Tinted Semi-Transparent Solar Panels allow Concurrent Production of Crops and Electricity on the Same Cropland

Elinor P. Thompson, Emilio L. Bombelli, Simon Shubham, Hamish Watson, Aldous Everard, Vincenzo D'Ardes, Andrea Schievano, Stefano Bocchi, Nazanin Zand, Christopher J. Howe and Paolo Bombelli*.

E.P. Thompson, S. Shubham, N. Zand.
School of Science, University of Greenwich, Chatham Maritime, Kent ME4 4TB,
United Kingdom.

E. L. Bombelli
Via San Francesco 35, Melegnano, 20077,
Italy.

H. Watson
Polysolar Ltd., Aurora BAS, High Cross, Madingley Road, Cambridge, CB3 0ET,
United Kingdom.

A. Everard
Sheffield Solar, Department of Physics and Astronomy, Hicks Building, Hounsfield Road,
Sheffield, S3 7RH,
United Kingdom.

V. D'Ardes
Department of Agricultural and Environmental Sciences - Production, Landscape, Università degli Studi di Milano, Via Celoria, 2, 20133 Milano,
Italy.

A. Schievano, S. Bocchi
Dipartimento di Scienze e Politiche Ambientali, Università degli Studi di Milano, Via Celoria, 2, 20133 Milano,
Italy.

C.J. Howe, P. Bombelli.
Department of Biochemistry, University of Cambridge, Hopkins Building, Cambridge CB2 1QW,
United Kingdom.
*E-mail: pb346@cam.ac.uk

Abstract

Agrivoltaics describes concurrent agricultural production of crops and photovoltaic generation of electricity on the same cropland. By using tinted semi-transparent solar panels, this study introduces a novel element to transform the concept of agrivoltaics from just solar-sharing to selective utilisation of different light wavelengths. Agrivoltaic growth of basil and spinach was tested. When compared with classical agriculture, and based on the feed-in-tariff of the experimental location, agrivoltaic co-generation of biomass and electricity is calculated to result in an estimated financial gross gain up to +2.5% for basil and +35% for spinach. Marketable biomass yields did not change significantly for basil, while a statistically significant loss was observed for spinach. This was accompanied by a relative increase in the protein content for both plants grown under agrivoltaic conditions.

Agrivoltaics implemented with tinted solar panels improved the biomass production per unit amount of solar radiation up to 68%, with up to 63% increase in the ratio of leaf and stem biomass to root. Agrivoltaics can enrich the portfolio of farmers, mitigate risks associated with climate, and vastly enhance global photovoltaics capacity without compromising agricultural production.

1. Introduction

Plants and photovoltaic (PV) panels both harness solar light (**Fig.1A)**[1], using photosynthesis to produce biomass, and the photovoltaic effect to generate electricity. Apart from both needing sunlight, photosynthetic and photovoltaic systems have distinct requirements in light quality and quantity. The quality of light absorbed by photovoltaic panels can be customised to harness the entire solar spectrum (e.g., opaque panels[2]) or, for tinted semi-transparent panels, specific portions (**Fig.1B**). For plants, absorption spectra depend on their photosynthetic pigments (**Fig.1C**). The quantity of light absorbed and used to generate products further differentiates plants and solar panels. For solar panels, electrical output typically correlates linearly with intensity of incident light[3]. For plants, generation of biomass necessarily requires light energy but this does not correlate linearly above a certain intensity, as numerous linked, complex metabolic steps limit the rate[4]. Plants can be grown to produce biomass or food whereas photovoltaic panels generate electricity cooperatively on the same plot of land. This is termed *agrivoltaics* or *solar sharing*[5-13].

Agrivoltaics has been reported to bring several positive benefits to agricultural activity under appropriate circumstances. Protection provided by the solar canopy has been reported to create favourable microclimatic conditions[14]. Plants grown under the canopy of solar panels benefit from more effective water/rain redistribution[15], wind mitigation, moderation of temperature variation[16], reduction in evapotranspiration, improvement in soil humidity, protection against climatic uncertainty and extreme events such as hailstones[17]. Additionally, implementation of agrivoltaics on soil-less vertical farming technologies could intensify food production, while avoiding widespread natural ecosystems disruption caused by conventional agriculture[18]. Agrivoltaics can also offer a direct financial advantage compared with classical farming[19,20]. Several studies have modelled performance and benefits of agrivoltaics[15,19,21-27] and tested its effect with experiments on plant growth (e.g., lettuce[28-30], cucumber[17], wheat[16,31], onion[32], tomato[6,14,33-36] and pepper[14]. By creating opportunities for sustainable dual land usage, agrivoltaics may alleviate the risk of competition between solar panels and agriculture for land with suitable climatic conditions. As discussed recently[37] the climatic conditions that are favourable for agricultural land (*e.g.*, air temperature, humidity, *etc*.) are also ideal for operation of solar panels.

Until now, agrivoltaics has been implemented using opaque and neutral semi-transparent solar panels[6,38,39]. Those panels attenuate the solar radiation uniformly across the entire visible spectrum. Using tinted semi-transparent solar panels for agrivoltaic applications has been suggested before[9] but no experimental data on the effects on plant growth have been published. Here we show the combination of tinted semi-transparent solar panels with growth of two crops of major commercial significance, basil and spinach (**Fig.1D**). The tinted semi-transparent solar panels used in the study were manufactured by Polysolar in Taiwan (further details are given in section 5.6). Basil and spinach are particularly appropriate crops as they are frequently farmed in protected agricultural systems (e.g., greenhouses) where implementation of agrivoltaics can be facilitated readily using existing infrastructure. In this case, plants and solar panels not only share the amount of solar radiation falling on the agrivoltaics installation, but selectively harness different portions of the electromagnetic spectrum. Physiological/metabolic variation were analysed for agrivoltaic growth versus conventional agricultural growth. Based on real field data, energetic, practical and financial implications of agrivoltaics tinted semi-transparent panels were determined. Also, for both basil and spinach, the relative contents of carbohydrate, lipid and protein from plants grown under agrivoltaic conditions were compared versus control plants.

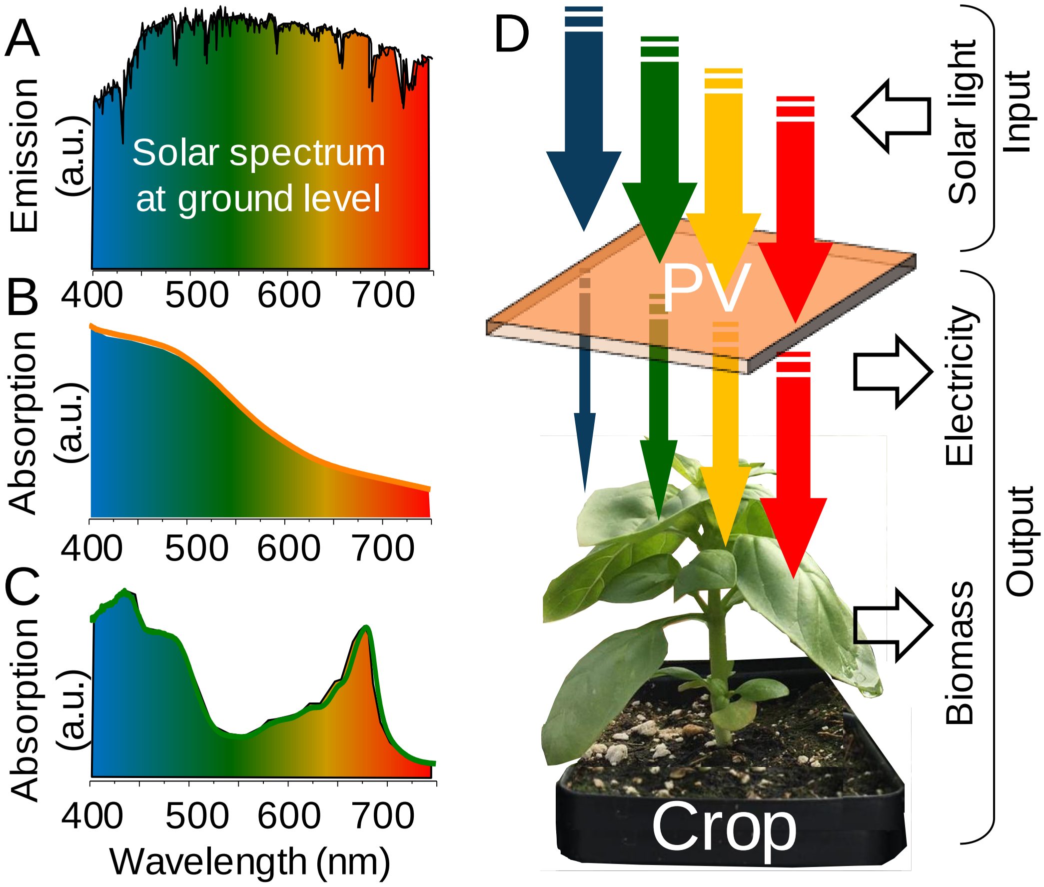


Figure 1. Agrivoltaics for food and energy double-generation implemented with tinted semi-transparent solar panel. (**A**) Solar radiation spectrum in the visible range at the ground level. (**B**) Absorption spectrum for the tinted semi-transparent solar PV panel (a-Si single-junction) used in this study. (**C**) Absorption spectrum for a basil plant leaf. (**D**) Schematic representation of the input (solar energy) and the two contextual outputs of agrivoltaics (i.e., electricity and biomass).

2. Results

2.1 Effect of agrivoltaics on basil growth

Ocimum basilicum, subsequently referred to as basil (cultivar: Italiano Classico, **Sup.Fig.1**) was grown during the Spring/Summer season. Basil seeds were sown in 12 growth units (GU), six of them built using clear glass (*i.e.*,GU-C) and six of them built using tinted semi-transparent solar panels (*i.e.*,GU-PV) (**Sup.Fig.2,3**). The combination of tinted semi-transparent PV glass and borosilicate clear glass resulted in a solar radiation intensity in the

GU-PV approximately 43% of that in the GU-C as described in the methods section. During the experimental run (71 days), the mean temperature was 18.7±5.6 C° with a daily mean solar radiation of ~233 W m^{-2}, which equates to a total solar energy input of 397 kWh m^{-2} (**Sup.Fig.4**).

Figure 2 shows the collected data on basil plants grown in GU-Cs (**fig.2A**) compared with the plants grown in GU-PVs (**Fig.2B**) at day 71. The mean dry weight (DW) for leaf, stem and root accumulated over the entire experimental run was 627±92 gDW m^{-2} for the plants grown in the GU-Cs. For the plants grown in the GU-PVs the mean was ~30% less (441±43 gDW m^2, **Fig.2C)**. An even more dramatic reduction (~48%) was observed when only the tissue below ground (root) was considered, with 236±23 and 121±23 gDW m^{-2} for plants grown in GU-C and GU-PV, respectively (**Fig.2D).** In contrast, when the biomass for tissues above ground (leaf+stem) was considered separately, plants grown in the GU-PVs accumulated a dry weight biomass of 319±31 gDW m^{-2}, which is only ~18% less than those grown in GU-C (391±82 gDW m^{-2}) (**Fig.2E**). This reduction was not statistically significant ($p=0.078$) (**Sup.Tab.1**). The yields of biomass observed are in line with those reported for commercial basil production (**Sup.Tab.2,3**).

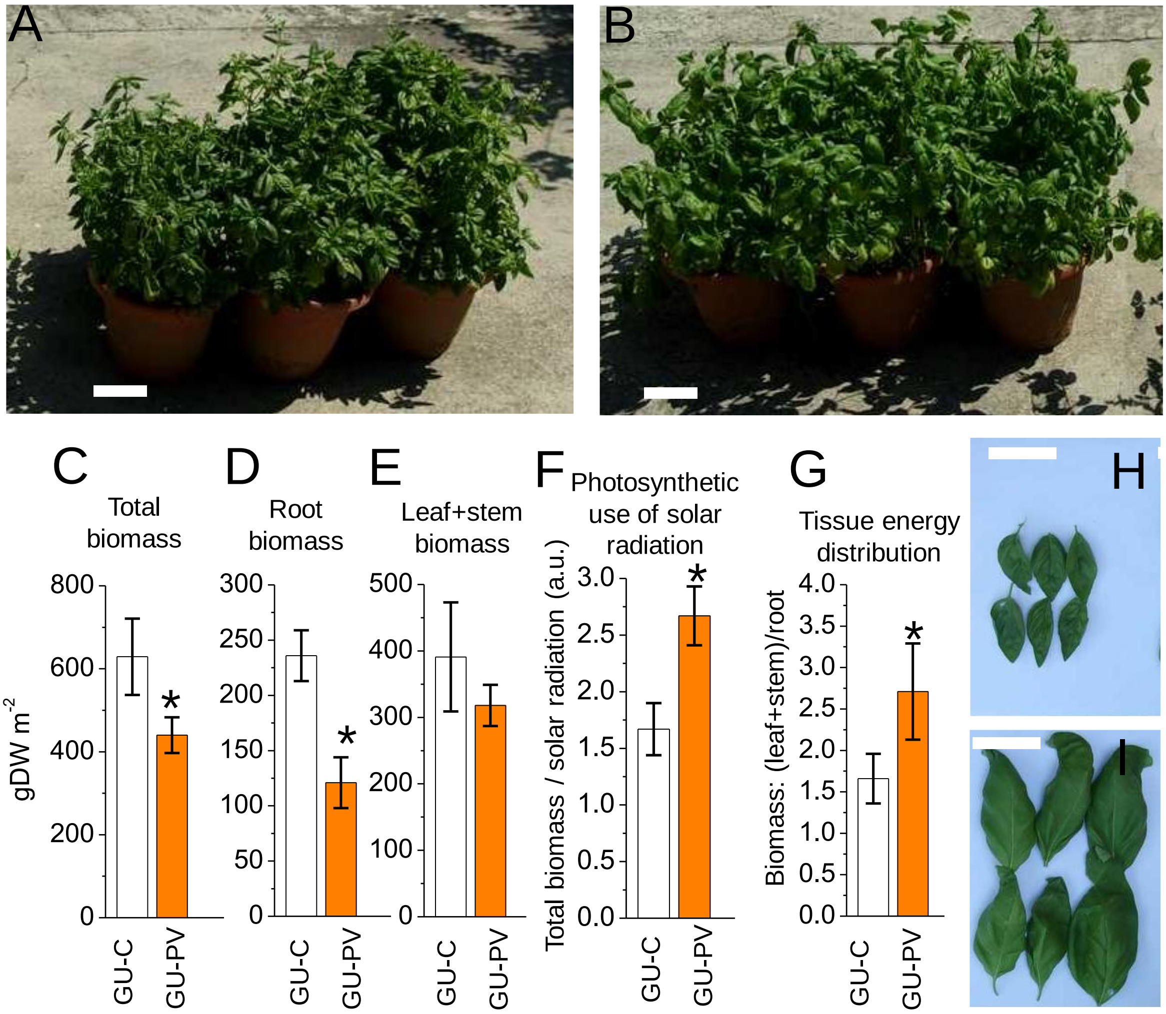


Figure 2 A-B) Overview of the pots of basil plants grown in the GU equipped with clear glass (GU-C) (**A**) and GU equipped with tinted semi-transparent solar panels (GU-PV) (**B**) respectively at the completion of the experimental run (day 71). The white horizontal bar represents 100 mm. **C-E**) Total biomass accumulation (**C**), root (**D**) and leaf + stem (**E**) for basil plants at the completion of the experimental run grown in the GU-C (white histogram) and GU-PV (orange histogram). **F**) Ratio of the total biomass accumulated to the solar radiation. **G**) Ratio of the biomass above ground (leaf+stem) to the biomass below ground (root) for basil plants at the completion of the experimental run grown in the GU-C (white histogram) and GU-PV (orange histogram). The error bar represents ±SD and the asterisk represents statistically significant difference ($p<0.05$) (T-test: **Sup.Tab.1**). **H-I**) Representative examples of leaves of basil from plants grown in the GU-C (**H**) and GU-PV (**I**). The white horizontal bar represents 50 mm.

2.2 Effect of agrivoltaics on spinach growth

Spinacia oleracea, subsequently referred to as spinach (cultivar: Spinacio America, **Sup.Fig.1B**) was grown in two Autumn/Winter seasons (first season 2016; second season

2019 **Sup.Fig.5**). For the first season (2016), spinach seeds were sown in 12 GUs, six of them built using clear glass (*i.e.*,GU-C) and six of them built using tinted semi-transparent solar panels (*i.e.*,GU-PV). For the second season (2019), spinach seeds were sown in 6 GUs, three of them built using clear glass (*i.e.*,GU-C) and three of them built using tinted semi-transparent solar panels (*i.e.*,GU-PV). The mean temperature was 11.7±7.7 C° and 13.6±6.4 C° for the first and second season respectively. The daily mean solar radiation for the season 2016 was ~95 W m^{-2}, which equates to a total energy input of 253 kWh m^{-2}. The daily mean solar radiation for the season 2019 was ~94 W m^{-2}, which equates to a total energy input of 250 kWh m^{-2} (**Sup.Fig.5**).

Figure 3 shows the collected data on spinach plants grown during both seasons in the GU-Cs (**Fig.3A**) compared with the plants grown in the GU-PVs (**Fig.3B**) at day 111. The mean dry weight (DW) for leaf, stem and root accumulated over the entire experimental run was 218±42 gDW m^{-2} for the plants grown in the GU-Cs. For the plants grown in the GU-PVs the mean was ~28% lower (158±29 gDW m^{2}, **Fig.3C)**. For the tissue below ground (root) the accumulated biomass was 22.6±3.5 and 12.4±3.1 gDW m^{-2} for plants grown in GU-C and GU-PV, respectively (**Fig.3D).** For the tissue above ground (leaf+stem), the accumulated biomass was 196±57 and 145±40 gDW m^{-2} for plants grown in GU-C and GU-PV, respectively (**Fig.3E).** For all those comparisons, the differences between the plants grown in the GU-C and those in the GU-PV were statistically significant ($p<0.05$) **(Sup.Tab.4)**. The yields of biomass observed are in line with those reported for commercial spinach production (**Sup.Tab.5,6**).

2.3 Effect of agrivoltaics on plant metabolism and phenotype

The use of tinted semi-transparent solar panels resulted in basil and spinach grown in the GU-PVs receiving ~ 57% less solar radiation compared with the control (GU-Cs) (**Sup.Fig.3A** and **3B**). Nevertheless, the total biomass (leaf+stem+root) accumulated per land unit by those crops decreased only by ~30% for basil and ~28% for spinach, relative to the control plants grown in the GU-Cs. Plants responded to the depletion of solar energy with a more efficient photosynthetic use of light. This can be quantified by dividing the total biomass (DW) accumulated by the total solar energy falling on the growth area during the experimental trial. For both basil (**Fig.2F**) and spinach (**Fig.3F**), the ratio increased by 63% and 68% respectively, for plants grown in GU-PV compared the control plants (**Sup.Tab.1,4)**.

In addition, plants redistributed metabolic energy so that more was dedicated to the tissues above the ground (leaf and stems), at the expense of the tissue below ground (root). The distribution of the metabolic energy caused by agrivoltaics can be quantified by calculating the ratio of the biomass (DW) accumulated in leaf+stem by the biomass accumulated in root. For basil and spinach, this ratio increased by 63% and 35% respectively for the plants grown under an agrivoltaic regime compared to the control plants (**Fig.2G** and **3G**) (**Sup.Tab.1,4)**. For this reason, agrivoltaics is probably more beneficial when the edible/marketable biomass is not developed below ground.

Morphological changes were also observed for basil and spinach plants grown under the agrivoltaic regime compared to control plants. Leaves of basil were larger (**Fig.2H-I**) and the stems of spinach longer in the GU-PV plants (**Fig.3H-I** and **Sup.Fig.6**). Both morphological changes are in line with the above discussed changes in the photosynthetic use of light and metabolic energy redistribution.

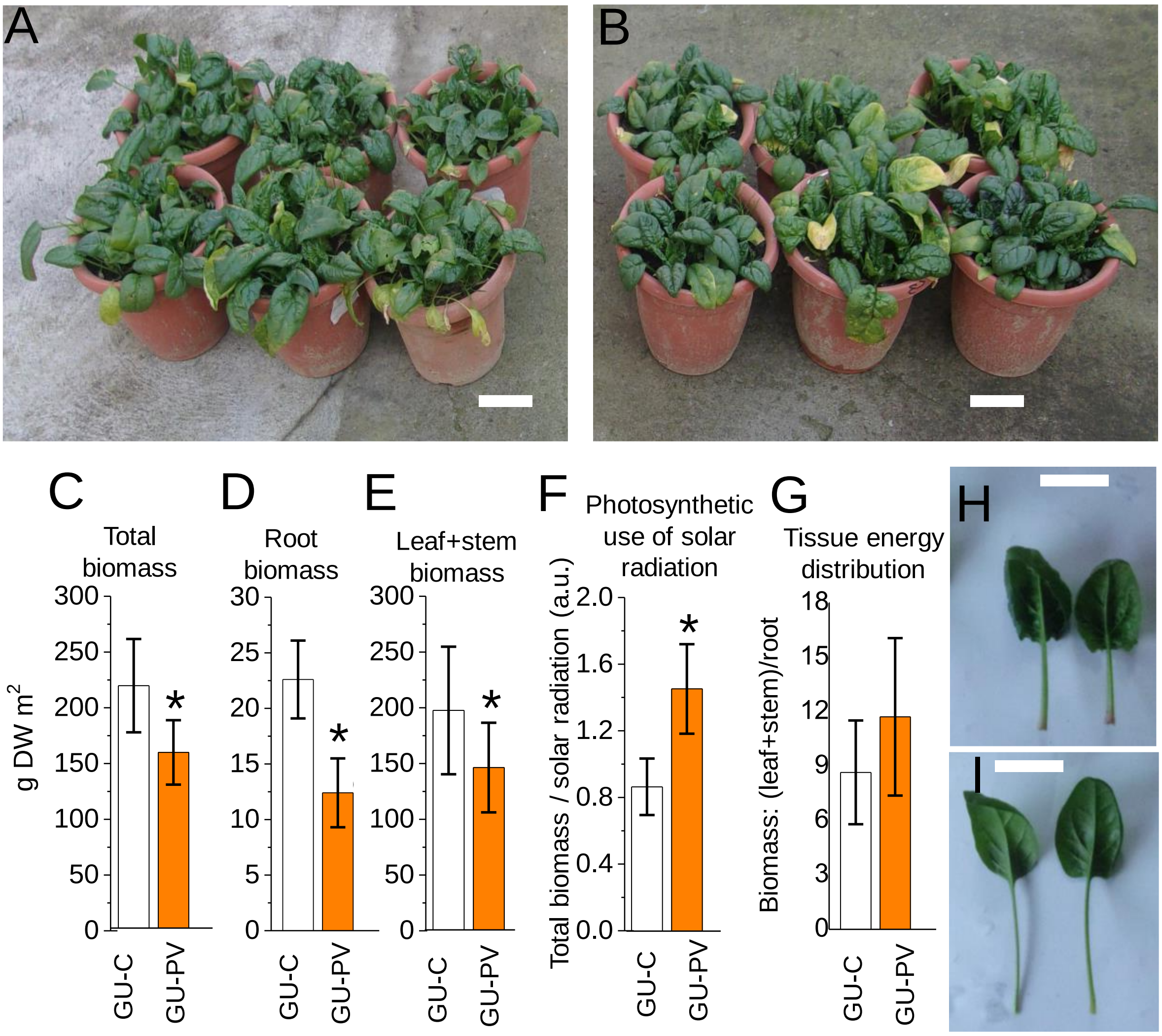


Figure 3 A-B) Overview of the pots of spinach plants grown during the first season in the GU equipped with clear glass (GU-C) (**A**) and GU equipped with tinted semi-transparent solar panels (GU-PV) (**B**) respectively at the completion of the experimental run (day 111). The white horizontal bar represents 100mm. **C-E**) Total biomass accumulation (**C**), root (**D**) and leaf+stem (**E**) for spinach plants grown during both seasons at the completion of the experimental run grown in the GU-C (white histogram) and GU-PV (orange histogram). **F**) Ratio of the total biomass accumulated to the solar radiation. **G**) Ratio of the biomass above ground (leaf+stem) to the biomass below ground (root) for spinach plants at the completion of the experimental run grown in the GU-C (white histogram) and GU-PV (orange histogram). The error bar represents ±SD and the asterisk represents statistically significant difference ($p<0.05$) (T-test: **Sup.Tab.4**). **H-I**) Representative examples of leaves and stems of spinach from plants grown in the GU-C (**H**) and GU-PV (**I**). The white vertical bar represents 50mm.

2.4 Effect of agrivoltaics on protein content

When the carbohydrate and lipid extracted from tissues of plants grown under agrivoltaics condition (GU-PV) were compared with plants grown under clear glass (GU-Cs), the data did not reveal any consistent differences. By contrast, agrivoltaic growth caused a consistent trend in the amount of protein extracted from tissues of both basil and spinach. For basil, there was an increase in the protein extracted from the leaf of plants grown in GU-PVs of +14.1% (p=0.056) compared with leaf from plants grown in GU-Cs. This rise was statistically significant in stem (+37.6%, p=0.004) and root (+9.6%, p=0.010) (**Fig.4A**). For spinach, when both seasons of growth were considered, the protein extracted from leaf, stem, and root of plants grown in GU-PV was respectively +53.1%(p=0.005), +67.9%(p=0.006) and +13.8%(p=0.198) compared with the equivalent tissues obtained from plants grown in GU-C (**Fig.4B**) (**Sup.Tab.7 and 8**).

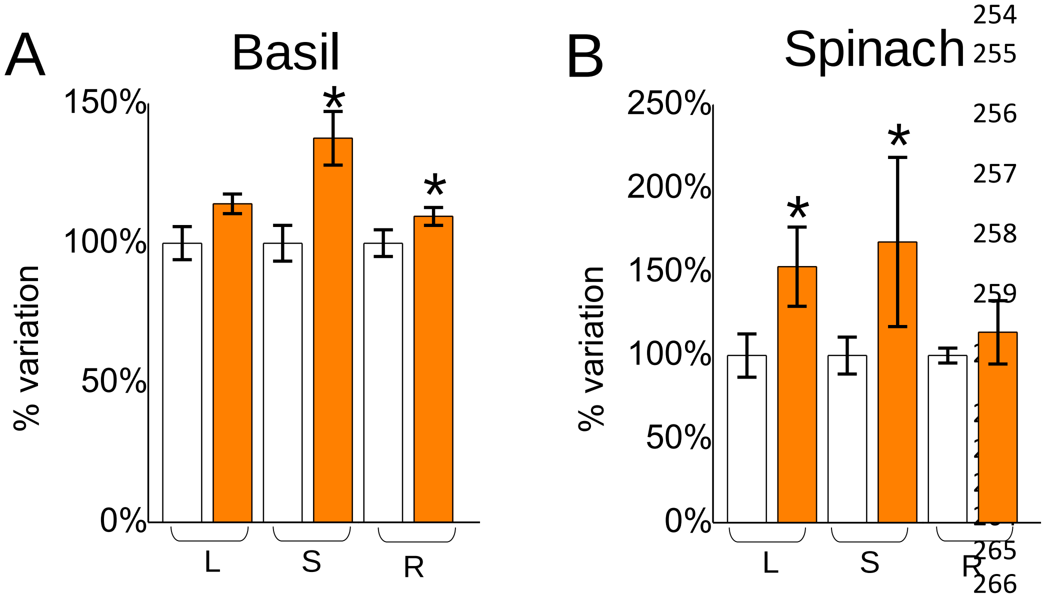


Figure 4 Protein extracted from basil plants (**A**) and spinach plants (**B**) at the completion of the experimental run for both seasons. The protein extracted for each tissue, leaf(L), stem(S) and root(R) for the plants grown in the GU-C (white histogram) is used as reference and given an arbitrary value of 100%. The protein extracted for each tissue, leaf(L), stem(S) and root(R) for the plants grown in the GU-PV (orange histogram) is normalised against its reference. The error bar represents ±SD and the asterisk represents statistically significant difference (T-test, p<0.05) (T-Test: **Sup.Tab.7,8**).

2.5 Financial impact of agrivoltaics

Given the total recorded solar radiation available (**Sup.Fig4B and 5B,D**) and the actual electrical efficiency measured for the tinted semi-transparent solar panel (**Sup.Fig.7**), we estimated the integrated financial balance of the agrivoltaic system. This calculation takes into account the measured yields of marketable biomass for basil and spinach, their actual wholesale global market price, and the actual feed-in-tariff available for electrical energy generated by large photovoltaic installations (>5MW) for the geographical location where the experimental run was conducted (*i.e.*, Italy). For basil, our data showed a decrease in the yield of marketable biomass (leaf) by ~15% for plants grown in GU-PV compared with the control plants grown in the GU-C. This loss in plant productivity was compensated by a generation of 27.8 kWh m^{-2} of electrical energy during the 71 days of the experimental run. Overall, the implementation of agrivoltaics with a tinted semi-transparent solar panel combined with the growth of basil was calculated to give a gross financial gain of about +2.5% compared with growth of basil without the solar panel (**Appendix 1, Table 1)**.

Table 1 Financial impact of agrivoltaics
The table shows the biomass production, the electrical output and their equivalent value in USD for conventional agriculture (GU-C) and agrivoltaic (GU-PV, orange shadowed) over the entire experimental run for basil and spinach (**Appendix 1,2**).

Crop (cultivar)	**Growth condition**	**Mean of the accumulated marketable biomass**		**Value of the marketable biomass**	**Expected electrical output**	**Value of the expected electrical output**	**Total gross value (biomass + electrical output)**
		gDW m^{-2}	**kgFW m^{-2}**	**USD m^{-2}**	**kWh m^{-2}**	**USD m^{-2}**	**USD m^{-2}**
Basil (Italiano Classico)	GU-C	245	3.43	22.8	-	-	22.8
	GU-PV	208	2.91	19.4	27.8	4.03	23.4
Spinach (Spinacio America)	GU-C	196	3.32	4.18	-	-	4.18
	GU-PV	145	2.47	3.11	17.6	2.55	5.66

For spinach, when both seasons of growth were considered, the yield of marketable biomass (leaf+stem) for plants grown in GU-PV decreased by ~26% compared with the control plants grown in the GU-C. This was compensated for by a generation of 17.6 kWh m^{-2} of electrical energy. Overall, the implementation of agrivoltaics with tinted semi-transparent solar panel combined with the growth of spinach was calculated to give a gross financial gain of about +35% compared with growth without the solar panel (**Appendix 2, Tab.1)**. The substantial difference in the gross financial gain between basil and spinach is explained by the market price of those crops, which is about five-fold larger for basil than for spinach at the time of writing.

3. Discussion

Agrivoltaics offers the strategic value of generating biomass together with electricity on the same piece of land[5,7-13,20,38-41]. With conventional agrivoltaics, opaque solar panels are used to cover a certain proportion of the agricultural land casting a shadow on the underlying plants. Maximising the generation of electricity is a desirable goal, but might be at the expense of biomass production. For example, for lettuce, the total biomass yield under agrivoltaic installation in Montpellier (France) was 15-30% less than the control conditions (i.e., full-sun conditions)[28,29]. When growth of tomato was tested in Japan, the yield in an agrivoltaic regime was about 10% lower than for conventional agriculture[36]. When the same crop was tested in Morocco, the yield in an agrivoltaic modified greenhouse was substantially the same as in an unmodified greenhouse[35].

With the use of tinted semi-transparent solar panels, photosynthetic organisms and photovoltaic systems can harness different parts of the visible spectrum. The advantage of that could be understood by examining how the light is absorbed and processed by photosynthetic organisms and photovoltaic panels. Chlorophylls, the main photosynthetic pigments in plants, have absorbance peaks in the blue (~400-500 nm) and red (~600-700 nm), and a trough in the green (~500-600 nm) (**Fig.1C**). Pigments such as carotenoids and anthocyanins have absorbance peaks in the blue (~400-500 nm) and green (~500-600 nm) respectively. However, those pigments function in absorbance and dissipation of excess/harmful solar energy (e.g., UV) to protect the photosynthetic apparatus from light stress[42-45]. Therefore, part of the solar energy absorbed in the blue and green portions of the electromagnetic spectrum is dissipated without contributing to photosynthesis. Customising the absorption spectra of photovoltaic panels allows them to harness light in the region of the solar spectrum where plants are less effective[2]. For example, the tinted semi-transparent solar panels used in this study absorb preferentially blue and green light, leaving most of the red for photosynthesis (**Fig.1B**). Therefore, the solar radiation falling in the GU-PV GUs is relatively red enriched (blue and green impoverished), permitting a more efficient photosynthetic use of light, as actually observed in this study (**Fig.2F** and **3F**).

Growth under the tinted semi-transparent solar panels increases the proportion of red light reaching plants, which may alter the balance of red-absorbing phytochrome and far-red absorbing phytochrome, and reduce the proportion of blue light that mediates the deleterious effects of too much red[46]. Under the normal outdoor spectrum, changes in carbon allocation occur when the far-red phytochrome is activated by far-red-enriched light reflected from overhanging vegetation near the plant, prompting the shade-avoidance response and promoting stem elongation at expense of leaf tissue[,47]. Thus, the altered architecture and chemical composition for the plants grown in the GU-PV might be a stress response.

The work described in our study was based on 6 measurements with basil and 9 with spinach. Our work shows that agrivoltaic growth under tinted semi-transparent solar panels effect the accumulation of protein in the tissues of the plants. The amount of protein extracted from leaf, stem and root in both crops grown under agrivoltaic conditions was consistently increased (**Fig.4**). Accumulating more protein is of particular interest in view of the need for alternative sustainable protein sources to substitute animal proteins[48] This is increasing interest, for example, in plant-based artificial meats and protein-rich ingredients[49]. Our study does not allow us to draw conclusions on the effect of agrivoltaics on plants where underground tissues might have different functions, e.g. storage in tubers. Further experimental trials using semi-transparent solar panels with specific, targeted optical properties might permit the development of novel methods for tailoring the content of specific nutrients in crops. In photosynthetic microorganisms this is already an objective of the biotechnology sector[50,51]. The morphological changes observed in the marketable biomass (leaf+stem) of spinach grown in the GU-PV could have additional economic benefits. For example, having longer stems on spinach (**Fig.3H-I** and **Sup.Fig.6**) will facilitate harvesting by mechanical tools.

Although agrivoltaics may offer a direct financial advantage compared with classical farming, this advantage depends on many variables (i.e., the local level of solar radiation, the type of crop, the costs for installing the solar panels, the costs associated with farming under canopy, the global/local market price for crops and electricity and also eventual public subsidy available for renewable energy). It is quite challenging to make an absolute algorithm for calculating the financial value of agrivoltaics, based on the interactions and variability of all these factors. However, a range of projections have been published. In 2011 Dupraz et al. predicted that agrivoltaic systems could increase global land productivity up to 73%[21]. Dinesh et al. computed that the value of co-generation of electricity and lettuce in US could reach over 30% when compared with conventional agriculture[19]. More recently, the revenue for farming grape under an agrivoltaic regime in India was foreseen to be several folds that of conventional grape farming[25]. This present study finds that the growth of basil and spinach combined with tinted semi-transparent solar panels could give a gross financial gain estimated at +2.5% and +35% for basil and spinach respectively compared with classical agriculture. These figures were based on the actual feed-in-tariff for electrical energy generated by large photovoltaic installations (>5 MW) for the geographical location where the experimental run was conducted (*i.e*., Italy) (**Appendix 1,2**). Calculations based on the cost to the consumer for the electricity produced would give greater predicted benefits of agrivoltaics. If the feed-in-tariff available for electrical energy and/or the price for agricultural products were substantially different from those assumed here (**Appendix 1,2**), the financial impact of agrivoltaics would clearly need to be reassessed.

Agrivoltaics allows further substantial practical benefits. First, this system permits the diversification of the portfolio of farmers, mitigating the risks associated with climatic and economical uncertainty. Second, the protection provided by the solar canopy creates favourable microclimate conditions. Indeed, the use of water could also be influenced by agrivoltaic practice because the latter allows more effective water-rain redistribution, mitigation of wind and temperature and evapotranspiration, and management of soil humidity. The deployment of large PV solar installations in arid areas might require regular water inputs for cleaning the surface of solar panels. This water could also be used for crop irrigation, maximizing the efficiency of land and water use[22]. The positive effect of agrivoltaics on the use of water has been demonstrated by work on lettuce and cucumber[17]. For unirrigated pasture soil, implementation of agrivoltaics was found to maintain higher soil moisture and causing a significant increase of the yield of biomass[52].

Agrivoltaic production is in principle applicable to any agricultural land. Having said that, the installation of solar panels will be facilitated if an existing physical infrastructure is already in place. This is the case in protected agriculture, which uses a confined environment in which to grow crops (e.g., greenhouses). Therefore, the global potential impact of agrivoltaics on the PV expansion could be inferred based on the land area in use for protected agriculture. Farming on protected agriculture is a growing reality throughout the world with an estimated global vegetable area of 5,630,000 ha[53]. Implementing the tinted semi-transparent solar panels tested in this study, on the area currently in use for protected agriculture, would permit a vast expansion of the installed PV capacity to ~3547 GWp (**Appendix 3**). This figure is about fivefold that of the current PV installed capacity[54,55]. This estimate does not take account of installation of agrivoltaics on soil-less vertical/indoor farming, which promises to be one of the main solutions to avoid increasing the use of arable land and therefore limiting agriculture's contribution to climate change[56-58].

As this study suggests, the use of agrivoltaics depends on a multitude of variables, some of those associated with local and perhaps transitory conditions (*e.g.*, public subsidy). Nevertheless, in order to offer a practical guideline for the implementation of agrivoltaic systems on cropland, we have compiled a repository table to summarise the key factual elements characterising agrivoltaic installations as available in published studies, but excluding geo-economical elements (**Sup.Tab.9**)[59,60]. The database includes: a) the location where the agrivoltaic is installed; b) the chosen crop; c) the growth season during which the agrivoltaic was tested; d) and e) the yield of marketable biomass without and with agrivoltaic regime; f) the model of solar panel installed; g) the proportion shade level (%) caused by agrivoltaic use on the incident solar radiation at level of the growth area; and h) the mean of the electrical output during the experimental run.

4. Conclusion

This paper provides an important advance in the field of agrivoltaics. For the first time, the results of using tinted semi-transparent solar panels tested with crops of global value (basil and spinach) are presented. Agrivoltaic growth produced four measurable effects on the physiology of basil and spinach: i) plants demonstrated a more efficient photosynthetic use of light (up to 68% for spinach); ii) the metabolic energy of plants was preferentially redirected toward tissues above ground (up to 63% for basil); iii) the phenotype of plant parts above ground was different from the control plants; iv) the amount of protein extracted from the both plants was increase in leaf (basil: +14.1%, spinach: +53.1%), stem (basil: +37.6%, spinach: +67.9%) and root (basil: +9.6%, spinach: +15.5%).

Even with a loss in the yield of marketable biomass for both basil (15%) and spinach (26%), projection of our experimental data has shown that agrivoltaics could give a substantial overall financial gain calculated to be +2.5% for the basil and +35% for the spinach compared with classical agriculture. Finally, by compiling the available published data on agrivoltaics (**Sup.Tab.9**), we have defined a list of key minimum parameters required for the characterisation of published installations. With this, we aim to introduce clarity in the field and facilitate the expansion of agrivoltaics and permitting growth of the global PV capacity without compromising the use of arable land for food production.

5. Experimental Section

5.1 The GU

The experimental runs were conducted in GUs. Each one was formed by a timber frame (the overall dimensions were 500mm height x 350mm x 350mm) as shown in **Sup.Fig.2**. The GUs were divided in two groups designated GU-C or GU-PV. In the GU-Cs the timber frames were covered with borosilicate clean glass, one glass sheet on the top (350mm x 350mm) and 4 glass sheets on the sides (350mm x 200mm) (**Sup.Fig.2A,B**).

In the GU-PVs the timber frames were covered with tinted semi-transparent PV glass, one PV glass sheet on the top (350mm x 350mm), 2 PV glass sheets on the sides (350mm x 200mm) and 2 borosilicate clean glass sheets on the other sides (350mm x 200mm) (**Sup.Fig.2C,D**). The combination of tinted semi-transparent PV glass and borosilicate clear glass resulted in a solar radiation in the GU-PV approximately 43% of the solar radiation falling in the GU-C (**Sup.Fig.3A** and **Sup.Fig.3B**).

The lower part of each GU (250 mm height) was left open to permit ventilation and prevent overheating. One plastic pot (260mm diameter, 250mm height, 11L internal volume) was placed in each GU at the centre of the frame (**Sup.Fig.3C**). The top edge of the pot placed inside the GU reached approximately the lower edge of the lateral glass sheets. The soil used was commercial compost, Levington Professional Growing Medium – M3, and was not autoclaved.

5.2 Experimental set-up

The GUs were arranged in three lines and four rows in a plot of land located 45°21‘ N 9°19‘ E (Melegano, Italy). The GU-Cs and GU-PVs were arranged alternately and placed on the ground leaving a gap of ~0.50m in between each GU (**Sup.Fig.8**).

5.3 Seed sowing

For the Spring/Summer run (from April 2016 to June 2016) basil (*Ocimum basilicum* L.) was used. Seeds were obtained from an Italian seed supplier (http://www.franchisementi.it/) (**Sup.Fig.1A**). The cultivar chosen was Italiano Classico. Each pot was sown with ~100 mg of seeds (approximately 105 seeds). Seeds were placed in the ground on the 21st of April (2016) and left in place until the end of June for a total of 71 days. Decanted tap water was dispensed in a quantity of ~1.0L per pot every other day for the entire duration of the experimental run. The percentage of germination for the plants grown in the six GU-Cs and the plants grown in the six GU-PVs were 42.7±7.3% and 38.3±8.6% respectively (**Sup.Fig.1C**).

For the Autumn/Winter run (season 1: from September 2016 to December 2016; season 2: from September 2019 to December 2019) spinach (*Spinacia oleracea* L.) was used. Seeds were obtained from an Italian seed supplier (http://www.franchisementi.it/)(**Sup.Fig.1B**). The cultivar chosen was Spinacio America. Each pot was sown with 20 seeds. Seeds were placed in the ground at the beginning of September (season 1: 3rd, 2016; season 2: 1st, 2019) and left in place until the third week of December (season 1: 23rd, 2016; season 2: 21st, 2019) for a total of 111 days. After germination (ca. 10 days), the numbers of seedlings were adjusted to 7 per pot in each GU. This was done to avoid an unequal plant distribution and excessive crowding in the growing area. The percentage of germination for the plants grown in the six GU-Cs and the plants grown in the six GU-PVs were 70.8±15.3% and 77.5±15.1% respectively (**Sup.Fig.1D**). Decanted tap water was dispensed in a quantity of ~0.5L per pot every other day until the end of October, and then the quantity was reduced to ~0.25L per pot every other day.

5.4 Plant tissues harvesting and mass determination

Plant tissues were harvested at the end of each experimental run. Leaf, stem and root were separately stored in paper bags. Leaf and stem were dried in a 45°C oven for 15 days. Soil was carefully removed from the radical system. Then roots were washed in tap water three times and finally stored in paper bags to be dried in a 45°C oven for 15 days. Dry weight (DW) of the dried biomass was determined using a Precision 100M-300C balance (JOHNSON PRECISA).

5.5 Protein determination

For basil and spinach (season 1), protein quantification was carried out on dried plant tissues by applying Kjeldahl’s factor (http://www.fao.org/fao-who-codexalimentarius) to the proportion of nitrogen in samples subjected to elemental analysis [Flash EA1112, Thermo Scientific, Loughborough, UK] according to the manufacturer’s instructions.

For spinach (season 2), protein quantification was carried out on dried plant tissues using the Dumas technique (Method 990.03) (AOAC 2006) using Nitrogen analyser Rapid MAX N Exceed – ELEMENTAR – Langenselbold (Germany) as described[61].

5.6 Solar PV panel

The photovoltaic technology used is thin-film amorphous silicon with a transparent zinc oxide back conductive layer and clear front glass coated with Fluorine Tin Oxide. The PV panels are a glass laminate with the PV layers sandwiched between. They absorb light in the blue and green part of spectrum and let through light in the red part of the spectrum, which gives them an orange tint (transmission spectrum and data points are is shown in **Sup.Fig.9** and **Sup.Tab.10** respectively). The panels have a nominal efficiency and power output of 8% and 66 W m^{-2} respectively[62].

The solar module data used in this study is taken from a test bed run by the Sheffield Solar group, at the University of Sheffield, where the test modules are short circuited and the current is sampled on a two minutely basis. Module power output is calculated by the ***equation 1***.

Equation 1 $P_{out} = (J_{scob} \times P_{max}) / J_{sc}$

Where P_{out} is output power, J_{scob} is the observed short circuit current, P_{max} is the module maximum rated power and J_{sc} is the short circuit current at P_{max}.

Acknowledgements

The authors thank the Leverhulme Trust RPG-2015-393 and the Italian Ministry of University and Research (MIUR), within the SIR2014 Grant, project RBSI14JKU3 to support the work of PB.

They thank Devyani Amin, Prof David Wray, Dr Giacomo Cocetta, Dr Daniele Cavalli for help with practical work and provision of equipment, Emily Anderson for help with some of

the photographic material and Dr Alistair McCormick for providing valuable critical comments.

EPT, ELB, SS, VD and PB carried out practical work.

DA, NZ, EPT supervised the CHN analysis and the CHN analyser is in the lab of DW.

HCJ, HW, EPT and NZ arranged funding.

EPT, HW, AE, VD, AS, SB, NZ, CJH and PB contributed to discussion.

EPT, CJH and PB wrote the manuscript.

Conflict of interest

HW and Polysolar provided the tinted semi-transparent solar panel.

References

1. S. T. M. Standard, G173-03, 2008 Available online: www.astm.org/Standards/G173.htm (accessed on 17 May 2019).
2. S. De Wolf, J. Holovsky, S.J. Moon. P. Löper, B. Niesen, M. Ledinsky, F.J. Haug, J.H. Yum, C. Ballif, *J. Phys. Chem. Lett.*, *5* (6), 2014, 1035–1039
3. A. El-Shaer, M. T. Y. Tadros, M. A. Khalifa, *International Journal of Emerging Technology and Advanced Engineering*, 2014, 4, 8, 311-318
4. R. E. Blankenship, D. M. Tiede, J. Barber, G. W. Brudvig, G. Fleming, M. Ghirardi, M. R. Gunner, W. Junge, D. M. Kramer, A. Melis, T. A. Moore, C. C. Moser, D. G. Nocera, A. J. Nozik, D. R. Ort, W. W. Parson, R. C. Prince, R. T. Sayre, *Science,* 2011, 332, 6031, 805-809
5. A. Yano and M. Cossu, *Renewable and Sustainable Energy Reviews*, 2019, 109, 116–137
6. R. H. E. Hassanien. M. Li, F. Yin, *Renewable Energy*, 2018, 121, 377-388
7. A. Marucci and A. Cappuccini, *Applied Energy*, 2016, 170, 362–376

8. A. Scognamiglio, *Renewable and Sustainable Energy Reviews*, 2016, 55, 629–661

9. C. S.Allardyce, C. Fankhauser, S. M.Zakeeruddin, M. Grätzel, P J.Dyson*, Solar Energy*, 2017, 155, 517–522

10. C. Li, H. Wang, H. Miao, B. Ye, *Applied Energy*, 2017, 190, 204–212

11. T. Wang, G. Wu, J. Chen, P. Cui, Z. Chen, Y. Yan, Y. Zhang, M. Li, D. Niu, B. Li, H. Chen, *Renewable and Sustainable Energy Reviews*, 2017, 70, 1178–1188

12. M. Cossu, A. Cossu, P. A. Deligios, L. Ledda, Z. Li, H. Fatnassi, C. Poncete, A. Yano. *Renewable and Sustainable Energy Reviews*, 2018, 94, 822–834

13. N. Irie, N. Kawahara, A. M. Esteves, *Renewable Energy*, 2019, 139, 1463-1476

14. G. A. Barron-Gafford, M. A. Pavao-Zuckerman, R. L. Minor, L. F. Sutter, I. Barnett-Moreno, D. T. Blackett, M. Thompson, K. Dimond, A. K. Gerlak, G. P. Nabhan, J. E. Macknick. *Nature Sustainability*, 2019, 2, 848-855

15. S. Amaducci, X. Yin, M. Colauzzi, *Applied Energy*, 2018, 220, 545–561

16. H. Marrou, L. Guilioni, L. Dufour, C. Dupraz, J.Wery, *Agricultural and Forest Meteorology,* 2013, 177, 117-132

17. H. Marrou, L. Dufour, J.Wery, *Europ. J. Agronomy*, 2013, 50, 38– 51

18. K. Wiebe, S. Robinson, A. Cattaneo, *Sustain. Food Agric.*, 2019, 55–74

19. H. Dinesh and J. Pearce J. *Renewable and Sustainable Energy Reviews*, 2016, 54, 299–308

20. R. H. E. Hassanien, E. Hassanien*, M. Li., W. D. Lin,* Renewable and Sustainable Energy Reviews, 2016, 54, 989–1001

21. C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, Y. Ferard, *Renewable Energy*, 2011, 36(10), 2725-2732

22. S. Ravi, D. B. Lobell, C. B. Field, *Environ. Sci. Technol*., 2014, 48, 3021−3030

23. H. Fatnassi, C. Poncet, M. M. Bazzano, R. Brun., N. Bertin, *Solar Energy*, 2015, 120, 575–584

24. S. Sacchelli, G. Garegnani, F. Geri, G. Glilli, A Paletto, P. Zambelli, M. Ciolli, D. Vettorato, *Land Use Policy*, 2016, 56, 90–99

25. P. R. Malu, U. S. Sharma, J. M. Pearce, *Sustainable Energy Technologies and Assessments*, 2017, 23, 104–110

26. D. Majumdar and M. Pasqualetti. *Landscape and Urban Planning*, 2018, 170, 150–168

27. L. Dias, J. P. Gouveia, P. Lourenço, J. Seixas, *Land Use Policy*, 2019, 81, 725–735

28. H. Marrou, J.Wery, L. Dufour, C. Dupraz, *Europ. J. Agronomy*, 2013, 44, 54– 66

29. B, Valle, T. Simonneau, F. Sourd, P. Pechier, P. Hamard, T. Frisson, M., Ryckewaert, A. Christophe, *Applied Energy*, 2017, 206, 1495–1507, (2017).

30. G. Trypanagrostopoulos. A. Kavga, M. Souliotis, Y. Trypanagrostopoulos, *Renewable Energy*, 2017, 111, 724-731

31. C. Dupraz, G. Talbot, H. Marrou, J. Wery, S. Roux, F. Liagre, Y. Ferard, A. Nogier, Proceedings of the 5th WCCA, 2011, Brisbane, Australia

32. M. Kadowaki, A.Yano, F. Ishizu, T. Tanaka, S. Nodad, *Biosystems engineering*, 2012, 111, 290-297

33. J. Pérez-Alonso, M. Pérez-García, M.Pasamontes-Romera, A.J.Callejón-Ferrea, *Renewable and Sustainable Energy Reviews*, 2012, 16, 4675–4685

34. R. Ureña-Sánchez, Á. J. Callejon-Ferre, J. Pérez-Alonso, A. Carreño-Ortega, *Sci. Agric.*, 2012, 69(4), 233-239

35. K. Ezzaeria, H. Fatnassi, R. Bouharroud, L. Gourdo, A. Bazgaou, A. Wifaya, H. Demrati, A. Bekkaoui, A. Aharoune, C. Poncet, L. Bouirden, *Solar Energy*, 2018, 173, 1126–1134

36. A. Leon and K. N. Ishiharab, *Journal of Environmental Management*, 2018, 226, 493–498

37. E. H. Adeh, S. P. Good, M. Calaf, C. W. Higgins, *Scientific Reports*, 2019, 9:11442

38. A. Yano, M. Onoe, J. Nakata, *Biosystems engineering*, 2014, 122, 62-73

39. M. Cossu, A. Yano, Z. Li, M. Onoe, H. Nakamura, T. Matsumoto, J. Nakata, *Applied Energy*, 2016, 162, 1042–1051

40. E. Marrau, *Nature Sustainability*, 2019, 2, 793-794

41. A. Goetzberger and A. Zastrow, *International Journal of Solar Energy*, 1982, 1(1), 55-69

42. D. B. Adams and W. W. Adams III, *Annual Review of Plant Physiology and Plant Molecular Biology*, 1992, 43, 599-626

43. P. Jahnsa and A. R. Holzwarthb, *Biochimica et Biophysica Acta (BBA) – Bioenergetics*, 2012, 1817(1), 182-193

44. *K. S. Gould, K. R. Markham, R. H. Smith, J. J. Goris*, *J. Exp. Bot*., 2000, 51(347), 1107-1115

45. P. K. Sharma and D. O. Hall, *Photosynthesis: photoreactions to plant productivity*, Dordrecht, 1993, 469–478

46. P. F. Devlin, PNAS, 113 (27) 7301-7303 (2016)

47. Kaiser, T. Ouzounis, H. Giday, R. Schipper, E. Heuvelink, L. F. M. Marcelis, Front. Plant Sci., 9, 1-11 (2019)

48. A. Shepon, G. Eshel, E. Noor, R. Milo, *Proc. Natl. Acad. Sci.*, 2018, *115* (15)

49. K. Kyriakopoulou, B. Dekkers, A. J. van der Goot, Chapter 6, 2019, Plant-Based Meat Analogues. *Sustainable Meat Production and Processing*, 103-126

50. B. M. Berla, R. Saha, C. M. Immethun, C. D. Maranas, T. S. Moon, H. B. Pakrasi, *Front. Microbio*l., 2013, 4, 1-14

51. H. Kirst, C. Formighieri, A. Melis, *Biochim Biophys Acta*, 2014, 1837(10), 1653-64

52. E. H. Adeh, J. S. Selker, C. W. Higgins, Plos One, 2018, 13(11): e0203256

53. R. Cuesta, 2019, https://www.producegrower.com/article/cuesta-roble-2019-global-greenhouse-statistics/ (Accessed on 17 May 2019).

54. NFU, 2013 https://www.nfuonline.com/solarpv_nfubriefing4/ (accessed on 17 May 2019).

55. IEA, 2016, Snapshot of global photovoltaic market 2016 http://www.iea-pvps.org/fileadmin/dam/public/report/statistics/IEA-PVPS_-_A_Snapshot_of_Global_PV_-_1992-2016__1_.pdf (accessed on 17 May 2019).

56. J. Germer, J. Sauerborn, F. Asch, J. de Boer, J. Schreiber, G. Weber, J. Müller, *J. für Verbraucherschutz und Leb.*, 2011, 6(2), 237–251

57. K. Bemke and B. Tomkins B. *Sustain. Sci. Pract. Policy*, 2017, 13(1), 13–26

58. A. M. Beacham, L. Vickers, J. Monaghan, *J. Hortic. Sci. Biotechnol.*, 2019, 94(3), 277–283

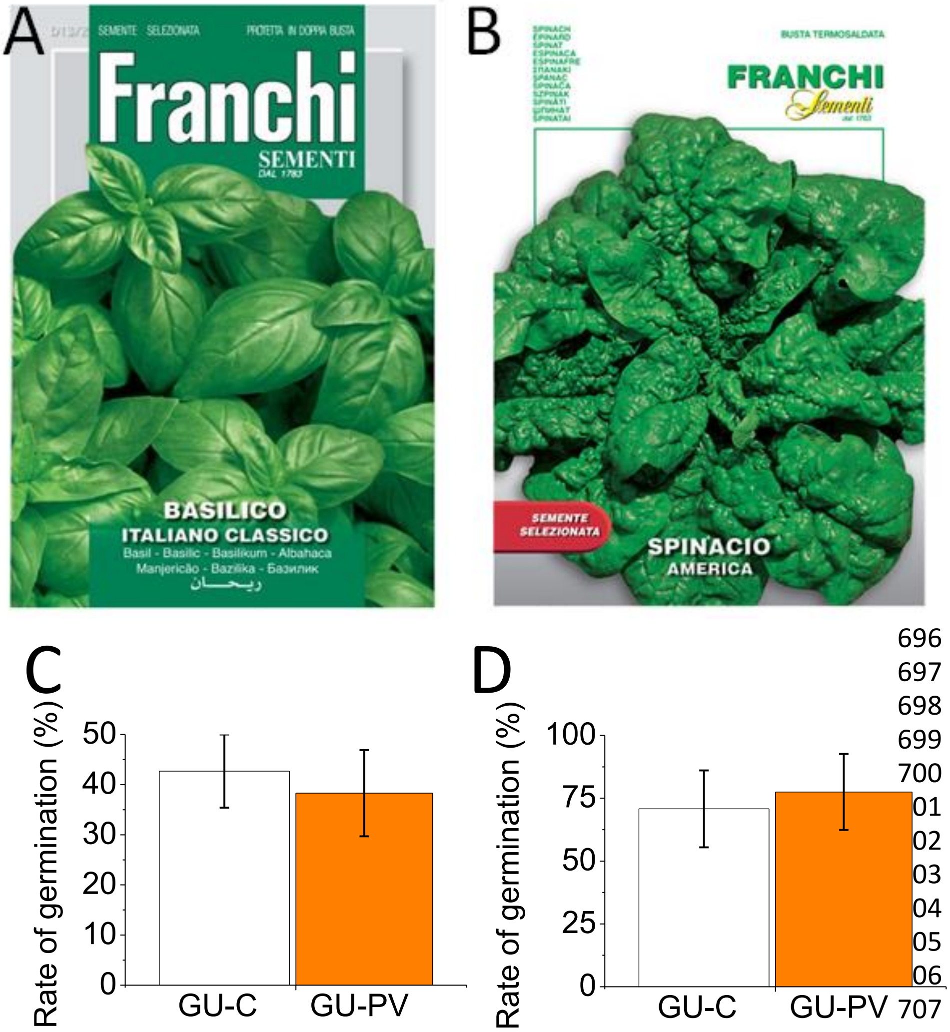
59. A. Yano, M. Kadowaki, A. Furue, N.Tamaki, T.Tanaka, E.Hiraki, Y.Kato, F.Ishizu, S.Noda, *Biosystems Engineering*, 2010, 106, 367-377

60. R. H. E. Hassanien and L. Ming, Int. J Agric.&Biol.Eng. 2017, 10,6, 11–22

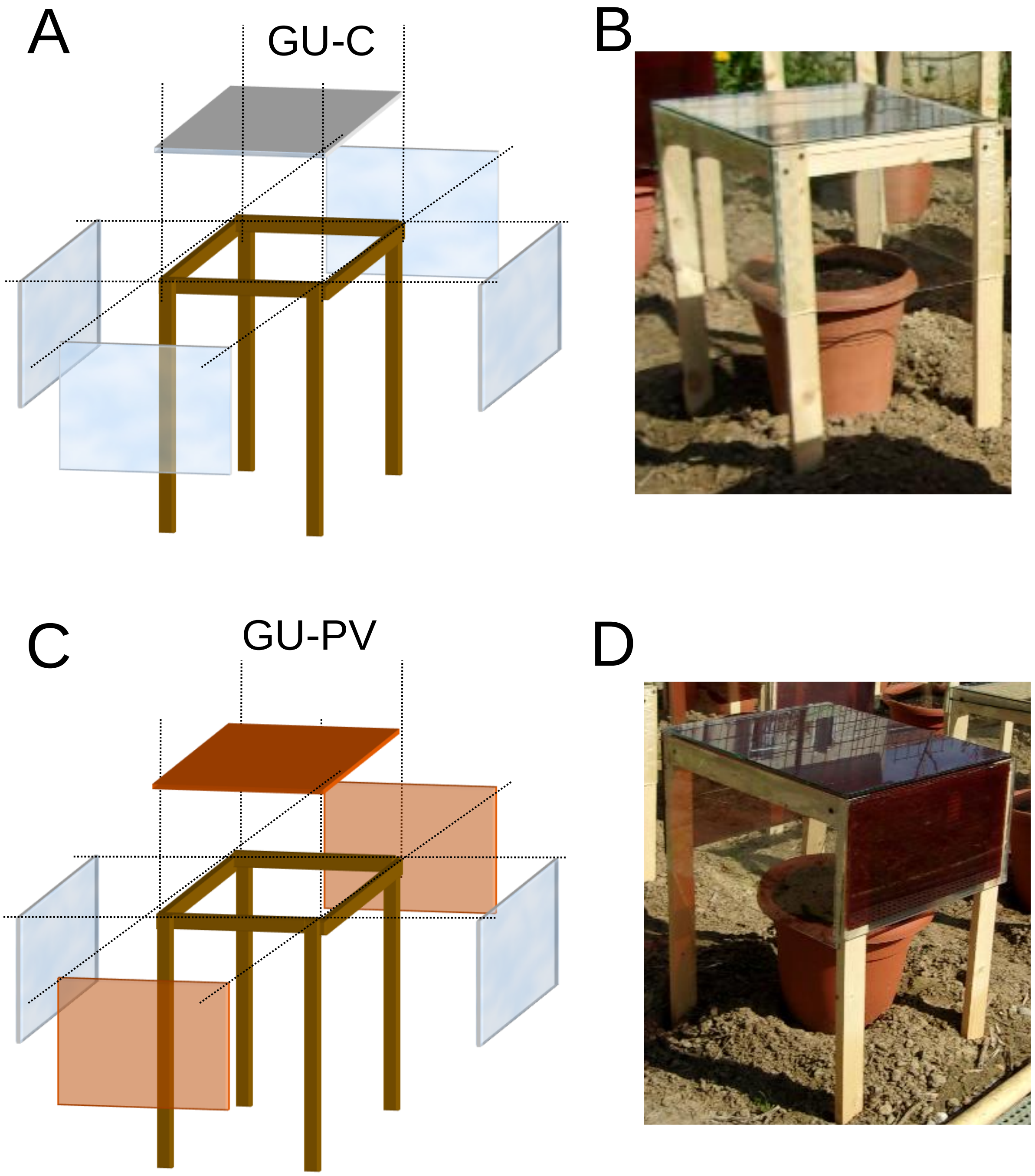
61. N. Thiex, *Journal of AOAC INTERNATIONAL*, 2009, 92(1), 1, 61–73

62. https://www.enf.com.cn/Product/pdf/Crystalline/59e5ca07ebf24.pdf

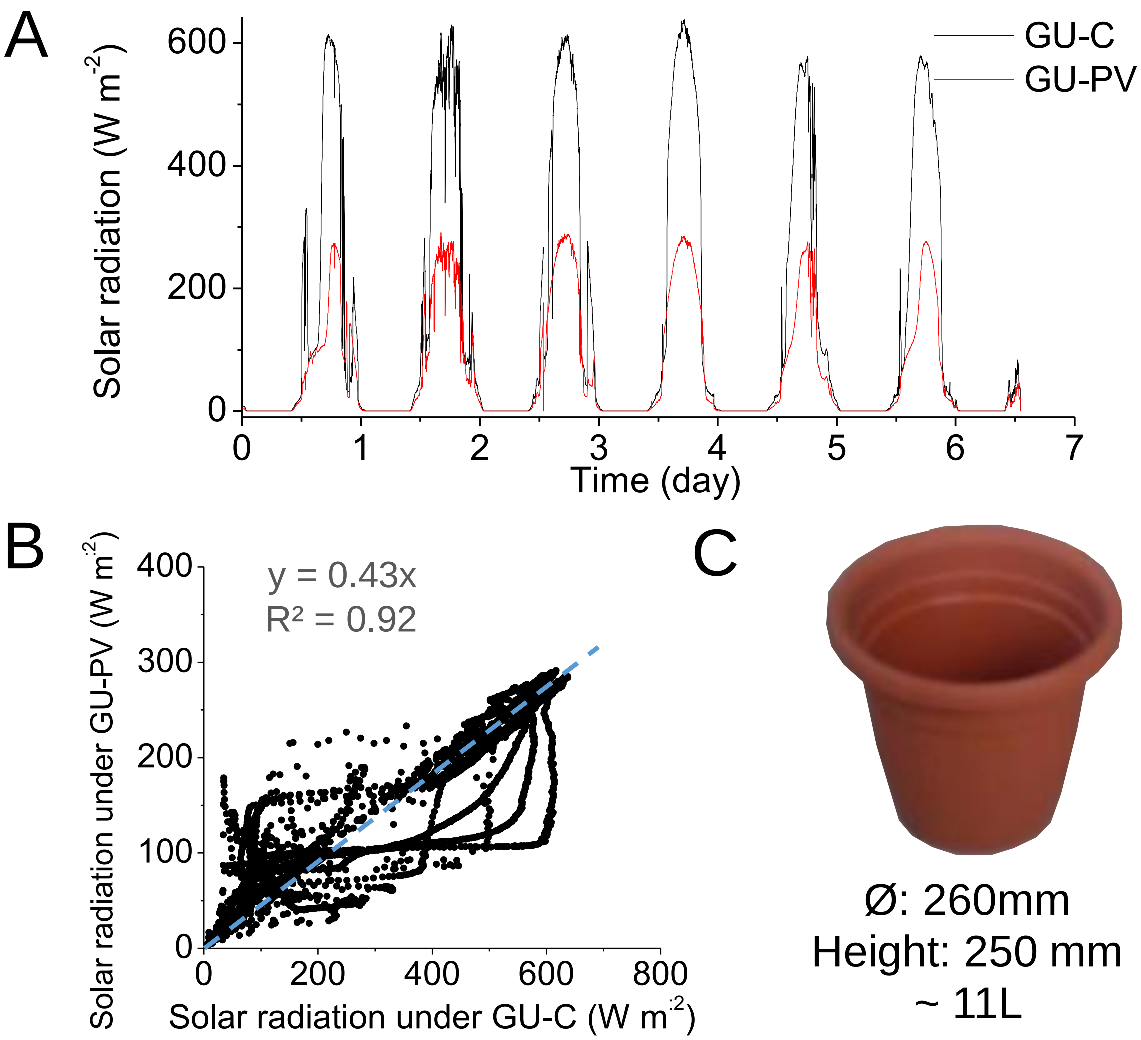
Supporting Information: Supplementary figure



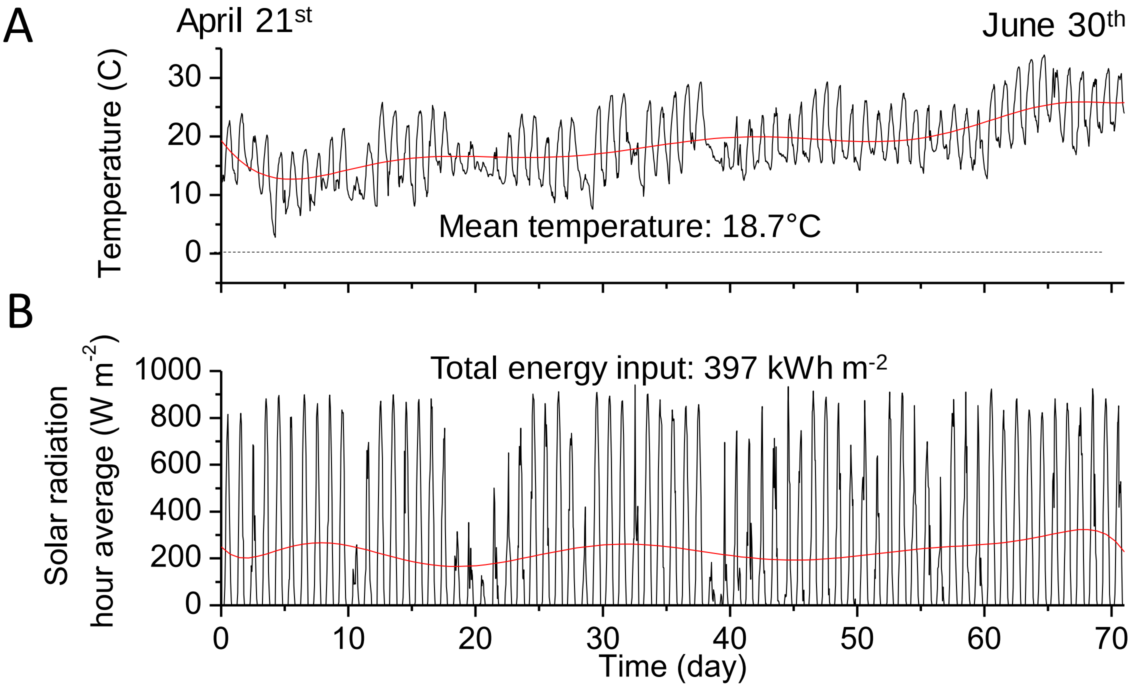
Sup.Fig.1 A) Cultivar of basil used during the Spring/Summer experimental run. **B**) Cultivar of spinach used during the Autumn/Winter experimental run. **C**) Percentage of germination for basil. **D**) Percentage of germination for spinach. The error bar represents ±SD.



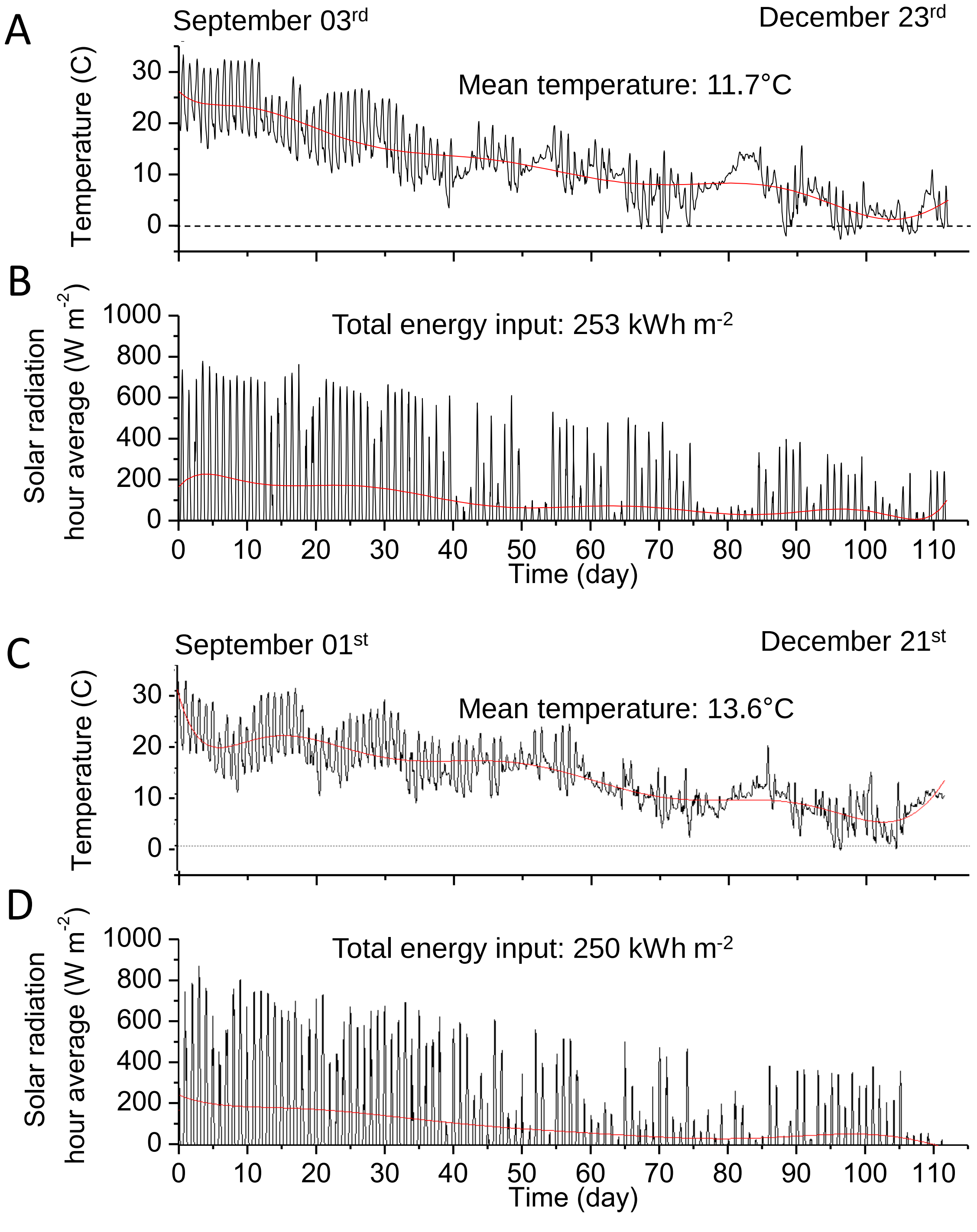
Sup.Fig.2 A and **B**) Semi-exploded cartoon and actual photo of the GU-C. **C** and **D**) Semi-exploded cartoon and actual photo of the GU-PV.



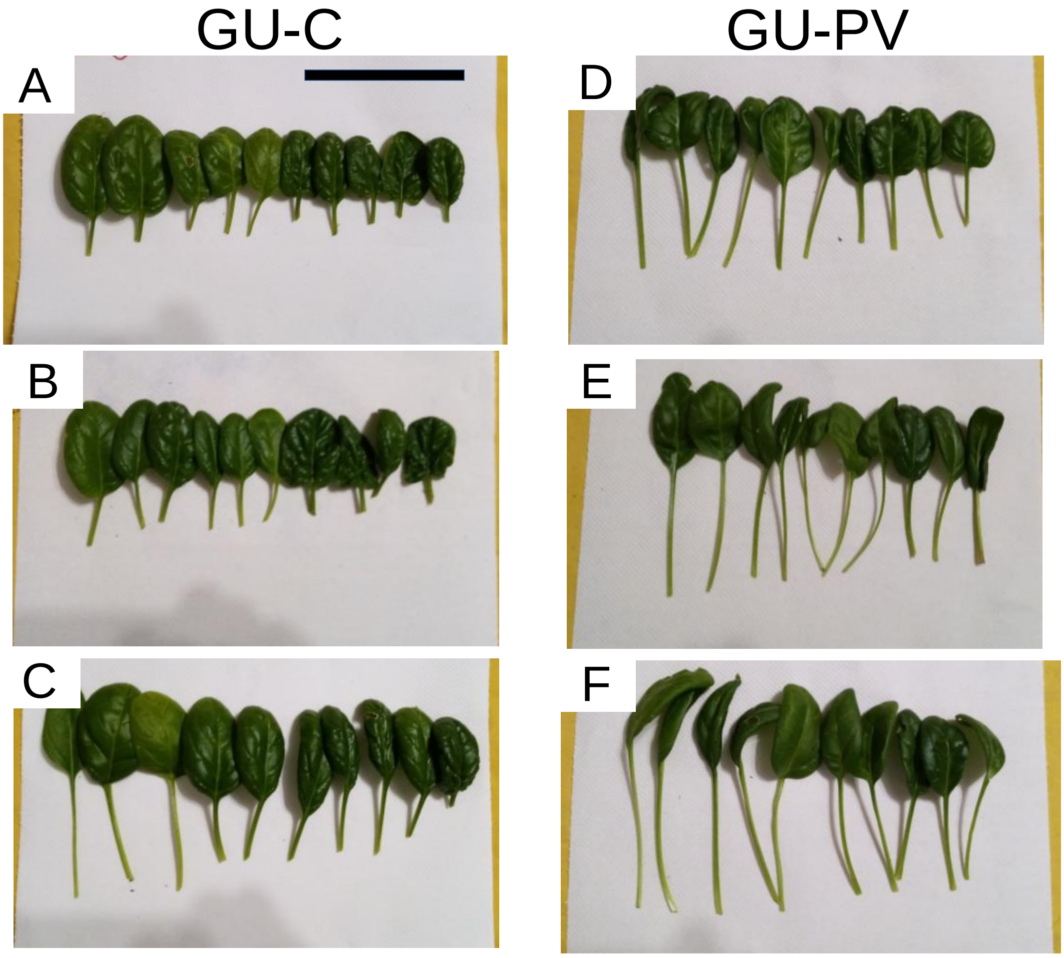
Sup.Fig.3 A) Solar radiation simultaneously recorded in the GU-C unit and the GU-PV unit. **B)** Solar radiation recorded inside the GU-C vs solar radiation recorded inside the GU-PV unit **C**) Actual photo of the pot used to grow the basil and spinach plants.



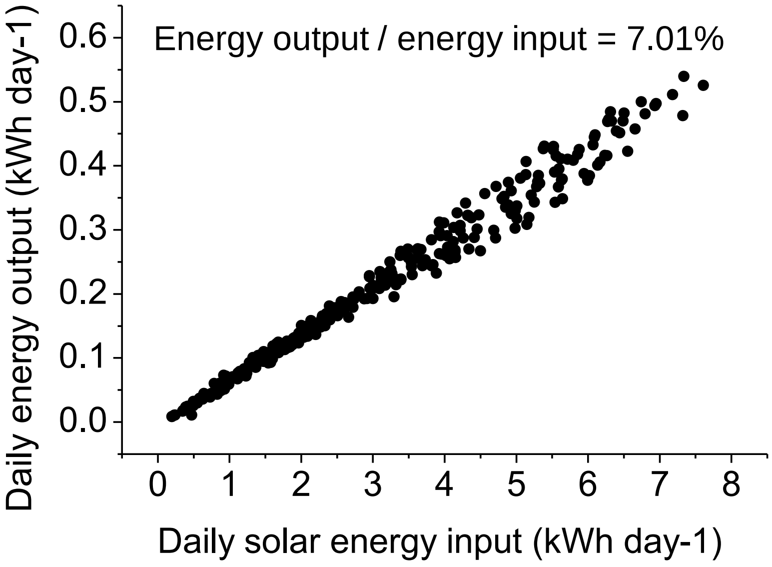
Sup.Fig.4 Climatic conditions during the Spring/Summer experimental run. **A**) Hourly mean air temperature. **B**) Hourly mean solar radiation. The red lines represent the trend line (obtained by polynomial fitting) for the temperature (**A**) and the solar irradiation (**B**) respectively.



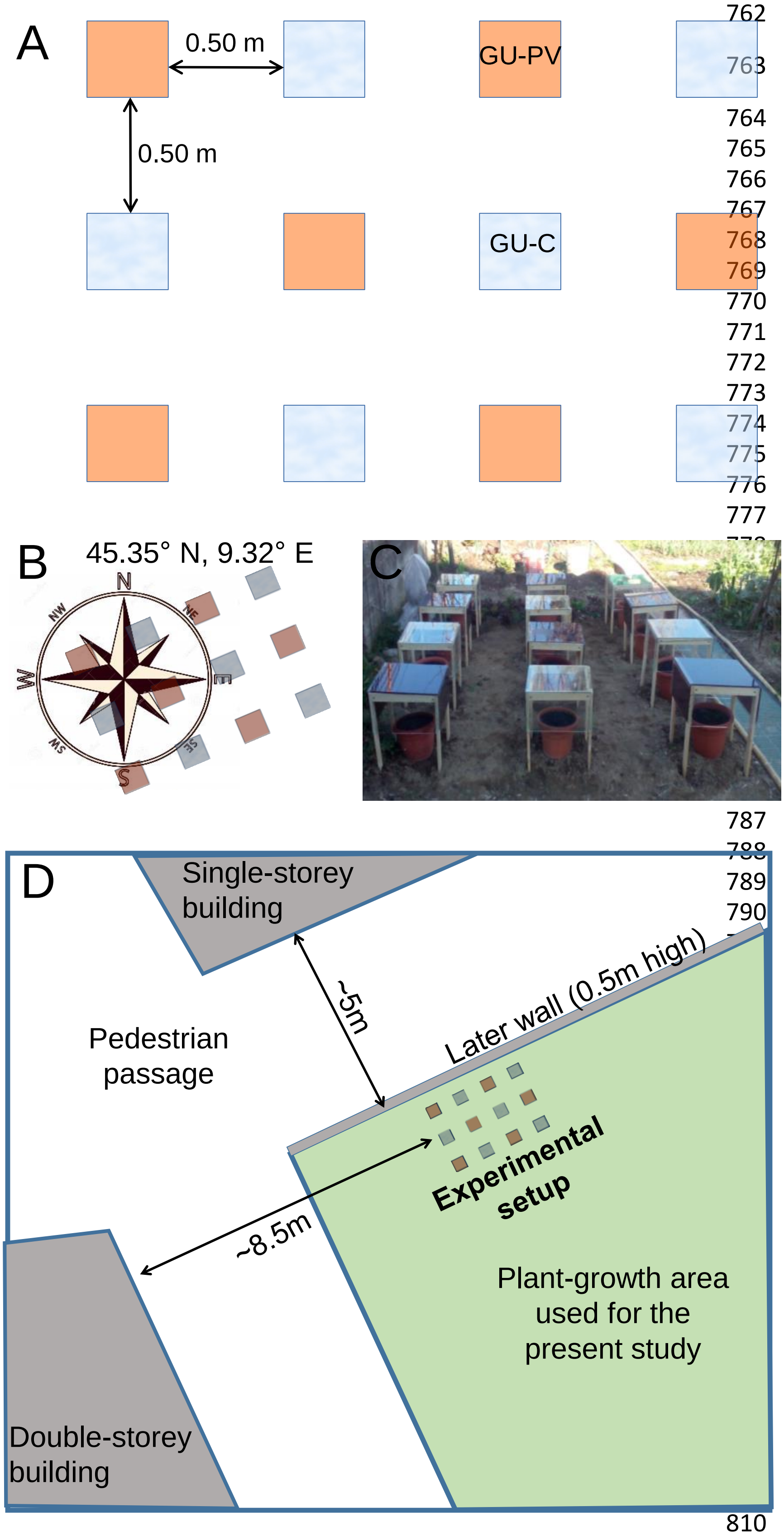
Sup.Fig.5 Climatic conditions during the Autumn/Winter experimental runs. **A-C**) Hourly mean air temperature for the season 2016 and 2019 respectively. **B-D**) Hourly mean solar radiation for the season 2016 and 2019 respectively. The red lines represent the trend line (obtained by polynomial fitting) for the temperature (**A-C**) and the solar irradiation (**B-C**) respectively.



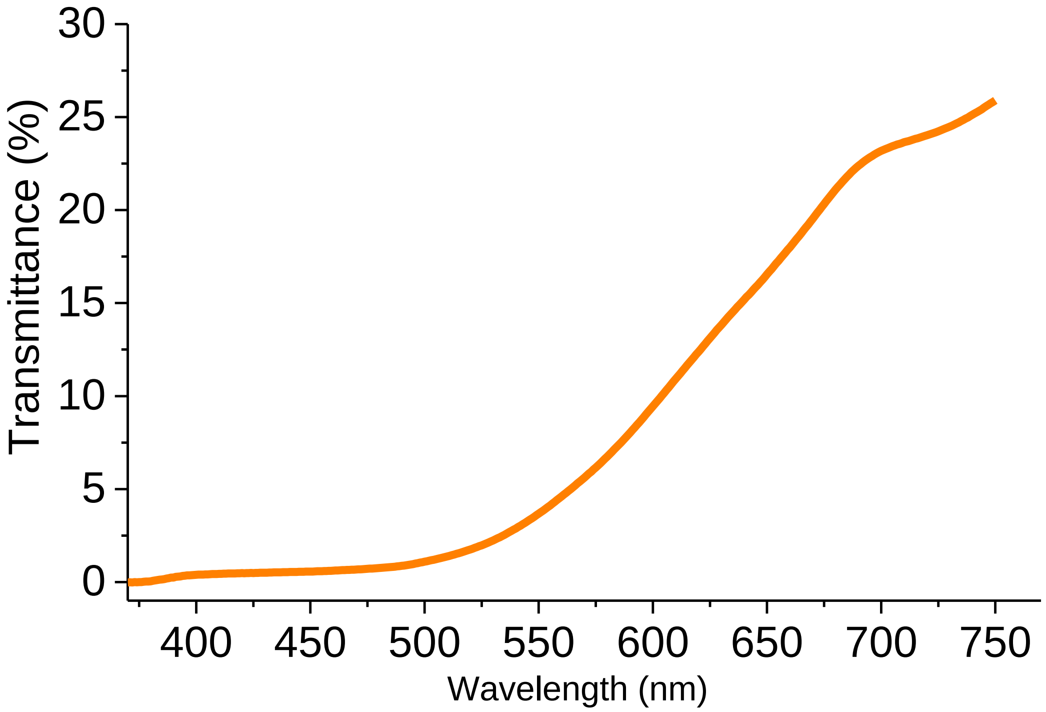
Sup.Fig.6 Sample of leaves and stems of spinach from plants grown during the season 2 in the GU-C (**A-C**) and GU-PV (**D-F**). The black horizontal bar represents 100mm.



Sup.Fig.7 Daily energy output (kWh day^{-1}) for the semi-transparent solar panels (a-Si single-junction) versus daily solar energy input (kWh day^{-1}). Data obtained from PV-live, University of Sheffield (https://www.solar.sheffield.ac.uk/pvlive/).



Sup.Fig.8 A) Relative position of the 12 GUs. **B**) Orientation and coordinate location of the experimental setup. **C**) Photo for the actual experimental setup with the 12 Gus before planting. **D**) site map depicting the area where the experimental setup was located.



Sup.Fig.9 Spectral transmittance (%) in the visible range of the tinted semi-transparent solar panel used in this study.

Supporting Information: Supplementary Table

Sup. Table 1

Collected data for biomass DW (dray weight) accumulation in plants of basil grown in GU-Cs (white background) compared with the plants grown in GU-PVs (yellow background). Ratio for biomass DW of leaf+stem to root. Ratio for total biomass DW to total solar radiation.

		gDW m^{-2}		p(T-test)	%
Growth condition	**Tissue**	**Mean**	**St.Dv.**	**GU-PV *vs* GU-C**	**GU-PV / GU-C**
GU-C	Leaf	245	30		
GU-PV	Leaf	208	26	0.0613	84.9%
GU-C	Stem	147	54		
GU-PV	Stem	112	9	0.0997	76.2%
GU-C	Root	236	23		
GU-PV	Root	121	23	0.0002	51.3%
GU-C	Leaf+Stem	391	82		
GU-PV	Leaf+Stem	319	31	0.0782	81.6%
GU-C	Leaf+Stem+Root	627	92		
GU-PV	Leaf+Stem+Root	441	43	0.0068	70.3%
		(ratio)			
GU-C	(Leaf+Stem) /Root	1.66	0.30		
GU-PV	(Leaf+Stem) /Root	2.71	0.58	0.0072	163.3%
GU-C	Total (DW) / Tot solar radiation	1.58	0.23		
GU-PV	Total (DW) / Tot solar radiation	2.58	0.25	0.0012	163.3%

Sup. Table 2

Measurement of fresh weight (FW) and dry weight (DW) for basil.

	Fresh weight (FW) and dry weight (DW)		
	DW (g)	**FW (g)**	**FW / DW**
Leaf	1.29	17.46	13.577
	0.65	9.67	14.969
	3.31	40.87	12.359
	2.21	32.70	14.796
	1.82	26.05	14.313
		Mean	**14.00**

The data in the first column of the table above were obtained by measuring the mass of five samples of fresh basil leaf (fresh weight). The data in the second column were obtained by measuring the mass of the same five samples of basil leaf after drying (dry weight). The leaves were dried at 45C° for 96h, under ventilation.

Sup. Table 3

Dry weight (DW, g m^{-2}) and equivalent fresh weight (FW, t ha^{-1}) for basil.

Fresh biomass (leaf)		DW (g m^{-2})		FW (t ha^{-1})	
	Sample	**GU-PV**	**GU-C**	**GU-PV**	**GU-C**
	1 (2016)	229.6	263.5	32.2	36.9
	2 (2016)	228.6	215.9	32.0	30.2
	3 (2016)	203.9	210.0	28.6	29.4
	4 (2016)	160.1	285.9	22.4	40.0
	5 (2016)	206.4	259.0	28.9	36.3
	6 (2016)	217.0	234.0	30.4	32.8
	Mean	**208**	**245**	**29.1**	**34.3**
	StDv	***26***	***30***	***3.6***	***4.2***

The mean of the ratio of the fresh weight (FW) / dry weight (DW) for basil leaves displayed in Sup. Table 2 was used to calculate the fresh weight FW (t ha^{-1}) from the measured DW (g m^{-2}). The mean of the computed fresh weight (t ha^{-1}) was compared with that reported for commercial basil production in the "Basil Production 2009" report, published by the Department of Agriculture, Forestry and Fisheries.

https://www.nda.agric.za/docs/Brochures/ProGuiBasil.pdf

(accessed on 17 May 2019).

Sup. Table 4

Collected data for biomass DW (dray weight) accumulation in plants of spinach for both seasons grown in GU-Cs (white background) compared with the plants grown in GU-PVs (yellow background). Ratio for biomass DW of leaf+stem to root. Ratio for total biomass DW to total solar radiation.

		gDW m^{-2}		p(T-test)	%
Growth condition	**Tissue**	**Mean**	**St.Dv.**	**GU-PV *vs* GU-C**	**GU-PV / GU-C**
GU-C	Leaf	130	29		
GU-PV	Leaf	97	23	0.0046	74.6%
GU-C	Stem	65	30		
GU-PV	Stem	48	18	0.0079	73.8%
GU-C	Root	22.6	3.5		
GU-PV	Root	12.4	3.1	0.0012	54.9%

GU-C	Leaf+Stem	196	57		
GU-PV	Leaf+Stem	145	40	0.0034	74.2%
GU-C	Leaf+Stem+Root	218	42		
GU-PV	Leaf+Stem+Root	158	29	0.0160	72.5%
		(ratio)		-	
GU-C	(Leaf+Stem) /Root	8.65	2.86		
GU-PV	(Leaf+Stem) /Root	11.71	4.34	0.1800	135.4%
GU-C	Total (DW) / Tot solar radiation	0.87	0.17		
GU-PV	Total (DW) / Tot solar radiation	1.46	0.27	0.0010	167.8%

Sup. Table 5

Measurement of fresh weight (FW) and dry weight (DW) for spinach.

	Fresh weight (FW) and dry weight (DW)		
	DW (g)	**FW (g)**	**FW / DW**
Leaf	0.975	14.73	15.108
	1.674	27.97	16.708
	3.152	55.92	17.741
	3.87	67.47	17.434
	3.16	56.67	17.934
		Mean	**16.98**

The data in the first column of the table above were obtained by measuring the mass of five samples of fresh spinach leaf (fresh weight). The data in the second column were obtained by measuring the mass of the same five samples of spinach leaf after drying (dry weight). The leaves were dried at 45C° for 96h, under ventilation.

Sup. Table 6

Dry weight (DW, g m^{-2}) and equivalent fresh weight (FW, t ha^{-1}) for spinach for both seasons.

Fresh		**DW (g m^{-2})**	**FW (t ha^{-1})**	**FW (pound acre^{-1})**

	Sample	**GU-PV**	**GU-C**	**GU-PV**	**GU-C**	**GU-PV**	**GU-C**
	1 (2016)	154.95	170.49	26.3	29.0	23481.0	25835.4
	2 (2016)	134.63	132.90	22.9	22.6	20401.8	20139.2
	3 (2016)	87.23	209.94	14.8	35.7	13218.8	31814.1
	4 (2016)	120.32	123.84	20.4	21.0	18232.9	18766.6
	5 (2016)	115.42	191.90	19.6	32.6	17490.9	29080.2
	6 (2016)	117.51	143.39	20.0	24.4	17807.7	21728.8
	1 (2019)	258.96	197.93	44.0	33.6	39242.3	29993.4
	2 (2019)	261.24	191.27	44.4	32.5	39587.3	28984.0
	3 (2019)	267.53	187.56	45.4	31.9	40539.9	28423.0
	Mean	**196**	**145**	**33.2**	**24.7**	**29637.1**	**22003.7**
	StDv	***57***	***40***	***9.7***	***6.7***	***8664.3***	***5998.8***

The mean of the ratio of the fresh weight (FW) / dry weight (DW) for spinach leaves displayed in the Sup. Table 5 was used to calculate the fresh weight FW (t ha^{-1} and pound acre^{-1}) from the measured DW (g m^{-2}). The means of the computed fresh weight (t ha^{-1} and pound acre^{-1}) were compared with the reported fresh weight for commercial spinach production in the "SAMPLE COSTS TO PRODUCE AND HARVEST ORGANIC SPINACH" report, published by the University of California Cooperative Extension Agriculture and Natural Resources – Agricultural Issues Center (2015)

https://coststudyfiles.ucdavis.edu/uploads/cs_public/79/02/79023ea8-80a8-4fba-b69e-5d60225dbf8b/2015_organicspinach-finaldraftjan29.pdf

Sup. Table 7

For basil plants, the amount of protein extracted from leaf, stem, and root of plants grown in GU-Cs (white background) are compared with the plants grown in GU-PVs (yellow background).

		mg of protein in extraction		p(T-test)	%
Growth condition	**Tissue**	**Mean**	**St.Dv.**	**GU-PV *vs* GU-C**	**GU-PV / GU-C**
GU-C	Leaf	0.202	0.012		

GU-PV	Leaf	0.231	*0.007*	0.056	114.1%
GU-C	Stem	0.106	0.007		
GU-PV	Stem	0.146	0.010	0.004	137.6%
GU-C	Root	0.117	0.006		
GU-PV	Root	0.128	0.004	0.010	109.6%

Sup. Table 8

For spinach plants for both seasons, the amount of protein extracted from leaf, stem, and root of plants grown in GU-Cs (white background) are compared with the plants grown in GU-PVs (yellow background).

		mg of protein in extraction		p(T-test)	%
Growth condition	**Tissue**	**Mean**	**St.Dv.**	**GU-PV *vs* GU-C**	**GU-PV / GU-C**
GU-C	Leaf	0.200	0.026		
GU-PV	Leaf	0.307	0.048	0.005	153.1%
GU-C	Stem	0.122	0.013		
GU-PV	Stem	0.205	0.049	0.006	167.9%
GU-C	Root	0.123	0.006		
GU-PV	Root	0.140	0.023	0.198	113.8%

Sup. Table 9

(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	
Location	**Crop (cultivar)**	**Growth season**	**Yield of marketable biomass conventional agriculture DW: Dry Weight FW: Fresh Weight**	**Yield of marketable biomass agrivoltaic DW: Dry Weight FW: Fresh Weight**	**Solar panel model**	**Shade levels (%) caused by agrivoltaic on the incoming solar radiation at the growth area level compare control condition**	**Mean of the electrical output expected during the experimental run**	**Ref**
Melegnano, Italy 45°21‘ N 9°19‘ E	Basil (Italiano Classico)	Spring / Summer	245±30 gDW m^{-2}	208±26 gDW m^{-2}	PS-C Series, a-Si single-junction (tinted solar panel)	57%	0.392 kWh m^{-2} day^{-1}	**This study**
	Spinach (Spinacio America)	Autumn / Winter	163±33 gDW m^{-2}	122±22 gDW m^{-2}			0.159 kWh m^{-2} day^{-1}	
Kyoto, Japan 34°74‘ N 135°84‘ E	Tomato	All year	103.02 tFW ha^{-1}	66.36 tFW ha^{-1}	OPV, KMM1015E3F	~14%	0.02 kWh m^{-2} day^{-1}	36
Agadir Marocco 30°13‘ N 9°23‘ E	Tomato (Zayda)		--	--	MX-FLEX Protect	10%		35
Kunming, China 25°07‘ N 102°68‘ E	Tomato (Cerry)	Winter season (Sep.-Feb.)	--	--	CD-BIPV-64/5M170	-- %	0.14 kWh m^{-2} day^{-1}	6 58
Montpellier France 43°6'N 3°8'E	Lettuce (Kiribati)	Spring	33 gDW	19 gDW (HD) 20 gDW (ST)	JT185Wc, Jetion Solar Holdings Limited, Jiangsu, China	HD (Half Density): 50% ST (Solar Tracking): --%		29
		Summer	15 gDW	10 gDW (HD) 11 gDW (ST)				
		Autumn	13 gDW	13 gDW (HD) 13 gDW (ST)				
	Lettuce (Madelona)	Spring	36 gDW	21 gDW (HD) 30 gDW (ST)				
		Summer	26 gDW	18 gDW (HD) 19 gDW (ST)				
		Autumn	16 gDW	13 gDW (HD) 14 gDW (ST)				
South-West Greece	Lettuce	Winter / Spring	175 gFW 20 gDW	180 gFW 18 gDW	Polycrystalline silicon (pc-Si) PV panels	20%		30
Montpellier France 43°6'N 3°8'E	Lettuce (Tpurbilion)	Summer	26.2 gDW	19.4 gDW (HD) 13.9 gDW (FD)	JT185Wc, Jetion Solar Holdings Limited, Jiangsu, China	HD (Half Density): 50% FD (Full Density): 70%	3.92 kW /kWp/day (Estimated production, across the year, of the whole prototype made of 108 solar panels, including both the FD and the HD, knowing that HD produces exactly half of FD).	16 17 28
	Lettuce (Kiribati)		24.9 gDW	21.7 gDW (HD) 16.0 gDW (FD)				
	Lettuce (Emotion)	Spring	23.7 gDW	26.1 gDW (HD) 17.8 gDW (FD)				
	Lettuce (Model)	Spring	26.2 gDW	23.9 gDW (HD) 18.4 gDW (FD)				
	Lettuce (Bassoon)	Spring	24.9 gDW	21.9 gDW (HD) 18.9 gDW (FD)				
	Lettuce (Kiribati)	Spring	22.0 gDW	23.7 gDW (HD) 21.6 gDW (FD)				
	Lettuce (Emocion)	Spring / Summer	100% DW	107% DW (HD) 80% DW (FD)				
	Lettuce (Model)		100% DW	81% DW (HD) 47% DW (FD)				
	Lettuce (Bassoonl)		100% DW	61% DW (HD) 56% DW (FD)				
	Lettuce (Kiribati)		100% DW	90% DW (HD) 96% DW (FD)				
	Cucumber	Summer	100% DW	79% DW (HD) 42% DW (FD)				
	Cucumber	Summer	1759 kg/ha DW 35744 kg/ha FW	840kg/ha DW (FD) 1129kg/ha DW (HD) 19300kg/ha FW(FD) 25140 kg/ha FW (HD)				
	Lettuce	Spring	311.6 g FW 18 g DW	17.2 g DW (FD) 21.3 g DW (HD) 319.4 g FW (FD) 387.9 g FW (HD)				
	Wheat	winter	4.13 t/ha DW	2.35t/ha DW (FD° 3.68 t/ha DW (HD°				
Japan 35°5'N 133°0'E	Onion (Natsuhiko)	Autumn 42 day cultivation in 2007	--	--	FPV1024S; Fuji Electric Systems Co. Ltd., Japan in an E-W straight arrangement (5% module efficiency)	0-64% depending on the plant position 29% in average	0.013 kWh m^{-2} day^{-1}	32
		Autumn 52 day cultivation in 2008	--	--	FPV1024S; Fuji Electric Systems Co. Ltd., Japan in a checkerboard arrangement (5% module efficiency)	1-44% depending on the plant position 18% in average	0.016 kWh m^{-2} day^{-1}	
Almeria, Spain 36°2'N 21°17'E	Tomato (Daniela)	Sept.-April	FW: 9.15 kg m^{-2} (T0)	FW: 8.64 kg m^{-2} (T1) FW: 9.69 kg m^{-2} (T2)	FujiElectricSystems Co.,Ltd.,Japan	T1: twelve flexible solar panels were installed T2: six flexible solar panels were installed	0.018 kWh m^{-2} day^{-1} (greenhouse ground surface)	33 34
Tucson, AZ, USA 32.6°N 110.9°W	Chiltepin pepper	Spring - Summer	~8.0 (number of fruits per individual plant)	~22.9 (number of fruits per individual plant)			C377 MWh per the entire agrivoltaic installation (9.1m x 18.2m) per year	17
	Jalapeno		~8.4 (number of fruits per individual plant)	~6.5 (number of fruits per individual plant)				
	Tomato		~17.7 (number of fruits per individual plant)	~35.7 (number of fruits per individual plant)				

Sup. Table 10

The actual data points for the transmission spectrum (T%) in the visible range of the tinted semi-transparent solar panel used in this study.

nm	T(%)	nm	T(%)	nm	T(%)	nm	T(%)	nm	T(%)	nm	T(%)	nm	T(%)	nm	T(%)	nm	T(%)
370	-0.02	413	0.455	456	0.575	499	-0.02	542	2.473	585	6.158	628	11.81	671	17.56	714	23.79
371	-0.01	414	0.461	457	0.578	500	0.976	543	2.536	586	6.271	629	11.95	672	17.71	715	23.83
372	-0.03	415	0.458	458	0.583	501	1.976	544	2.605	587	6.389	630	12.09	673	17.85	716	23.87
373	0	416	0.465	459	0.583	502	2.976	545	2.678	588	6.505	631	12.24	674	18	717	23.9
374	-0.01	417	0.465	460	0.592	503	3.976	546	2.747	589	6.627	632	12.38	675	18.15	718	23.95
375	-0	418	0.471	461	0.595	504	4.976	547	2.815	590	6.744	633	12.53	676	18.3	719	23.98
376	-0.01	419	0.473	462	0.601	505	5.976	548	2.882	591	6.87	634	12.68	677	18.45	720	24.02
377	0.015	420	0.478	463	0.607	506	6.976	549	2.956	592	6.992	635	12.82	678	18.6	721	24.06
378	0.024	421	0.475	464	0.615	507	7.976	550	3.03	593	7.12	636	12.96	679	18.76	722	24.1
379	0.024	422	0.481	465	0.618	508	8.976	551	3.107	594	7.242	637	13.12	680	18.91	723	24.15
380	0.037	423	0.481	466	0.623	509	9.976	552	3.183	595	7.368	638	13.26	681	19.06	724	24.19
381	0.064	424	0.49	467	0.632	510	10.98	553	3.259	596	7.498	639	13.41	682	19.22	725	24.23
382	0.09	425	0.485	468	0.638	511	11.98	554	3.342	597	7.631	640	13.55	683	19.38	726	24.28
383	0.111	426	0.494	469	0.641	512	12.98	555	3.423	598	7.762	641	13.69	684	19.53	727	24.34
384	0.133	427	0.493	470	0.648	513	13.98	556	3.506	599	7.893	642	13.83	685	19.69	728	24.39
385	0.14	428	0.497	471	0.655	514	14.98	557	3.593	600	8.032	643	13.97	686	19.85	729	24.44
386	0.162	429	0.5	472	0.661	515	15.98	558	3.677	601	8.168	644	14.11	687	20.01	730	24.49
387	0.189	430	0.502	473	0.667	516	16.98	559	3.766	602	8.305	645	14.24	688	20.17	731	24.54
388	0.209	431	0.504	474	0.676	517	17.98	560	3.851	603	8.446	646	14.39	689	20.33	732	24.6
389	0.243	432	0.513	475	0.681	518	18.98	561	3.938	604	8.586	647	14.52	690	20.49	733	24.66
390	0.238	433	0.516	476	0.688	519	19.98	562	4.033	605	8.725	648	14.65	691	20.64	734	24.72
391	0.281	434	0.517	477	0.697	520	20.98	563	4.124	606	8.87	649	14.79	692	20.8	735	24.79
392	0.285	435	0.519	478	0.703	521	21.98	564	4.219	607	9.016	650	14.93	693	20.95	736	24.85
393	0.305	436	0.523	479	0.711	522	22.98	565	4.314	608	9.158	651	15.06	694	21.1	737	24.92
394	0.328	437	0.525	480	0.719	523	23.98	566	4.411	609	9.305	652	15.19	695	21.25	738	24.98
395	0.337	438	0.528	481	0.726	524	24.98	567	4.506	610	9.45	653	15.32	696	21.39	739	25.06
396	0.36	439	0.533	482	0.737	525	25.98	568	4.602	611	9.587	654	15.45	697	21.52	740	25.13
397	0.362	440	0.536	483	0.748	526	26.98	569	4.701	612	9.737	655	15.58	698	21.66	741	25.2
398	0.369	441	0.537	484	0.757	527	27.98	570	4.797	613	9.886	656	15.72	699	21.79	742	25.27
399	0.381	442	0.54	485	0.764	528	28.98	571	4.895	614	10.03	657	15.85	700	21.92	743	25.34
400	0.395	443	0.543	486	0.774	529	29.98	572	4.996	615	10.18	658	15.98	701	22.05	744	25.41
401	0.397	444	0.545	487	0.784	530	30.98	573	5.096	616	10.33	659	16.12	702	22.16	745	25.5
402	0.403	445	0.551	488	0.797	531	31.98	574	5.197	617	10.48	660	16.26	703	22.27	746	25.59
403	0.398	446	0.552	489	0.806	532	32.98	575	5.304	618	10.63	661	16.4	704	22.38	747	25.67
404	0.41	447	0.555	490	0.816	533	33.98	576	5.406	619	10.78	662	16.55	705	22.48	748	25.74
405	0.414	448	0.56	491	0.829	534	34.98	577	5.511	620	10.92	663	16.69	706	22.57	749	25.82
406	0.418	449	0.562	492	0.842	535	35.98	578	5.615	621	11.07	664	16.83	707	22.67	750	25.9
407	0.43	450	0.562	493	0.854	536	36.98	579	5.724	622	11.22	665	16.98	708	22.76		
408	0.432	451	0.566	494	0.87	537	37.98	580	5.83	623	11.36	666	17.13	709	22.84		
409	0.436	452	0.575	495	0.887	538	38.98	581	5.937	624	11.51	667	17.27	710	22.91		
410	0.444	453	0.578	496	0.906	539	39.98	582	6.052	625	11.66	668	17.42	711	22.98		
411	0.446	454	0.583	497	0.926	540	40.98	583	6.158	626	11.81	669	17.56	712	23.06		
412	0.452	455	0.583	498	0.948	541	41.98	584	6.271	627	11.95	670	17.71	713	23.12		

Supporting Information: Appendix

Appendix 1

During the Spring/Summer run, basil plants were grown for 71 days. The total solar radiation during this time reached 397 kWh m^{-2} (**Sup.Fig.4**). The mean of marketable biomass of basil (leaf) accumulated over the entire experimental run was 245±30 gDW m^{-2} for the plants grown in the GU-Cs and 208±26 gDW m^{2} for the plants grown in the GU-PVs. Those figures equate to 3.43±0.42 kgFW m^{-2} (34.3±4.2 tFW ha^{-1}) and 2.91±0.36 kgFW m^{-2} (29.1±3.6 tFW ha^{-1}) for plants grown in the GU-Cs and GU-PVs respectively.

Basil global wholesale price: 6.65 USD per kg (FW)

https://www.tridge.com/intelligences/basil

(accessed on 29 May 2019).

Expected financial gross income obtained from agricultural product only.

GU-C: (3.43 kgFW m^{-2}) x (6.65 USD kg^{-1}) = 22.81 USD m^{-2}

GU-PV: (2.91 kgFW m^{-2}) x (6.65 USD kg^{-1}) = 19.35 USD m^{-2}

Based on the solar radiation falling on the experimental area, the tinted semi-transparent solar panel (**Sup.Fig.6**), is expected to generate: 397 kWh m^{-2} x 7.01% = 27.8 kWh m^{-2}

Gross value of the expected electrical energy generated per surface area.

The FiT (Feed-in-Tariff) in Italy, assuming for agrivoltaic large installation (>5MW), varies from a minimum of 0.141 USD kWh^{-1} (groundmounted) to a max of 0.149 USD kWh^{-1} (rooftop). As an agrivoltaic installation could be either described as groundmounted as well as rooftop, an average value 0.145 USD $kWh^{-1}$is taken.

https://www.renewableenergyworld.com/2012/12/06/italy-abandons-rps-adopts-system-of-feed-in-tariffs/#gref (accessed on 27 May 2020).

Expected financial gross income due production of electricity only.

(27.8 kWh m^{-2}) x 0.145 USD kWh^{-1} = 4.03 USD m^{-2}

Expected gross financial balance due the implementation of agrivoltaic

GU-C: 22.81 USD m^{-2} (from the biomass only)

GU-PV: 19.35 USD m^{-2} (from the biomass) + 4.03 USD m^{-2} (electricity) = 23.38 USD m^{-2}

The implementation of agrivoltaic is expecting to deliver a gross gain of

((23.38 USD m^{-2}) / (22.81 USD m^{-2})) -1 = (0.177) ~2.5%

DW: dry weight
FW: fresh weight

Appendix 2

During the Autumn/Winter run, spinach plants were grown for 111 days during both season 1 (2016) and season 2 (2019). The total solar radiation during this time reached 253 kWh m^{-2} and 250 kWh m^{-2} for season 1 and 2 respectively (**Sup.Fig.5**).

The mean marketable biomass of basil (leaf+stem) accumulated over the entire experimental run during both seasons was 196±57 gDW m^{-2} for the plants grown in the GU-Cs and 145±40 gDW m^{2} for the plants grown in the GU-PVs.

Those figures equate to 3.32±0.97 kgFW m^{-2} (33.2±9.7 tFW ha^{-1}) and 2.47±0.67 kgFW m^{-2} (24.7±6.7 tFW ha^{-1}) for plants grown in the GU-Cs and GU-PVs respectively.

Spinach global wholesale price: 1.26 USD per kg (fresh weight) https://www.tridge.com/products/spinach

(accessed on 29 May 2019).

Expected financial gross income obtained from agricultural product only.

GU-C: (3.32 kgFW m^{-2}) x (1.26 USD kg^{-1}) = 4.18 USD m^{-2}

GU-PV: (2.47 kgFW m^{-2}) x (1.26 USD kg^{-1}) = 3.11 USD m^{-2}

Based on the solar radiation falling on the experimental area, the tinted semi-transparent solar panel (**Sup.Fig.6**), is expected to generate: 253 kWh m^{-2} x 7.01% = 17.7 kWh m^{-2} for the first season and 250 kWh m^{-2} x 7.01% = 17.5 kWh m^{-2} for the second season (mean 17.6 kWh m^{-2}).

Gross value of the expected electrical energy generated per surface area.

The FiT (Feed-in-Tariff) in Italy, assuming for agrivoltaic large installation (>5MW), varies from a minimum of 0.141 USD kWh^{-1} (groundmounted) to a max of 0.149 USD kWh^{-1} (rooftop). As an agrivoltaic installation could be either described as groundmounted as well as rooftop, an average value 0.145 USD $kWh^{-1}$is taken.

https://www.renewableenergyworld.com/2012/12/06/italy-abandons-rps-adopts-system-of-feed-in-tariffs/#gref

(accessed on 27 May 2020).

Expected financial gross income due production of electricity only.

(17.6 kWh m^{-2}) x 0.145 USD kWh^{-1} = 2.55 USD m^{-2}

Expected gross financial balance due the implementation of agrivoltaic

GU-C: 4.18 USD m^{-2} (from the biomass only)

GU-PV: 3.11 USD m^{-2} (from the biomass) + 2.55 USD m^{-2} (electricity) = 5.66 USD m^{-2}

The implementation of agrivoltaic is expecting to deliver a gross gain of

((5.66 USD m^{-2}) / (4.18 USD m^{-2})) – 1 = ~35%

DW: dray weight

FW: fresh weight

Appendix 3

Effect of implementing the semi-transparent solar panels (a-Si single-junction) used in this study over the area currently in use for protected agriculture.

Estimated area in used for farming on protected agriculture: 5,630,000 ha.
https://www.producegrower.com/article/cuesta-roble-2019-global-greenhouse-statistics/
(Accessed on 17 May 2019).

The semi-transparent solar panels (a-Si single-junction) were obtained by Polysolar.Inc.

The complete technical specification is available on the flowing link
http://www.polysolar.co.uk/documents/PS-C%20Technical%20Specification%20sheet.pdf
(Accessed on 17 May 2019).
Declared power output Wp: 63 W m^{-2}

Global cumulative PV capacity in gigawatts (GW_p): ~700 GW (Global Market Outlook For Solar Power 2016 – 2020)
http://www.solareb2b.it/wp-content/uploads/2016/06/SPE_GMO2016_full_version.pdf

The expected capacity obtainable by implementing the semi-transparent solar panels (a-Si single-junction) over the area currently in use for protected agriculture
(5.63×10^{10} m^2) m^2 x 63 W m^{-2} = ~ 3547 GWp.