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Increasing the agricultural sustainability of closed agrivoltaic systems with the integration of vertical farming: A case study on baby-leaf lettuce

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HIGHLIGHTS

- The experimental integration of closed agrivoltaics and vertical farming was studied.
- The land productivity and the environmental impact were assessed on baby-leaf lettuce.
- The yield increased by 13 times and the PV energy was essential for the profitability.
- The land consumption ranged from 5 to 14 times the vertical farm area.
- The optimal trade-off between PV energy production and land consumption was identified.

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ABSTRACT

The photovoltaic (PV) greenhouses are closed agrivoltaic (CA) systems that allow the production of energy and food on the same land, but may result in a yield reduction when the shading of the PV panels is excessive. Adopting innovative cropping systems can increase the yield of the CA area, generating a more productive and sustainable agrosystem. In this case study we quantified the increase of land productivity derived from the integration of an experimental vertical farm (VF) for baby leaf lettuce inside a pre-existing commercial CA. The mixed system increased the yield by 13 times compared to the CA and the average LER was 1.31, but only 12 % of the energy consumption was covered by the CA energy. To achieve the energy self-sufficiency and avoid the related CO_2 emissions, the VF area should not exceed 7–18 % of the CA area, depending on the PV energy yield and the daily light integral (DLI) of the LED lighting, meaning a land consumption from 5 to 14 times higher than the VF area. The support of the PV energy was essential for the profitability of the VFCA. Design features and solutions were proposed to increase the agronomic and economic sustainability of the VFCA. The VFs can be considered a possible answer for the reconversion of the actual underutilized CAs with high PV cover ratios into productive and efficient cropping systems, but a trade-off between energy production and land consumption should be identified to ensure an acceptable environmental sustainability of the mixed system.

1. Introduction

The greenhouse horticulture is characterized by a high energy demand for microclimate control [1] which affects the energy and environmental vulnerability of the countries with large and advanced greenhouse farming infrastructures [2]. The photovoltaic (PV) energy is one of the most promising sources for a significant energy production applied to greenhouse systems [3,4]. The PV greenhouse integrates the PV panels on the greenhouse roof and it is an example of closed agrivoltaic system (CA), in which the integration of energy and food production occurs in a protected environment. This dual land use of agrivoltaics can contribute significantly to the mitigation of climate change, resilience and stabilization of the food production sector [5]. All common horticultural crops grow with none or limited yield losses when the percentage of the projection of the PV panels on the roof to the greenhouse area (PV cover ratio) is under 20 %, and positive effects of the shade were reported when the solar irradiation was excessive on

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Nomenclature

μ_{led}	Energy conversion efficiency of the LED lamp (%)
μ_m	Conversion efficiency of the PV module (dimensionless)
μ_s	Conversion efficiency of the PV system on the greenhouse roof (dimensionless)
A_{CV}	Cultivation area of the VF (m^2)
A_f	Concrete floor area (m^2)
A_{kWp}	PV module area per unit of PV power (m^2 kWp^{-1})
A_r	Growth chamber wall area (m^2)
A_S	Heat exchange area to the air of the peat substrate (m^2)
BEP	Break-even point
BOS	Balance of System
CA	Closed agrivoltaic system
c_d	Cell degradation rate (% y^{-1})
C_L	Conversion factor from µmol to J of PAR of the LED lamp (µmol J^{-1})
COP	Coefficient of performance of the heat pump (dimensionless)
c_v	Caloric value (kJ 100 g^{-1})
CV	Coefficient of variation (%)
d	Days (d)
D	Dimmer (%)
DM	Dry matter content (%)
E_A	Energy consumption of the air conditioner (kWh)
EBC	Energy to biomass conversion efficiency (%)
E_{CA}	Energy production of the closed agrivoltaic system (kWh)
E_F	Energy consumption for fertigation (kWh)
E_H	Energy consumption of the dehumidifier (kWh)
E_{HVAC}	Energy consumption for the air conditioning (kWh)
E_{kWp}	PV energy yield per unit of PV power (kWh kWp^{-1})
E_{LED}	Energy consumption for LED lighting (kWh)
EUI	Energy Utilization Index (kWh kg^{-1})
E_V	Energy consumption for ventilation (kWh)
E_{VFCA}	Energy production of the integrated system (kWh m^{-2})
h	Photoperiod (h)
h_f	Floor heat transfer coefficient (W m^{-2} K^{-1})
h_r	Wall growth chamber heat transfer coefficient (W m^{-2} K^{-1})
h_s	Substrate heat transfer coefficient (W m^{-2} K^{-1})
I_g	Average monthly global radiation (kWh m^{-2})
k_1	Polystyrene foam thermal conductivity (W m^{-1} K^{-1})
k_2	Concrete thermal conductivity (W m^{-1} K^{-1})
k_f	Concrete floor thermal conductivity coefficient (W m^{-1} K^{-1})
k_r	Insulator thermal conductivity coefficient (W m^{-1} K^{-1})
k_s	Peat substrate thermal conductivity coefficient (W m^{-1} K^{-1})
k_s	Substrate thermal conductivity coefficient (W m^{-1} K^{-1})
LED	Light emitting diode
PAI	Photovoltaic area index (dimensionless)
P_{led}	LED lamp nominal power (W)
P_{led}	Power absorption of the LED lights (W)
P_m	Maximum power absorption (kW)
P_{max}	Maximum LED lamp power absorption (W)
P_{mc}	Air conditioner power (kW)
P_{md}	Dehumidifier power (kW)
P_{mf}	Fertigator power (kW)
P_{mv}	Destratificator power (kW)
PPE	Photosynthetic photon efficacy (µmol J^{-1})
PPF	Photosynthetic photon flux (µmol s^{-1})
PPI	Photovoltaic power index (kWp m^{-2})
PV	Photovoltaic
Q_A	Heat load for air conditioning (kWh_t)
Q_C	Heat transfer due to conduction (kWh_t)
Q_H	Heat exchange due to conduction (kWh_t)
Q_{LED}	Heat dissipated by the LED lamps (kWh_t)
Q_S	Heat absorbed by the substrate (kWh_t)
Q_V	Heat dissipation from dehumidifier and destratifiers (kWh_t)
RH	Relative humidity (%)
RUE	Radiation use efficiency (g mol^{-1})
RUE_d	Radiation use efficiency on dry weight (g mol^{-1})
RUE_f	Radiation use efficiency on fresh weight (g mol^{-1})
s_f	Floor thickness (m)
s_r	Insulator thickness (m)
TEC	Total energy consumption (kWh m^{-2})
T_g	CA temperature (°C)
TLI	Total Light Integral (mol m^{-2})
T_o	Outside temperature (°C)
T_r	Growth chamber temperature (°C)
T_s	Substrate temperature (°C)
VF	Vertical farm
VFCA	Vertical farm integrated in a closed agrivoltaic system
V_r	Growth chamber volume (m^3)
w_B	Ratio of blue light in the spectrum (dimensionless)
w_R	Ratio of red light in the spectrum (dimensionless)
w_W	Ratio of white light in the spectrum (dimensionless)
Y_d	Total dry yield (kg m^{-2})
$Y_{f\ CA}$	Total Fresh yield of the CA (kg m^{-2})
$Y_{f\ VFCA}$	Total Fresh yield of the VFCA (kg m^{-2})
Y_f	Total fresh yield (kg m^{-2})
y_s	Age of the CA (y)
η	Electrical efficiency (%)
ρ_a	Air density at 60 % RH (kg m^{-3})

tomato [6], pepper [7] and onion [8]. Most CAs in Europe and China were designed to maximize the energy production with a high PV cover ratio from 50 to 100 %, generating conspicuous and speculative profits from the energy selling, incentivization and repurchase at a higher cost [9], to the detriment of the plant photosynthesis, the yield and the underutilization of the agricultural land [10]. Several design solutions have been proposed to increase the agricultural sustainability of new CAs, including the increase of the gutter height, the decrease of the PV cover ratio below 20 %, the use of the North-South orientations, the homogenous distribution of the PV panels on the roof area (checkerboard pattern) [8], the implementation of semi-transparent PV technologies such as the spherical silicon microcells [11], the organic panels [12], parabolic concentrators [13], PV blind systems and dynamic CAs that can vary the shading level using only the excess of irradiation for producing energy [14].

In this paper we propose an alternative approach to increase the agricultural sustainability of the CA with the experimental integration of the vertical farm (VF) technology, characterized by yields, light and resource use efficiency consistently higher than conventional greenhouses [15]. The plants grow in vertical stacked shelves and use light emitting diodes (LED) installed close to the plants, achieving a high photosynthetic use efficiency and a year-round production, without using pesticides or herbicides [16]. VFs are usually employed for growing short crops such as leafy vegetables, pharmaceutical and aromatic species. Among leafy vegetables, the baby leaves are commonly grown due to their short cycle, compact size [17] and a market that has rapidly increased since the early 1980′s, both for fresh and minimally processed products [18]. The critical disadvantage is the high energy consumption mostly due to the LED lighting [19], which affects its economic and environmental sustainability, especially when fossil fuels are employed.

The PV technology is considered the most promising renewable source to meet the energy demand of VFs [20,21], together with the wind energy microgeneration [22]. Whereas the integration of the PV energy to VFs has the aim of reducing the energy consumption and the related CO_2 emissions, the proposed integration of the VF into the CA (VFCA) aims to increase the land productivity through higher yields. The higher is the PV cover ratio of the CA, the lower is the yield, but the higher is its capacity to cover the energy demand of the VF, and the PV energy can be valorized by self-consuming it in the farm. According to this, the VFCA can be considered a mixed agrosystem potentially able to mitigate the chronic low-yield performance of CAs with high PV cover ratio. The VFCA shares the same advantages of open-field agrivoltaics, thus the combination of power and crop production that increase the revenues and payback period of the whole system [23], supporting the EU programmes for renewable energy production and decarbonization. The environmental sustainability of this integration should be assessed: operating a VF using solar energy requires an additional agricultural area for the PV panels, with potential repercussions on the land use change, the competition towards other agricultural activities, the biodiversity and carbon cycling [24,25], especially when the VFCA is designed aiming to the energy self-sufficiency. The Land Equivalent Ratio (LER) can be used to evaluate the land productivity of mixed cropping systems in comparison to the individual ones [26]. The VFCA should increase the LER compared to the sole CA, meaning and increase of yield, but it should also achieve an optimal trade-off between PV energy production and PV area to minimize its environmental impact in terms of land consumption. Previous studies already examined the additional land required for powering on VF systems, such as herbaceous crop land, urban and forest areas [27]. The land area saved from moving conventional lettuce cropping systems to high-productive VF can be used to generate enough PV energy fulfilling the energy demand [28], but there is no land use assessment on the integration of VF to agrivoltaic or CA systems.

The aim of this case study is to quantify the land productivity, the PV area and power required by an experimental VFCA obtained from the integration of a VF into a CA with a high PV cover ratio of 100 %. The yield was quantified on green and red baby-leaf lettuce varieties, adopting four lighting treatments, expressed as Daily Light Integral (DLI) and compared to a control CA. The LER, the PV area and the CO_2 emissions of the mixed system were quantified in two scenarios: 1) actual VFCA and 2) energy self-sufficient VFCA, as a function of the efficiency of the LED lights, the DLI and the PV energy yield. The profitability was compared to the two systems as singles, depending on the price of both lettuce and energy. The optimal trade-off between the energy demand of the VF to be covered with PV energy and the PV land consumption was identified. The results can be employed as technical and economic decision support information to increase the land productivity and environmental sustainability of low-productive CAs.

2. Materials and methods

2.1. Vertical farm and photovoltaic greenhouse structure

The experimental VFCA was located in the municipality of Villaperuccio (Sardinia, Italy, 39°06′54″N, 8°41′15″E) and installed inside an iron-plastic pre-existing greenhouse built in 2011, with a PV cover of 100 % (Fig. 1). The CA had an area of 244 m^2 (44.5 × 5.5 m), a gutter height of 2.5 m and a roof slope of 22° with 176 multi-crystalline silicon PV panels (PEPV 230 W, Eurener, Grassobio, Italy), with an area of 1.67 m^2 each, for a total PV roof area of 294 m^2 and a peak power of 40.48 kWp. The conversion efficiency of the PV system (μ_s) was:

$$\mu_s = [\mu_m - (\mu_m \bullet c_d \bullet y_s)] \bullet BOS \tag{1}$$

where μ_m was the conversion efficiency of the PV module (13.75 %), c_d the cell degradation rate (0.8 % y^{-1}), y_s the age of the CA (11 years) and BOS the Balance of System (estimated 0.84). Both μ_m and c_d were retrieved from the technical specifications of the PV module. The overall μ_s resulted equal to 10.53 %. The CA benefited from a total revenue (public feed-in tariff and energy selling) of 0.39 € kWh^{-1}, which lasts for 20 years from the connection of the CA to the grid [29], whereas the average current electricity price for farmers was 0.24 € kWh^{-1} [30].

The VF structure was formed by an insulated rectangular block with a growth chamber, an antechamber, a germination chamber and a working area. The growth chamber (6.00 × 4.00 × 3.00 m, area of 24 m^2 and volume V of 72 m^3) contained 10 cultivation racks (1.35 × 0.60 × 2.00 m), each one with four shelves (levels), corresponding to a total cultivation area (A_{CV}) of 32 m^2. Walls and roof were insulated with expanded polystyrene foam (thermal conductivity coefficient k_r of 0.035 W m^{-1} K^{-1}) with a thickness s_r of 0.08 m, while the floor was made with concrete (thermal conductivity coefficient k_f of 0.100 W m^{-1} K^{-1}), with a thickness s_f of 0.25 m. Each shelf had a height of 40 cm and

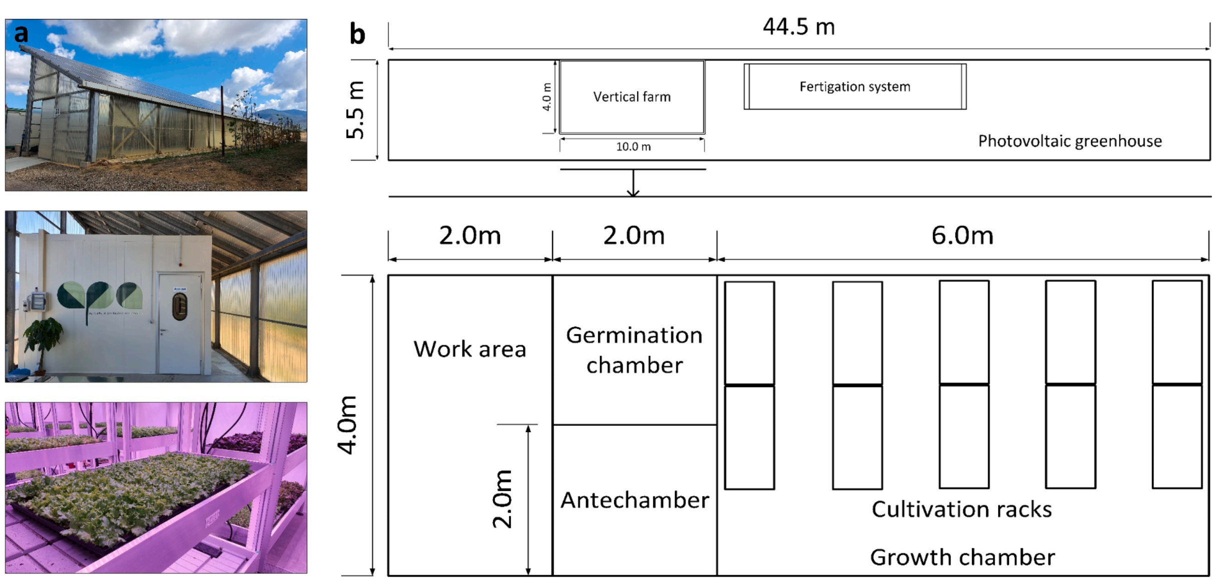

Fig. 1. Experimental closed agrivoltaic system with integrated vertical farm. External and internal view of the VF (a) and general layout (b).

was provided with 8 LED (light emitting diode) dimmable lamps (LED Circular, C-LED, Imola, Italy), each one with a nominal power P_{led} of 22 W, a Photosynthetic photon flux (PPF) of 52 μmol s^{-1} and a Photosynthetic photon efficacy (PPE) of 2.38 μmol J^{-1}. Due to the driver employed (C-LED Daly 48 V), which efficiency was 85 %, the maximum electrical power absorption measured P_{max} was 25.8 W, equal to 258 W m^{-2} of cultivated area. The lighting system had a maximum power of 8.2 kW and was provided with dimmers to regulate the power supplied to the lamps at 10 % power steps. The light spectrum was composed by 55 % White, 33 % Red and 11 % Blue wavelengths. The conversion factor C_L from μmol to J of photosynthetic active radiation (PAR) was estimated according to the equation (A.1) in Appendix and was equal to 4.76 μmol J^{-1} of PAR. During the crop cycle, the hourly total energy consumption of the growth chamber (TEC) was measured with a power meter.

The fertigation system (Idro-X, Idroterm Serre, Mantova, Italy) was installed next to the VF structure, provided with recirculation and UVC disinfection, with an overall P_{mf} of 1.6 kW. The air conditioner (SER srl TSD 5 ED, Vellezzo Bellini, Italy) had a power P_{mc} of 2.55 kW, formed by a heat pump with of 0.77 kW and average coefficient of performance (COP) of 2.2, coupled to ventilators with a total power of 1.57 kW. The air conditioner was provided with a CO_2 diffuser connected to an external gas cylinder that measured and administered automatically the gas in the chamber till the target concentration was reached. In addition, a dehumidifier (FRAL FDHE402, Padua, Italy, P_{md} 1.0 kW) and two air destratifiers (P_{mv} 0.25 kW each) were installed in the growth chamber.

2.2. Baby-leaf lettuce varieties, agricultural and energy parameters

Four varieties of baby-leaf lettuce (*Lactuca sativa* L.) were chosen for the experimental trial: two varieties with green leaf (Falstaff and Cassandra) and two with red leaf (Copacabana and Hoja Roble) due to their different productivity, being the yield of green varieties usually higher than the red ones [31]. The germination time was 2 days for all varieties. The cycle lasted 29–33 days from seeding (from 4 January to 6 February 2022) depending on the varieties. Three harvests (mowing after 18, 25 and 34 days from seeding) were conducted when the average commercial height (8–10 cm) was reached.

The four lettuce varieties were grown under four lighting treatments, with a photosynthetic photon flux density (PPFD) ranging from 130 to 320 μmol m^{-2} s^{-1} (Table 1), with a daily cumulated PAR radiation, expressed as Daily Light Integral (DLI), thus the amount of daily cumulated PAR radiation in mol m^{-2} d^{-1}, which is function of the PPFD and the photoperiod. The different PPFD levels were obtained by dimming the LED lamps from 40 to 100 % and the actual values were measured using a photoradiometer located on the shelf (Delta Ohm 2102.2, Delta Ohm, Padua, Italy). The photoperiod was set to 20 h, which is common for artificial lighting on lettuce, where it operates usually from 12 to 21 h [32]. The same DLI of Table 1 can be obtained using different combinations of PPFD and photoperiods according to eq. (2) and Fig. 2:

Table 1
Cultivation parameters used during the crop cycle. The values of temperature and CO_2 enrichment were different between day/night daily periods.

Microclimate and plant density		Nutrient solution (mg L^{-1})	
Temperature (°C)	18/23	992 NO_3^-, 23 NH_4^+, 126 PO_4^{3+}, 313 K^+, 160 Ca^{2+}, 49 Mg^{2+}, SO_4^{2-}, 3.0 Fe, 0.5B, 0.5 Mn, 0.02 Cu, 0.05 Zn, Mo 0.01	
Humidity (%RH)	65		
CO_2 level (ppm)	700/1000		
Photoperiod (h)	20	pH	6.0
LED dimming (%)	60	Electrical conductivity (mS cm^{-1})	2.5
Plant density (plants m^{-2})	1820	Nutrient flow on the shelf (L min^{-1})	18
Lighting parameters			
PPFD (μmol m^{-2} s^{-1})	DLI (mol m^{-2} d^{-1})	Daily PAR (MJ m^{-2})	Dimmer (%)
130	9	1.90	40
160	12	2.39	50
255	18	3.81	80
320	23	4.78	100

$$DLI = PPFD \bullet h \bullet 0.0036 (mol m^{-2} d^{-1}) \quad (2)$$

The growth chamber temperature (T_c) and the CO_2 enrichment were 23 °C and 1000 ppm during the photoperiod, respectively, and 18 °C and 700 ppm during the dark period. The germination took place in the dark at constant 18 °C and 80 % RH for 2 days. The seedlings were then transferred to the growth chamber and grown with a plant density of 1820 plants m^{-2} using plateaux and sandy peat as substrate. The fertigation was supplied by flooding the shelves at one-hour intervals for 35 s during the photoperiod (flow rate of 15 L min^{-1}), except during the first week, when it was supplied twice a day. The fertigation solution was identified among those already tested on leafy vegetables in VFs [33].

The cumulated DLI during the crop cycle, also called Total Light Integral (TLI) [34], was calculated with the product of the DLI by the cycle duration (d) in days. The radiation use efficiency (RUE) was calculated on the dry weight (RUE_d) with the following equation:

$$RUE_d = \frac{Y_d}{TLI} (gmol^{-1}) \quad (3)$$

where Y_d is the total dry yield. The dry matter content (DM) for the calculation of Y_d was determined by dehydrating 5 plants per variety and treatment in an oven at 65 °C for 4 days till constant weight. The energy utilization index (EUI) was calculated as a function of the total energy consumption of a m^2 of cultivation area (TEC) after the cycle:

$$EUI = \frac{TEC}{Y_f} (kWhkg^{-1}) \quad (4)$$

The caloric value (c_v) was retrieved from the nutritional label of the seed providers and was averagely 63 and 61 kJ 100 g^{-1} on green and red varieties, respectively. The c_v was assumed equal to 63 kJ 100 g^{-1} also on the romaine lettuce. According to this, the conversion efficiency from energy to the aerial biomass (EBC) was calculated as following:

$$EBC = \frac{c_v \bullet 10 \bullet Y_t}{TEC \bullet 3600} (\%) \quad (5)$$

The PV power required to cover the annual TEC of the cultivation area (PPI) was equal to:

$$PPI = \frac{TEC}{E_{kWp}} (kWpm^{-2}) \quad (6)$$

where E_{kWp} is the annual energy yield per unit of PV power. Finally, the PV area index (PAI) was the PV area on the horizontal plane required to cover the annual TEC of the cultivation area:

$$PAI = \frac{TEC \bullet A_{kWp}}{E_{kWp}} \quad (7)$$

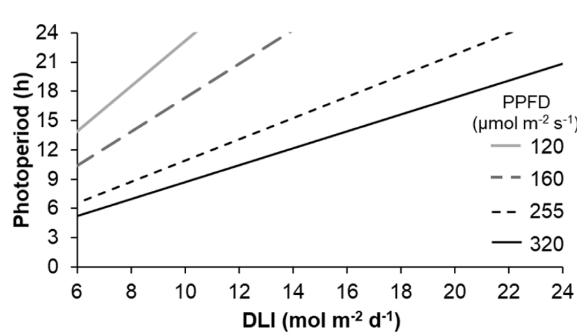

Fig. 2. Relation between DLI and photoperiod for the four PPFD levels used in the case study.

where A_{kWp} is the PV horizontal area occupied per unit of PV power.

The energy consumption of the germination chamber, antechamber and working area was not considered. The energy consumption for fertigation (E_F) was calculated according to the pump power and the operation time of the fertigation schedule reported in Table 1. The CA temperature T_g was measured at 1 h intervals using a thermohygrometer (Galtec Mela KPC2-ME, Bondorf, Germany) installed near the VF block, connected to a datalogger (Squirrel SQ2020, Grant Instruments, UK), with data available from January 2021, since the CA was established prior the VF. The average monthly outside temperature T_o was retrieved from local web meteorological datasets based on the closest weather station [35]. The average monthly global radiation (I_g) for the months (m) incident on the PV panels (South orientation, tilt of 22°) was retrieved from PVGIS [36] for the actual location and used to calculate the annual energy production of the CA (E_{PV}) with the following sum:

$$E_{PV} = \sum_{0}^{m=12} I_g \bullet \eta_s \tag{8}$$

The environmental impact of the VF powered with PV energy in terms of CO_2 emissions derived from the energy consumption was calculated considering an emission equal to 372 g CO_2 kWh^{-1} from fossil fuels in 2022 [37]. An economic evaluation was conducted through the Net Present Value (NPV), the Payback time and the Breakeven Point (BEP) over 20 years, comparing the VF with and without the support of the PV energy of the CA. The only variable cost considered was the energy consumption, whereas the fixed costs were listed in Table 2. The average European gross market price of VF lettuce was 2.5 € kg^{-1} [38].

2.3. Agricultural and environmental sustainability of the cropping systems

To compare the lettuce biomass production of the VFCA to the initial CA cropping system, an experimental trial was carried out inside a CA module identical to the reconverted one and in the same location (Fig. 3). Since the baby-leaf lettuce varieties were specific for VF cultivation and could not adapt to a conventional greenhouse, a romaine lettuce variety (cv. Patrona) was chosen as control crop. No supplementary lighting or air conditioning was available. The crop cycle lasted 55 days from sowing (from 18 March to 12 May 2022) and was conducted on 5 plant rows with a plant density of 11 plants m^{-2}. At the centre of each plant row, a photoradiometer measured the PPFD at 50 cm from the ground at 15 min intervals (Delta Ohm 2102.2, Delta Ohm, Padua, Italy). The T_g was measured using a portable thermohygrometer in the central part of the CA (Extech datalogger SD500, Extech, Boston, USA). A ternary complex fertilizer (15–15–15 NPK) was distributed before transplantation at a dose of 165 g m^{-2}. Drip irrigation was applied with a water amount of 6 L m^{-2} d^{-1}. The revenues from this crop were calculated using the average gross national market price for lettuce (0.6 € kg^{-1}) [39].

The LER was adopted to compare the increase of land productivity (both in terms of food and energy production) of the VFCA to the two

Table 2
Fixed costs per unit of cultivated area used for the economic evaluation of the investment. The depreciation costs were assumed equal to 4.5 % of the initial investment.

VF cost (€ m^{-2})	2200
CA cost (€ m^{-2})	307
VF depreciation costs (€ m^{-2})	113
CA depreciation costs (€ m^{-2})	13
Interest rate (%)	2.0
Baby-leaf lettuce price (€ kg^{-1})	2.5
Labour cost (€ m^{-2} y^{-1})	41
Electricity price (€ kWh^{-1})	0.24
Electricity selling price (€ kWh^{-1})	0.39
Seeds (€ m^{-2})	0.24
Nutrient solution (€ m^{-2})	3.12
Substrates and plateaux (€ m^{-2})	7.56

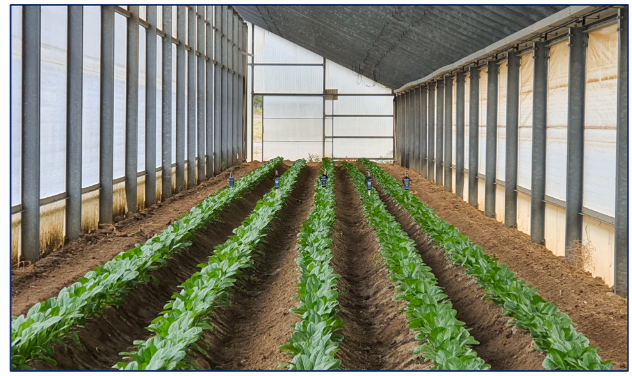

Fig. 3. Romaine lettuce control cycle inside a CA module identical and close to the VFCA. The photoradiometers are located in the centre of each row.

sole systems prior the reconversion (CA and VF separately). The LER was calculated with the following expression [26,40]:

$$LER = \frac{Y_{fVFCA}}{Y_{fCA}} + \frac{(E_{VFCA} - TEC)}{E_{CA}} \tag{9}$$

where Y_{fVFCA} and E_{VFCA} are the average total fresh yield and the energy production of the mixed integrated system (VFCA), respectively, whereas Y_{fCA} and E_{CA} are the average total fresh yield and energy production of the control CA. The energy consuming nature of the VF was considered by subtracting its TEC of the VFCA from the E_{VFCA}.

The statistical analysis was carried out using one-way ANOVA with the 4 treatments (DLI levels) and 3 replications (plateaux). The LSD Fisher test determined the statistical differences between lighting treatments at $p < 0.05$ significance level. The test provided letters to the means: means sharing the same letter are not significantly different between them, whereas they are statistically different from those sharing another letter. Minitab statistical software was used (Minitab 17 Statistical Software, 2010. State College, United States. Minitab, Inc.). Fluctuations around the mean were calculated using the coefficient of variation (CV), equal to the ratio of the mean and standard deviation.

2.4. Energy balance for air conditioning

The energy consumption for the air conditioning, dehumidification and ventilation E_{HVAC} was calculated with the difference between TEC measured with the power meter and the calculated energy consumption of the LED lighting system, being E_{HVAC} defined as the sum of the following components:

$$E_{HVAC} = E_A + E_H + E_V(kWh) \tag{10}$$

where E_A, E_H and E_V are the energy consumptions of the air conditioner, the dehumidifier and the destratifiers, respectively. Both E_H and E_V were known, since they had a constant power absorption and can be assumed always operating, whereas E_A can fluctuate depending on the thermal load of the growth chamber. The annual heat load of the air conditioner Q_A was calculated from the following simplified heat balance on hourly basis:

$$Q_A = \sum_{d=1}^{d=365} Q_{LED} + Q_V + Q_C + Q_S(kWh_t) \tag{11}$$

where d is the day of the year, Q_{LED} is the hourly heat dissipation of the LED lamps, Q_V the heat dissipated from the other electrical appliances inside the growth chamber (dehumidifier and destratifiers), Q_C the heat transfer due to conduction and Q_S the heat transfer to the substrate. The addendums of eq. (11) were calculated based on the equations of the energy balance reported in Appendix. The energy consumption of the air conditioner E_A was calculated with the fraction:

$$E_A = \frac{Q_A}{COP}(kWh) \tag{12}$$

3. Results

3.1. Baby-leaf lettuce yield, energy consumption and efficiency

The green leaf varieties, with an average fresh yield (Y_f) of 6.0 kg m^{-2}, produced 70 % more than the red leaf varieties (3.5 kg m^{-2}) after three harvests, as the average of all DLI treatments (Table 3). The highest Y_f was observed with a DLI of 18 or 23 mol m^{-2} d^{-1}, with no significant difference between them, indicating that the DLI of 18 mol m^{-2} d^{-1} achieved the highest Y_f with the lowest TEC. The Y_f increased averagely by 0.73 % for each 1 % additional TLI on the green varieties, while it increased by 0.44 % on the red varieties. The average EUI was 23 kWh kg^{-1} for the green varieties and 74 % higher (40 kWh kg^{-1}) for the red varieties, whereas the average EBC at 18 mol m^{-2} d^{-1} was 0.47 and 0.85 %, respectively, without significant differences between DLI treatments (except on Falstaff). The highest RUE_f was observed usually with the lowest DLI of 9 mol m^{-2} d^{-1}.

The average energy consumption of the crop cycle at the DLI of 18 mol m^{-2} d^{-1} was 162 kWh m^{-2}, corresponding to an emission of 60 kg CO_2 m^{-2}. The TEC was due mainly to the LED lighting (59–78 % of the total depending on the DLI), followed by the air conditioning, which increased from the highest (21 %) to the lowest (40 %) DLI (Table 4). The incidence of fertigation was negligible and always under 0.6 %. The average Y_f of the romaine lettuce inside the control CA was 1.6 kg m^{-2} (70 % lower than the average Y_f of the green varieties in the VFCA), with an average DLI of 3.7 mol m^{-2} d^{-1} entering from the CA side walls, and no statistical differences between rows, except on row 5, oriented to South. The average RUE_f was 10.4 g mol^{-1}, thus 30 % lower than the green varieties in the VFCA with a DLI of 9 mol m^{-2} d^{-1}. The TEC of the control CA was considered negligible compared to the VFCA, due only to irrigation.

Table 4
Incidence of lighting, air conditioning and fertigation on the TEC for all DLI treatments.

DLI	Lighting	Conditioning	Fertigation
9	59 %	40 %	0.58 %
12	64 %	35 %	0.50 %
18	74 %	25 %	0.36 %
23	78 %	21 %	0.31 %

3.2. Annual energy consumption and production

The annual Y_f, the energy consumption and production of the VFCA were calculated based on the VF energy balance and the crop cycle data. In particular, given the duration of the crop cycle around 31 days for baby leaf lettuce, the annual Y_f of the VFCA was calculated on the hypothesis of 12 cycles per year, assuming a constant yield equal to that reported in Table 3 and multiplied for 12. Similarly, the annual Y_f of the CA was estimated on the hypothesis of 4 cycles per year (55 days each), leaving the greenhouse empty in the hottest and coldest months of the year, due to the lack of aerial control devices. The annual TEC of the VFCA was estimated by calculating the E_{LED} according to eq. (A.2) of the Appendix and considering it constant during the photoperiod, depending on the dimmer of the specific DLI level. The E_{HVAC} for the annual

Table 3
Total fresh yield, energy consumption and efficiency of the baby-leaf cycle on the four DLI treatments. Data included the romaine lettuce cycle inside the control CA. The TEC of the control CA was considered negligible compared to the VFCA. Means that do not share a letter are significantly different (LSD test, $p < 0.05$).

Varieties and DLI treatments (mol m^{-2} d^{-1})	Cycle duration (d)	Total yield (kg m^{-2})	RUE_f (g mol^{-1})	Yield and TLI linear regression	EUI (kWh kg^{-1})	TEC (kWh m^{-2})	EBC (%)
Green varieties							
Falstaff							
9	29	4.5b	15.0 a	$Y = 0.0084 \cdot TLI + 1.6050$ ($R^2 = 0.82$)	23b	97 a	0.84 % a
12		3.9b	10.5b		30 a	111b	0.64 % b
18		7.6 a	12.7 ab		22b	152c	0.9 % a
23		7.4 a	9.9b		26 ab	180 d	0.74 % ab
Cassandra							
9	33	5.1b	14.8 a	$Y = 0.0058 \cdot TLI + 3.044$ ($R^2 = 0.85$)	24	111 a	0.83 %
12		5.2b	12.0 ab		27	127b	0.74 %
18		7.8 a	11.4 ab		24	175c	0.80 %
23		7.6 ab	8.8b		29	206 d	0.66 %
Red varieties							
Copacabana							
9	31	2.8b	8.8 a	$Y = 0.0028 \cdot TLI + 1.6627$ ($R^2 = 0.88$)	44	104 a	0.48 %
12		2.5b	6.3b		38	119b	0.37 %
18		3.4 ab	5.3b		44	163c	0.36 %
23		4.0 a	5.0b		54	193 d	0.36 %
Hoja Roble							
9	30	2.4b	7.9	$Y = 0.0061 \cdot TLI + 0.6835$ ($R^2 = 0.85$)	38	101 a	0.43 %
12		2.9b	7.4		24	115b	0.44 %
18		5.2 a	8.4		35	158c	0.57 %
23		4.9 a	6.3		42	186 d	0.46 %
CA trial on romaine lettuce							
DLI on the plant rows							
Patrona							
3.6b	55	1.8	11.3 a	$Y = 0.0017 \cdot TLI + 1.331$ ($R^2 = 0.67$)	–	–	–
3.1b		1.5	10.7 a				
3.1b		1.6	11.5 a				
3.2b		1.3	9.3 ab				
5.5a		1.7	6.9b				

calculations was considered the annual average derived from the annual VF energy balance (eq. (10)). The E_F was considered constant and equal to 1 session h^{-1} (fertigation system operated for 90 s per session) during the photoperiod (20 sessions d^{-1}).

The average monthly TEC was 153 kWh m^{-2} (average annual emission of 57 kg m^{-2} CO_2), with the highest values in July and August, where it was 6.5 % higher due to the higher incidence (33 %) of the air conditioning in summer (Fig. 4a). The annual E_{PV} was 1116 kWh kWp^{-1}, equal to 185 kWh m^{-2} and covered averagely 10 % of the annual TEC (1865 kWh m^{-2} y^{-1}), resulting in a net CO_2 emission of 625 kg m^{-2} y^{-1} (emission avoided of 69 kg m^{-2} y^{-1}). The average monthly E_{LED} was nearly constant to 106 ± 3 kWh m^{-2} (incidence of 68 % on TEC). The average E_{HVAC} of 48 ± 4 kWh m^{-2} (incidence of 30 % on the annual TEC) showed fluctuations throughout the year (higher in summer) equal to a CV of 8 %. These fluctuations, already observed in plant factories [41], were due to the temperature trend in the CA (Fig. 4b). The T_g was 1.9 °C higher than the outside temperature T_o (18.6 °C) and affected the Q_C by 0.11 kWh$_t$ °C^{-1}, causing the air conditioner to work 94 % of its time in cooling mode during the year. The heat conduction between the VF and the CA contributed to the heat dissipation when the CA temperature was lower than the growth chamber. Furthermore, the air conditioner can take advantage of the lower temperature during the night-time and winter even in cold locations due to increased efficiency of the refrigeration cycle [42]. The TEC for air conditioning increased by 3.8 kWh m^{-2} °C^{-1} of the average T_o, with an EUI between 5 and 7 kWh kg^{-1} (on Cassandra with a DLI of 18 mol m^{-2} d^{-1}), resulting from 75 to 500 % higher than what simulated in high latitude and cold climates such as Stockholm, where it was between 1 and 4 kWh kg^{-1} of fresh lettuce, respectively in February and July [42]. The Q_{LED} was the main dissipation factor and amounted to 83 % of the annual heat balance.

In the hypothesis of 12 cycles per year, the highest annual Y_f at DLI of 18 mol m^{-2} d^{-1} was 92 and 53 kg m^{-2} for green and red varieties, respectively (Fig. 5a). The average TEC of the green varieties was 2 % higher than the red varieties among the DLI treatments, due to the different cycle duration. The annual E_{PV} per unit of horizontal area (185 kWh m^{-2}) covered from 8 to 17 % of the TEC (average of 12 %), inversely proportional to the DLI (Fig. 5b) and no statistical differences between varieties. The VFCA achieved a LER from 1.06 to 1.60 for the green varieties (average 1.31 for all DLI treatments), while it was lower on the red varieties (from 0.34 to 1.33) where it was averagely 0.79. The maximum LER of 1.53 at 18 mol m^{-2} d^{-1} of the green varieties indicated a land productivity similar to agrivoltaic systems, where the lettuce cultivation led to a LER of 1.3–1.6 [26], whereas it was lower in the red varieties (maximum LER of 1.09 at DLI of 12 mol m^{-2} d^{-1}).

The VFCA resulted up to 13 times more productive than the control CA (6.4 kg m^{-2} on the hypothesis of 4 cycles per year) and 4.5 times more than a conventional greenhouse, where the average Y_f per lettuce cycle ranged from 2.2 to 6.0 kg m^{-2}, depending on the season and the fertigation technique [31,43,44], resulting in an annual Y_f around 20 kg m^{-2} with 5 cycles per year (Fig. 6).

3.3. Energy self-sufficiency of the vertical farm

Since the actual E_{PV} of the CA per unit of horizontal area covered only a small fraction of the TEC, to reach the energy self-sufficiency the VFCA requires a higher land consumption for additional PV power. According to this, the PV power (expressed as PPI), the CA horizontal area (expressed as PAI) and the LER required to fulfil the annual TEC were calculated in Fig. 7. The average TEC of all varieties and an energy yield E_{kWp} from 1100 to 1500 kWh kWp^{-1} was considered, in order to generalize the results for different latitudes. An inverse linear relation was observed between the E_{kWp}, the PPI and the PAI, whereas they increased with the DLI (Fig. 7a and 7b).

The PPI for self-sufficiency decreased averagely by 0.1 kWp and the PAI by 0.7 for each additional 100 kWh kWp^{-1} of E_{kWp}. The highest Y_f observed at DLI of 18 mol m^{-2} d^{-1} reached the energy self-sufficiency with 1.7 kWp m^{-2} and a PAI of 11.6, considering the E_{kWp} around 1100 kWh kWp^{-1} of the present location, representative of a Mediterranean region. While the average LER of the green varieties inside the actual VFCA was 1.31 at 18 mol m^{-2} d^{-1}, in the scenario of energy self-

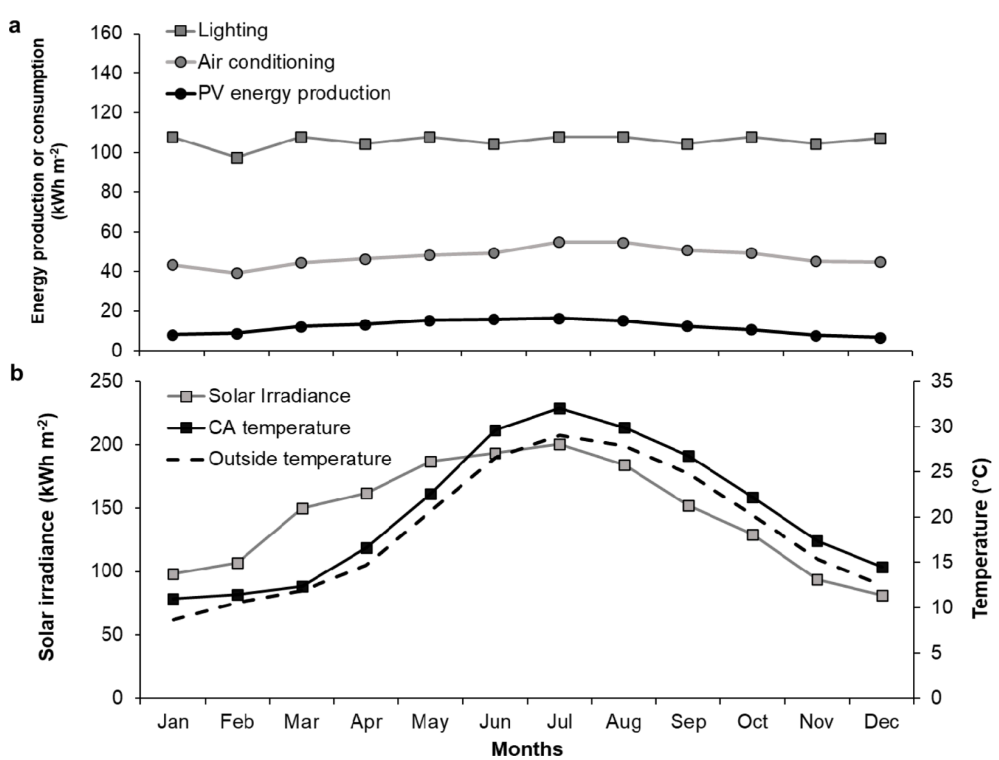

Fig. 4. Average monthly PV energy production, energy consumption for air conditioning and lighting of the vertical farm on all months (a). The average monthly solar irradiance and the CA temperature T_g are based on 2021–2022 site data (b).

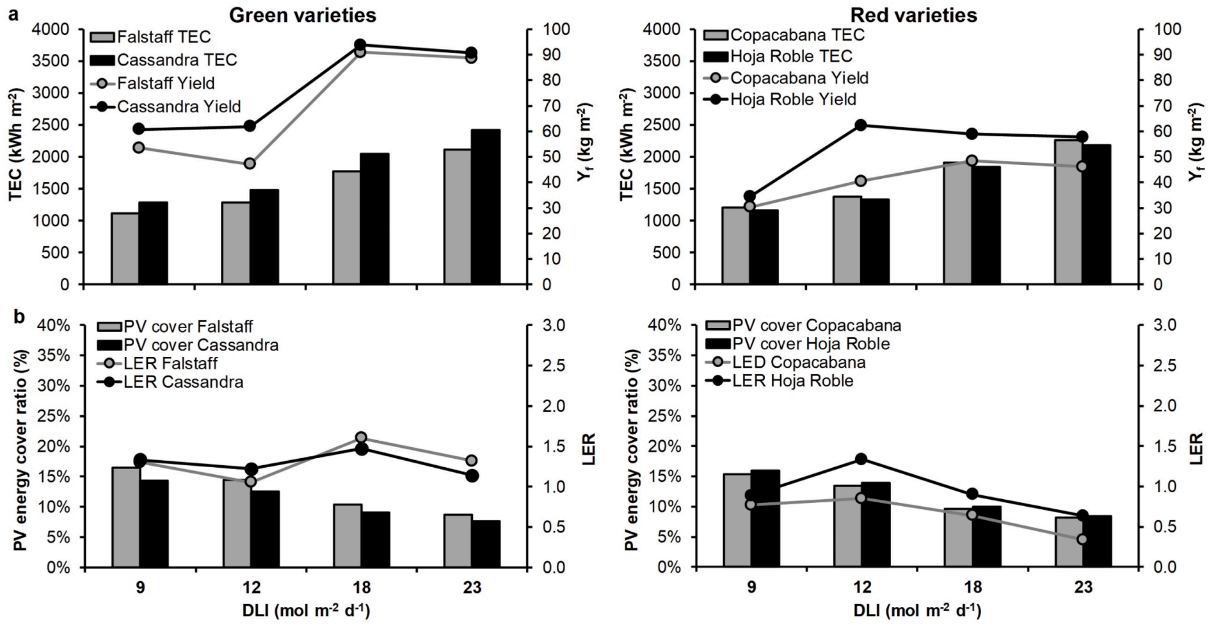

Fig. 5. Annual crop performance as a function of the DLI on a hypothesis of 12 crop cycles per year. The PV energy cover ratio is the percentage of TEC covered by the CA.

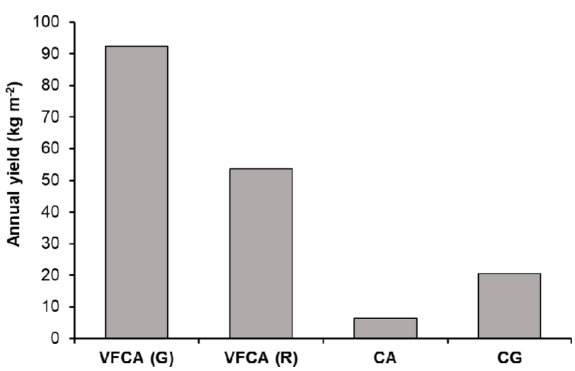

Fig. 6. Estimated annual yield of the VFCA with green (G) and red (R) varieties, in comparison to the control CA and a conventional greenhouse (CG).

sufficient VFCA it was lower (1.23) and increased averagely by 9 % for each additional 100 kWh kWp^{-1} of E_{kWp} (Fig. 7c). Indeed, when the TEC was fulfilled by the PV energy, the net E_{VFCA} was zero and decreased the overall LER. The red varieties had usually a LER lower than 1.00, as already depicted in Fig. 5, indicating a land consumption higher than the individual systems (VF and CA).

The PAI decreased according to an inverse relation to the conversion efficiency μ_m of the PV modules (Fig. 8). The PAI decreased about 1 % for each 1 % increase of the μ_m. With a DLI of 18 mol m^{-2} d^{-1} and a theoretical μ_m of 40 %, the PAI converges to 1, indicating that a PV horizontal area equal to the VFCA area would cover entirely its annual TEC. Lower DLI levels of 9 and 12 mol m^{-2} d^{-1} would achieve this parity with a μ_m around 38 %. The energy consumption of the VFCA was dependent on the PPE of the LED lamps: with the increase of the PPE that can be prospected in the future, the adoption of new lamps will contribute to decrease the TEC, requiring smaller PV systems. When the DLI of 18 mol m^{-2} d^{-1} was supplied with the actual LED lamps (PPE of 2.38 μmol J^{-1}), 94 Wp mol^{-1} were required to cover completely the TEC, with a PAI of 12.3 (Fig. 9). The PV power per unit of DLI and the PAI decreased by 36 % from a PPE of 2.4 to 3.2 μmol J^{-1}, equal to an average reduction of 1 % for each 0.1 μmol J^{-1} of additional PPE.

The energy self-sufficiency affected the environmental and

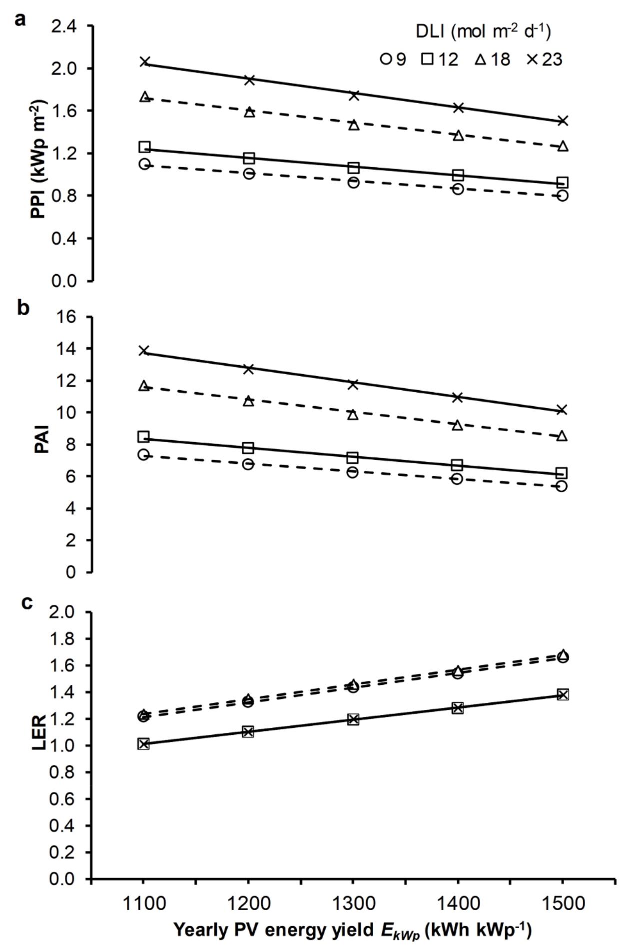

Fig. 7. PPI (a) and PAI (b) and LER (c) calculated in a energy self-sufficient scenario of the VFCA as a function of the PV energy yield and the DLI. All data is the average of the green leaf varieties.

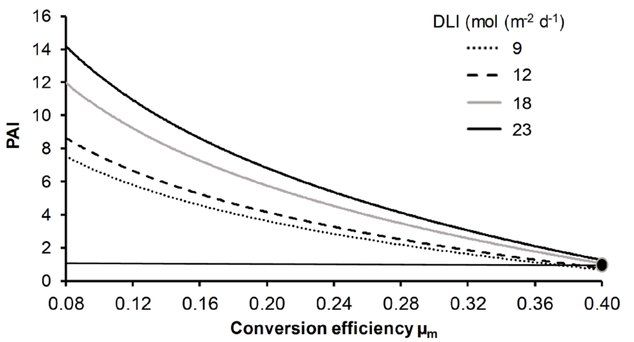

Fig. 8. PAI calculated as function of the conversion efficiency μ_m of the PV modules in the case of the energy self-sufficient VFCA. The black dot and the horizontal line indicate the μ_m of 0.40, in which the PAI is equal to 1 at a DLI of 18 mol m^{-2} d^{-1}.

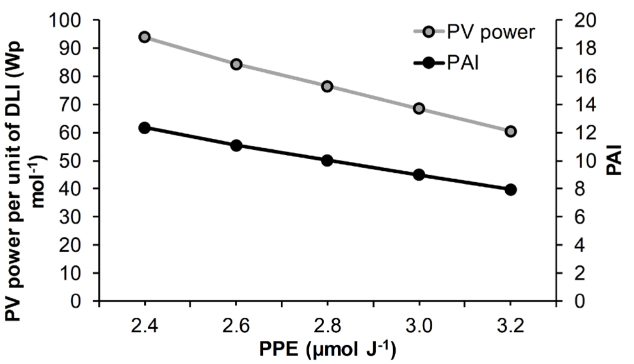

Fig. 9. Estimation of the PV power per unit of DLI and the PAI as a function of the PPE. Calculations were conducted with a DLI of 18 mol m^{-2} d^{-1} and an annual E_{kWp} of 1100 kWh kWp^{-1}.

agricultural sustainability by increasing the land consumption. The LER decreased inversely proportional to the PAI when the percentage of TEC covered with PV energy increased (Fig. 10). When a specific percentage of the TEC was covered, the PAI was minimized, resulting in a maximisation of the LER. In particular, by covering 16 % of the annual TEC, the PAI at an E_{kWp} of 1100 kWh kWp^{-1} was minimized and equalled the LER at 1.90. This percentage was directly correlated to the E_{kWp}: when it was 1500 kWh kWp^{-1}, 52 % of the TEC can be covered with PV energy to achieve the maximum LER of 4.41.

3.4. Economic sustainability

The support of the CA reduced the energy costs and increased the NPV, leading to an average payback time of 17 years as the average of all varieties (Fig. 11). The highest NPV was observed at a DLI of 18 mol m^{-2} d^{-1}, with a payback time from 11.5 to 18 years for the green and red varieties, respectively. In the sole VF, the energy cost was predominant (94 % of the total costs) and higher than the NPV, resulting in a non-profitable cultivation and a payback time around 20 years (Fig. 12a and 12b). The control CA had the highest NPV/NPC ratio and the shortest payback time (5 years) due to the lowest initial investment and costs, coupled to a high incidence of the PV feed-in tariffs (95 %) on the NPV. The minimum Y_f of the VFCA necessary to cover the production costs was 29 kg m^{-2} (Fig. 12c). However, in the sole VF scenario even the highest yield of 92 kg^{-2} was insufficient to cover the costs and the market price should be above 6.0 and 12 € kg^{-1} for the green and red varieties, respectively, to avoid economic losses.

4. Discussion

4.1. Agronomic and economic sustainability of the experimental VFCA

The DLI of 18 mol m^{-2} d^{-1} showed the highest Y_f, in agreement to the suitable DLI between 15 and 20 mol m^{-2} d^{-1} on lettuce [45,46] and with the minimum TEC, as shown by its EUI, which was only 11–29 % higher than what reported in other VFs, where it was usually between 10 and 17 kWh kg^{-1} [47,48]. The PV energy per unit of CA area covered only a limited part of the VF demand, but it was essential for its profitability. The VFCA proved that it was possible to produce sufficient energy for the VF operation and was crucial to generate profits. The energy bills have dropped by 19.5 % in Italy in 2023, allowing to improve the economic sustainability of the VFCA in the near future [49].

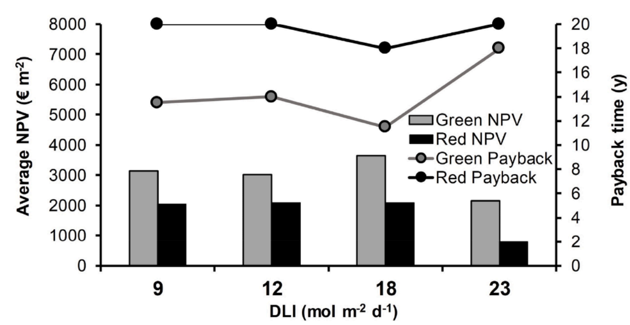

Fig. 11. Average net present value (NPV) over 20 years and payback time of the VFCA for the green and red varieties as a function of the DLI.

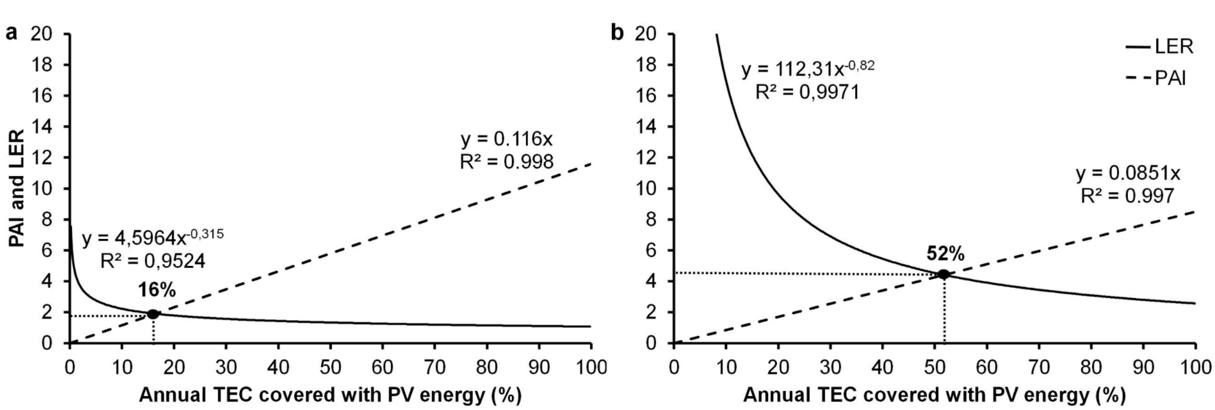

Fig. 10. Optimal trade-off of TEC covered with PV energy. Calculations were conducted on the actual average Y_f of the green varieties at a DLI of 18 mol m^{-2} d^{-1} and E_{kWp} of 1100 (a) and 1500 kWh kWp^{-1} (b).

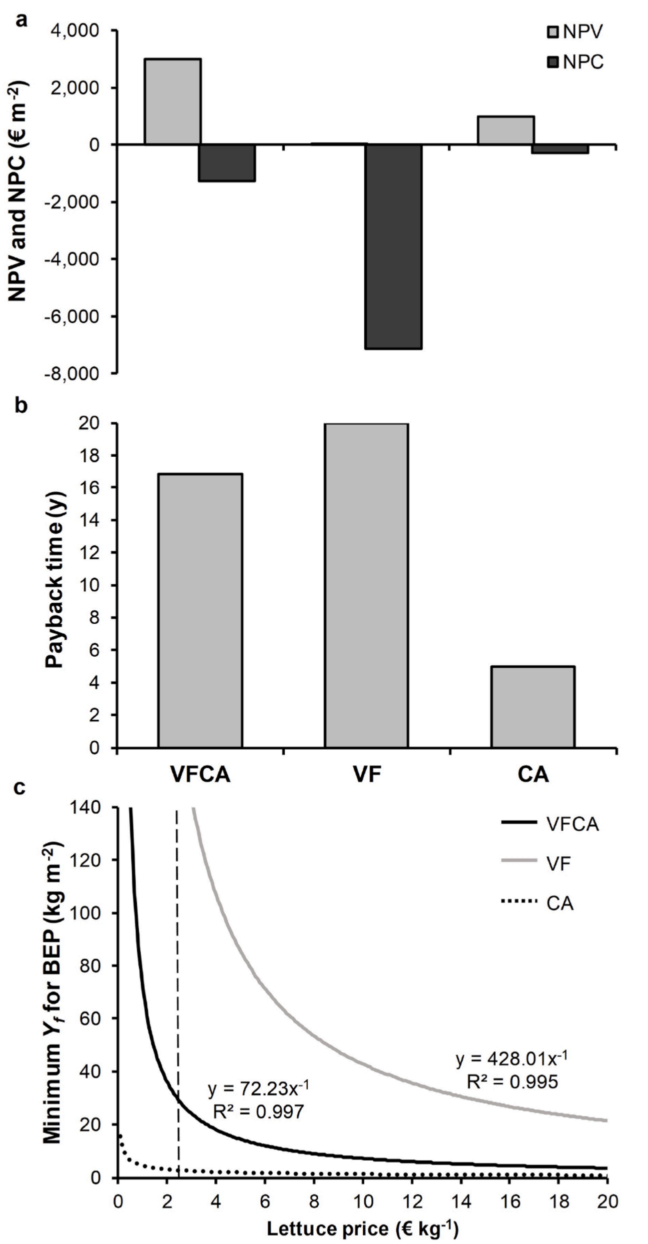

Fig. 12. Average net present value (NPV) over 20 years and average payback time of the VFCA (a), average payback time (b) and minimum yield necessary to reach the breakeven point, of the VFCA, the VF and the control CA (c), where the average baby leaf lettuce price of 2.5 € kg^{-1} is highlighted with a vertical dotted line.

The unprofitability of the sole VF scenario was due mainly to the small-scale (high incidence of the fixed costs), the current market price of lettuce and the electricity costs. Only the CAs has received the incentivization for PV energy production in Italy, regardless of the energy destination (selling or self-consumption), despite the open-field agrivoltaics [5]. When the public subsidies for PV energy are not available, the PV yield and the investment costs are the main factors affecting the competitiveness of PV systems [50]. The profitability of VFs coupled with low market price of the fresh product is debated, but the VFs in containers already showed that by increasing the scale of the investment, the payback time decreases, when the market is sufficiently developed to absorb the offer [51]. DLI levels applied in VFs usually range from 7 to 23 mol m^{-2} d^{-1} on lettuce [42,52,53] and the EUI was generally not affected by DLI variations. As a consequence, the choice of the DLI levels depends on economic evaluations based solely on the TEC, the expected yield and the market price of the fresh produce. The economic sustainability of the VFCA for baby-leaf production could dramatically change when strong fluctuations of the energy price occur. The profitability should be evaluated using a yield-energy approach [42], which includes the market price of both. The BEP simulations highlighted that the minimum price to avoid any economic losses was always higher than the lettuce price and a dedicated price was necessary for the sole VF scenario.

The EBC was higher than nalta jute and peppermint grown in plant factories, where the EBC was called BELA (Biomass conversion Efficiency of Light and Air conditioning) and was 0.13 and 0.62, respectively [54]. Such crops are comparable to lettuce, since they are both herbaceous crops with a similar cycle duration. The EBC can be considered as a preliminary indicator for designing VFs for baby-leaf production. In fact, given the good economic indicators of the green leaf varieties, an EBC around or higher than 0.80 % may indicate an acceptable profitability of VFs for baby-leaf lettuce. The control CA was the most profitable scenario due to the high incentives for PV energy production, even with the low romaine lettuce Y_f. The gross income of the CA derived mostly from the PV subsidies and it was considerably higher than that deriving from most horticultural crops. This was the main reason that led most CAs to be designed only for energy production [55].

The RUE_f (30 % lower than the green varieties inside the VF) indicated that the crop did not adapt to the scarce DLI inside the control CA, which resulted insufficient for an acceptable yield, compared to the VFCA with artificial lighting. The low DLI measured on the North and South plant rows would not justify its exploitation for energy production by installing additional PV panels on the CA sidewalls. Indeed, the CA object of this case study is part of a large-scale PV greenhouse installation, in which the CA modules were properly spaced only to minimize the mutual roof shading, but they represented an obstacle penalising the incident radiation on the sidewalls. However, the income of the CA resulted up to 75 % lower than the VFCA (maximum gross income of 306 € m^{-2}), which confirmed that the self-consumption of the PV energy for powering VFs is a profitable alternative to the PV energy selling, contributing to create a sustainable mixed system for both energy and crop production inside the reconverted CA.

4.2. Land consumption and carbon dioxide emissions

The integration of the VF into the CA contributed to the mutual environmental sustainability of both, reconverting the CA into a highly productive cropping system and covering part of the energy consumption of the VF simultaneously. The average LER of the actual VFCA (1.31) was comparable to other agrivoltaic systems for lettuce in Europe, where it ranged from 1.00 to 1.36 depending on the PV cover ratio [56], and led to an increase of the land productivity of the existing CA by 29 %. This value was modest compared to what expected by the VF, being the yield 13 times higher than the CA and 4 times higher than a conventional greenhouse. Indeed, the energy-self consumption of the VFCA contributed to decrease the E_{VFCA}/E_{CA} ratio, leading to a LER comparable to open-field agrivoltaics. The environmental trade-off of the VFCA would be reached by covering around 16 % of the VFCA energy demand, leading to a reduced PAI and a consequent increase of LER. This compromise implied that the VFCA would not be energy self-sufficient and a quota of CO_2 emissions occurred, but saved agricultural land proportionally to the E_{kWp} of the PV system. Under these circumstances, a PAI lower than the trade-off (1.90) would affect negatively the economic sustainability of the VFCA due to the increase of the electricity bill, as shown in the case of the sole VF scenario, with CO_2 emissions up to 700 kg m^{-2} y^{-1}.

The VFCA required a PAI from 5.4 to 13.9 times more than the VF area to achieve the energy self-sufficiency, depending on the PV energy yield and the DLI. The values are within the measurements of other authors for VFs in Spain and Sweden, ranging from 2.2 to 54.0, whereas the impact of wind energy would be up to 100.0 [28]. As a consequence, the reconversion of an existing CA should install a maximum VF area equal to 7–18 % of the CA area to be energy self-sufficient and avoid the related CO_2 emissions. These results challenge and highlight the environmental impact of VFs in terms of land consumption, which is usually neglected, since one of their common strengths are the limited area occupation, leading to lower and more efficient land use [33]. The land use change for energy production will become predominant, replacing and competing with agricultural activities such as crops or forests [25]. For this reason, other unmanaged or unused areas not suitable for agriculture and forestry could be converted to solar energy production. The mitigation of the land use includes the construction of VFs in locations with higher natural irradiation and the adoption of lower DLI levels to reduce the energy demand.

4.3. Perspectives and improvements of the VFCA

The first experimental VFCA allowed to identify three factors affecting its economic and environmental sustainability: energy, land consumption and CO_2 emissions. For each one of them, a compromise should be identified to maximise the LER, meaning an increase of land productivity of the investment. A higher LER may result in a decrease of the area occupied by the PV panels, but it is connected to a higher CO_2 emission. The optimal trade-off found in this case study (16 % of the energy demand covered with PV energy and a PAI of 1.90) would minimize the environmental impact of the VFCA. It is crucial for the future of agrivoltaics to avoid or solve their weaknesses such as the lucrative aspects concerning the PV energy in contrast to the food production [57], and the attempt of the VFCA was to switch the core business of the CA from the energy to the agricultural side.

Possible improvements to the VFCA were indicated by the average RUE_d, in agreement or lower than lettuce in growth chambers, where it ranged from 0.64 to 1.25 g mol^{-1}, depending on the DLI and light spectrum [58,59]. For this reason, the RUE_d suggested that there were margins of optimization of the VFCA, including a more efficient mineral and water nutrition, the use of different light spectra, including green and far red light [60], different red:blue ratios [61], more productive varieties, implementation of the latest and most efficient LED lamps, or different combinations of PPFD and photoperiods [61,62] to reduce the impact of lighting on the energy costs. Indeed, under the same DLI, lower fluxes and higher photoperiods result in a higher yield than higher fluxes and lower photoperiods, on both green and red leaf lettuce [63]. A higher energy conversion efficiency of the LEDs in the future will further decrease the energy consumption and the dimension of the PV systems to fulfil the VF energy demand, leading to about 36 % decrease of the PAI (up to 7.9) if the PPE would move from the current 2.3 μmol J^{-1} of the actual LEDs employed in the study (released in 2019) to 3.2–4.7 μmol J^{-1} by 2025, which is considered the target efficiency for the red and blue LEDs [64]. The application of another source of renewable energy beside the PV technology, such as the wind power, can contribute to decrease the energy costs [27]. The reconversion of CAs located in colder climate would result in a slight reduction of the cooling load, even if other authors already observed that the energy saving of the VF would not be significant [65].

The commercial VFs should exploit the features of LED lighting, which was demonstrated to improve the shelf life and nutritional features of vegetables compared to open field or greenhouse crops, by increasing the concentration of nutraceutical or pharmaceutical compounds [66,67]. The functional food could be valorised with a significant higher market price, emphasizing the benefits to the human health and meeting the arising food demand of consumers paying attention to a healthy diet and a sustainable food supply chain. In particular, VFs can produce food in which the concentration of nutraceutical compounds such as vitamins, antioxidants, mineral and probiotics can be increased within a strategy of personalised nutrition for specific consumers, depending on gender, age, metabolism, microbiome, eventual chronic diseases etc. [68,69]. The nutraceutical features may increase the market value of the fresh produce and improve the profitability of VFs. Furthermore, since the VF can ensure the fresh food supply independently from the external conditions, it can be considered a technology for the resilience to climate change [70], to possibly face the future challenges of the increasing global food demand, the degradation of the environment and the growing scarcity of resources [33]. Further studies should be carried out to investigate the environmental impact of the VFCA in terms of water use and depletion, acidification and eutrophication, still not examined in this case study.

The VFCA improved all economic indicators of the sole VF and increased the agricultural productivity of the CA, turning this innovative agrosystem and the energy self-consumption to a profitable alternative to selling the energy. The VF technology ensured constant optimal conditions for the crop growth in future perspectives, when conventional horticulture cropping systems may not be sustainable or profitable due to global warming. According to this, the VFs can be considered a possible answer for the reconversion of the current underutilized CAs with high PV cover ratios into productive and efficient cropping systems.

5. Conclusions

The closed agrivoltaic systems (CA) with high PV cover ratio were designed to maximize the energy production and the related profits. The consequent poor yields cannot compete with the income from PV energy, leaving the CA area underutilized or abandoned. The integration of the vertical farm (VF) was tested to quantify the increase of land productivity derived from the reconversion of the CA, using the high resource use efficiency of the VF technology. The original agrosystem integrated an experimental VF inside a pre-existing CA (VFCA) with a PV cover ratio of 100 %. The VFCA increased the yield up to 13 times compared to the sole CA and the CO_2 emissions decreased by 12 %, whereas the land productivity increased with a LER up to 1.60 on the green varieties. The case study quantified the high land consumption of this reconversion, with a CA area from 5.4 to 13.9 times higher than the VF area to achieve the energy self-sufficiency and avoid the related CO_2 emissions, meaning that only 7–18 % of the CA area can be reconverted to vertical farming. The optimal trade-off between PV area and LER was found by covering 16 % of the VF annual energy demand, which maximised the land productivity to a LER of 1.90. Given the actual market price of the energy and the baby leaf lettuce tested in the case study, only the support of the CA energy allowed the VFCA to be profitable. Increasing the yield and the VF resource use efficiency, or adding functional features to the fresh produce can contribute to justify a higher long-term profitable market price. The agricultural sustainability of the CA can increase remarkably with the VF technology, and this study contributed to identify the main design features to reconvert the existing and underutilized CAs into sustainable and efficient mixed agrosystems.

CRediT authorship contribution statement

Marco Cossu: Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Methodology, Software, Formal analysis. **Maria Teresa Tiloca:** Methodology, Investigation, Data curation. **Andrea Cossu:** Visualization, Writing – review & editing. **Paola A. Deligios:** Project administration, Writing – review & editing. **Tore Pala:** Investigation. **Luigi Ledda:** Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix. Equations of the energy balance for air conditioning

The equation for the calculation of the conversion factor from μmol to J of PAR of the LED lamp (C_L) was:

$$C_L = C_W \bullet w_W + C_R \bullet w_R + C_B \bullet w_B (\mu mol J^{-1}) \tag{A.1}$$

where C_W, C_R and C_B are the conversion factors of the white (4.57 μmol J^{-1}), red (5.42 μmol J^{-1}) and blue (3.75 μmol J^{-1}) light, respectively [71,72], with their respective fraction composition w_W, w_R and w_B on the light spectrum. According to this, C_L resulted 4.76 μmol J^{-1} of PAR.

The energy consumption of the LED lamps (E_{LED}) was calculated for the four dimmer switches listed in Table 1 with the following equation:

$$E_{LED} = P_{max} \bullet h \bullet [(D_1 \bullet N_1)+(D_2 \bullet N_2)+(D_3 \bullet N_3)+(D_4 \bullet N_4)](kWh) \tag{A.2}$$

where h is the fixed photoperiod in hours of the LED lights, D the dimmer set (four dimmer switches from 40 to 100 %, thus 40–50–80–100 %) depending on the DLI from 9 to 23 mol m^{-2} d^{-1}, N the number of lamps with the specific D.

The conversion efficiency of the LED lamp μ_{led} was equal to 50 %, calculated with the ratio:

$$\mu_{led} = \frac{PPE}{C_L} \tag{A.3}$$

where C_W, C_R and C_B are the conversion factors of the white (4.57 μmol J^{-1}), red (5.42 μmol J^{-1}) and blue (3.75 μmol J^{-1}) light, respectively [71,72], with their respective fraction composition w_W, w_R and w_B of the light spectrum reported above. The C_L resulted equal to 4.76 μmol J^{-1} of PAR.

The energy balance of eq. (11) of the manuscript was based on the following equations:

Q_{LED} was calculated as following:

$$Q_{LED} = P_{led} \bullet (1 - \mu_{led}) \bullet [(D_1 \bullet N_1)+(D_2 \bullet N_2)+(D_3 \bullet N_3)+(D_4 \bullet N_4)](kWh_t) \tag{A.4}$$

Q_A is calculated assuming an electrical efficiency of the dehumidifier and the two destratifiers η of 90 %:

$$Q_V = \eta \bullet (P_{md} + 2P_{mv})(kWh_t) \tag{A.5}$$

Q_C was calculated as:

$$Q_C = \frac{\left[\left(h_f \bullet A_f\right) + (h_r \bullet A_r)\right] \bullet \left(T_g - T_r\right)}{1000}(kWh_t) \tag{A.6}$$

where T_g is the hourly PV greenhouse temperature, T_r the growth chamber temperature. A_f, A_c and A_s are the floor, the wall area and the substrate surface area of the plateaux cells, respectively, whereas h_f and are the heat transfer coefficients of the floor and walls, respectively, calculated with following equations:

$$h_f = \frac{1}{\frac{s_f}{k_f}}(Wm^{-2}K^{-1}) \tag{A.7}$$

$$h_r = \frac{1}{\frac{s_r}{k_r}}(Wm^{-2}K^{-1}) \tag{A.8}$$

Finally, Q_S was calculated considering the temperature of the substrate (peat) in the plateaux equal to that of the fertigation solution T_s, assumed equal to 20 °C on average:

$$Q_S = h_s \bullet A_S \bullet (T_r - T_s)(kWh_t) \tag{A.9}$$

where A_S is the total heat exchange area to the air of the peat substrate in the plateaux cells and h_s is the heat transfer coefficient of the wet peat with thickness s_{su} of 0.04 m and a thermal conductivity coefficient k_s of 0.600 W m^{-1} K^{-1} [73], equal to:

$$h_s = \frac{1}{\frac{s_{su}}{k_s}}(Wm^{-2}K^{-1}) \tag{A.10}$$

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