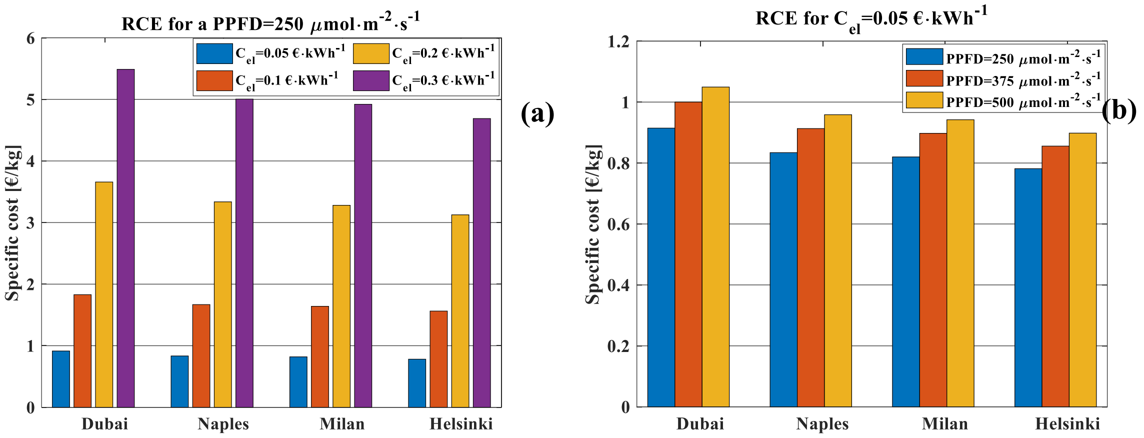

Figure 5 – Rate of cost for energy related to the kilogram of grown product: (a) RCE for a PPFD of 250 µmol·m^{-2}·s^{-1} and different electricity prices; (b) RCE for an electricity cost of 0.05 €·kWh^{-1} and different PPFD.

4. Conclusions

In this paper, an assessment of energy consumption and costs for a vertical farm producing lettuce has been conducted, considering different climate regions, lighting system conditions, and economic scenarios in terms of specific cost for electricity.

The system's energy demand increases with higher $PPFD$ levels. Simultaneously, also the productivity increase (from 1170 ton·year^{-1} with a $PPFD$ of 250 µmol·m^{-2}·s^{-1} to 2060 ton·year^{-1} with a $PPFD$ of 500 µmol·m^{-2}·s^{-1}). When comparing different cities, colder climates exhibit lower total energy demand due to reduced cooling requirements. Specifically, Dubai's energy demand is 15% higher than Helsinki's. furthermore, by fixing the PPFD level and thus the system productivity, in warmer climates the yearly specific energetic consumption, for each m^2 of cultivation, is significantly higher compared to the colder ones. The economic analysis has been carried out by assuming different specific cost for electricity in each considered climate and different PPFD levels. At a fixed price the RCE slightly increases with $PPFD$, whereas, by fixing the lighting level, the increase of electricity costs causes a huge rise in RCE index. Finally, in each considered climate region, scenarios with low electricity costs make the vertical farms a very interesting solution, with crop production costs lower than 1 €·kg^{-1}.

It is worth noting that the results obtained in this study neglect minor energy consumption sources and focus only on the growth phase of the crop. Future works should account for all other processes occurring in vertical farms, before and after crop growth, to quantify the total energy consumption and cost of the entire crop production process. Moreover, to carry out a careful assessment of the profitability of VFs, future works should consider also the income increase with higher productivity in order to find the optimum between the increase in the yield (due to lighting intensity augmentation) and energy costs one, with the aim to maximize the revenues.

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References

[1] https://unric.org/it/obiettivo-2-porre-fine-alla-fame-raggiungere-la-sicurezza-alimentare-migliorare-la-nutrizione-e-promuovere-unagricoltura-sostenibile/

[2] Fao. 2011. The state of the world’s land and water resources for food and agriculture (SOLAW) – Managing systems at risk. Food and Agriculture, Organization of the United Nations, Rome and Earthscan, London.

[3] https://unesdoc.unesco.org/ark:/48223/pf0000225741_eng

[4] https://ec.europa.eu/eurostat/databrowser/view/NRG_BAL_S__custom_624870/default/table?lang=en

[5] Van Ruijven B J, De Cian E, Sue Wing I 2019 Nature Communication 10 2762

[6] United Nations, Department of Economic and Social Affairs, Population Division 2017 World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP/248.

[7] FAO (2014). Walking the Nexus Talk: Assessing the Water-Energy-Food Nexus in the Context of the Sustainable Energy for All Initiative. Climate, Energy and Tenure Division (NRC). Food and Agriculture Organization of the United Nations, Rome

[8] UNESCO (2014). WWAP (United Nations World Water Assessment Programme). The United Nations World Water Development Report 2014: Water and Energy. Paris.

[9] https://ec.europa.eu/eurostat/databrowser/view/AEI_FM_USEFERT/bookmark/table?lang=en&bookmarkId=4d3d0db8-76c1-4884-86e3-bdb23b1dae21.

[10] https://ec.europa.eu/eurostat/databrowser/view/AEI_FM_SALPEST09/bookmark/table?lang=en&bookmarkId=53792fd3-191d-4201-aab5-c01c67fd927c

[11] Graamans L, Baeza E, van den Dobbelsteen A, Tsafaras I, Plant factories versus greenhouses: Comparison of resource use efficiency, Agricultural Systems 160 31-43, 2018

[12] Ohyama K, Yamaguchi J, Enjoji A, Resource Utilization Efficiencies in a Closed System with Artificial Lighting during Continuous Lettuce Production, Agronomy 10 723, 2020

[13] Harbrick K, Albright L D, Comparison of energy consumption: greenhouses and plant factories, Proc VIII Int. Symp. On Light Horticolture, 2016

[14] Kozai T, Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory, Proc Jpn Acad Ser. B, 2013

[15] Al-Kodmany K, The Vertical Farm: A Review of Developments and Implications for the Vertical City Buildings 8, 24, 2018

[16] Goto E, Plant Production in a Closed Plant Factory with Artificial Lighting, Proc. 7th IS on Light in Horticultural Systems, 2012

[17] Avgoustaki D D, Xydis G, Indoor Vertical Farming in the Urban Nexus Context: Business Growth and Resource Savings, Sustainability, 12, 2020

[18] Cossu M, Tiloca M T, Cossu A, Deligios P A, Pala T, Ledda L, Increasing the agricultural sustainability of closed agrivoltaic systems with the integration of vertical farming: A case study on baby-leaf lettuce, Applied Energy, 244, 2023, 121278

[19] Yalcin R A, Erturk H, Improving crop production in solar illuminated vertical farms using fluorescence coatings, Biosystems Engineering, 193, 2020, 25-36

[20] Teo Y L, Go Y L, Techno-economic-environmental analysis of solar/hybrid/storage for vertical farming system: A case study, Malaysia, Renewable Energy Focus, 37, 2021

[21] Graamans L, van den Dobbelsteen A, Meinen E, Stanghellini C, Plant factories: crop transpiration and energy balance, 2017 Agricultural Systems, 153, 138-147

[22] Weidner T, Yang A, Hamm M, Energy optimisation of plant factories and greenhouses for different climatic conditions, 2021 Energy Conversion and Management

[23] Carotti L, Graamans L, Puksic F, Butturini M, Meinen E, Heuvelink E, Stanghellini C, Plant factories are heating up: hunting the best combination of light intensity, air temperature and root-zone temperature in lettuce production, Frontiers in Plant Science, 11, 2021

[24] Lemmon E W Mc Linden M O, Huber M L, 2009 REFPROP NIST Database 23

[25] MATLAB 2019a Release, Mathworks