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Abstract
Excessive exploitation of natural resources has an environmental impact on ecosystems due to demographic and economic growth, and energy demand. For this reason, world economies have been implementing policy tools to achieve eco-friendly energy growth, minimizing environmental impact. It is necessary to increase Renewable Energies (RE) fraction in terms of electricity supply, improve energy efficiency and reduce energy consumption in greenhouses as well as in the agricultural sector. Thus, the European Green Deal (EGD) is a sustainable package of measures which, due to the ecological use of natural resources, strengthens the resilience of European food systems. The EGD's objectives include: ensuring food security, reducing environmental impact, and supporting the farm to fork strategy and energy communities. The aim of this review is to present innovative energy technologies integrated with agrivoltaic systems to produce and utilize energy with eco-friendly methods. In this review, agrivoltaic systems were presented in the EGD perspective, since, as shown by several studies, they increase simultaneously clean energy production and crop yield, avoiding limitations in land use. As agrivoltaic systems produce energy by the installation of PV panels, an overview of PV technology was provided. PV panels can feed electricity to the power grid. Nowadays, since there are many impoverished rural areas which do not have access to electricity, a lot of projects have been developed that utilize power generation from microgrids combined with hybrid systems (e.g., wind and solar energy) to feed agricultural facilities or community buildings.

Key words: European green deal; review greenhouses; economy agrivoltaic systems; PV greenhouses; cladding material greenhouses; microgrid rural communities.

Abbreviations
AC Alternative Current
AgroPV AgroPhotovoltaic
AVT Average Visible Transmission

a-Si Amorphous silicon
AVSs Agrivoltaic Systems
BIPV/BAPV Building Integrated- or Applied PV
CAP Common Agricultural Policy
c-Si Crystalline Silicon (Mono)
°C Celsius Degrees
CdTe Cadmium Telluride
CIGS Copper Indium Gallium (di) Selenide
COP Coefficient of Performance
COE Cost Of Electricity
CO_2 eq/kWh Grams of carbon dioxide equivalent per kilowatt-hour of electricity
DC Direct Current
DG Distributed Generation
DPP Discount Payback Period
DSSC Dye-Sensitized Solar Cells
EAHE Earth Air Heat Exchanger
EC Energy Counts
EPBT Energy payback time
EU European Union
EG European Green Deal
FPVs Floating Photovoltaic systems
GA Greenhouse Aquaponics
GHG Greenhouse gas
GiTPV Greenhouse integrated thin film Photovoltaic
GW GigaWatt
GWh/year GigaWatt per hour/ per year
GMPV Ground-mounted photovoltaic system
h Hours
HG Hydroponic Greenhouse
Kg Kilograms
kg/s Kilogram per second
KW KiloWatt
kWh Kilowatt-hour
kWhe/ ha Kilowatt-hours electric/ hectar
kWhel Kilowatt-hour electricity
kWp Kilowatt' peak
LCOE Levelized Cost of Energy
LCC Life Cicle Cost
LER Land Equivalent Ratio
LSC Luminescent Solar Concentrator
Multi-si Multi silicon cells
MW MegaWatt
MWh MegaWatt-hour
NPV Net present value
OPVs Organic Photovoltaic cells
PAR photosynthetically active radiation
PE Polyethylene
PN Net photosyntetic Rate
PUE Productive Use of Energy

PVC Polyvinyl Chloride
PV Photovoltaic
RE Renewable Energies
RH Relative Humidity
SDGs Sustainable Development Goals
SG Single Glass
Si Silicon
SPV Solar Photovoltaic
SPP Solar power plant
SSC Splitting Spectral Covering
STPV Semi-Transparent-Photovoltaic modules
STOSCs Semi-Transparent Organic Solar Cells
STSC Semi-Transparent-Cells
T Temperature
TCL Total Cultivated Land
TiO_2 Titanium dioxide
TWh/yr Terawatt-hour/year
UV Ultraviolet rays
UV/NIR Ultraviolet/ Near-Infrared
VIS Visible
W/m^2 Watt per square meter
Wp Watt peak
WSPV Wavelenght Selective Photovoltaic system
WT Wind Turbine
US$ United States dollars
$\mu mol \cdot m^{-2} \cdot s^{-1}$ Micromole per second and square meter
€ Euro
τG Transmission Coefficient

Introduction

An increasing pressure on natural resources through global energy, food and water demand is due to demographic, economic, social and climate change. Excessive exploitation of natural resources threatens the well-being of ecosystems (Ledari et al., 2023) as well as the world population growth, expected to hit 9.6 billion by 2050, growing urbanization, and limited arable land (Chaurasia, 2020). One of the goals of the UN 2030 Agenda for Sustainable Development (https://international-partnerships.ec.europa.eu/policies/sustainable-development-goals_en) is to ensure the availability of clean energy, water and food to protect the planet from degradation, including through sustainable consumption and production, sustainably managing its natural resources and taking urgent actions on climate change (United Nations, 2015). Agricultural greenhouses are the junction of the water-food-energy nexus, since they raise the production yield while reducing water demand. Conventional greenhouses usually rely on carbon-based fuels, thus contributing to climate change impacts, high production costs and depletion of fossil fuels). Global warming has boosted the problem of food scarcity and these situations have prompted researchers on extensive studies about food security using technologies, such as greenhouses (Mohebi and Roshandel, 2023) which pushing science-based solutions for optimal plant production, and reduction of energy use (Badji et al., 2022). Nowadays, the global economy underlines the need to achieve eco-friendly growth, minimizing the environmental impact statistics and increasing economic growth. It is necessary to rise the proportion of renewable energies in terms of electricity supply as well as to improve the energy efficiency and reduce power consumption in greenhouses to address energy transition issues (Kim et al., 2023). In recent years, world economies have been devising and implementing rigorous environmental policies to achieve national and international pollution reduction goals, *e.g.* those established by the Paris Agreement, thus highlighting that the core of all worldwide environmental policies is “transition toward Renewable Energies” (RE) (Lima et al., 2020). The Paris Agreement aims at limiting global warming well below 1.5 °C compared to pre-industrial levels and requires the 196 parties to reach the peak of greenhouse gas emission as soon as possible. The Paris Agreement, together with the UN 2030 Agenda, are two useful policy tools for international cooperation on sustainable development and its economic, social, environmental and governance dimensions (United Nations Framework Convention on Climate Change, 2015) to end poverty and protect the planet (https://sdgs.un.org/2030agenda). Another policy tool is the European Green Deal, adopted by the European Commission to make EU climate, energy, transport and taxation policies fit for purpose of reducing net greenhouse gas emissions by at least 55% by 2030, providing clean water, healthy soil and food, biodiversity, and energy-efficient buildings (European Commission, 2023d). Renewable Energy (RE) can significantly increase energy production allowing to access to electricity and mitigate the energy poverty in remote and impoverished locations where people otherwise do not have the possibility to generate it, due to the lack of enough financial resources to replace fossil fuels. Developed countries have already begun the environmental transition towards RE. For instance, the European Union (EU) aims to expand its share of RE consumption to 40% by 2030 (Muhammad et al., 2023). In China, researchers used a simulation model to carry out a study about the use of renewable energies leading agricultural economy to carbon neutrality. Findings have shown that the increase in renewable energy consumption and greenhouse areas results in the improvement of economic growth (Khan et al., 2022). As mentioned above, the access to electricity is difficult in poor countries, thus, in a developing country like India, most of the unelectrified rural sites are inaccessible geographical areas and, the connection of these with the central grid is an onerous and expensive task (D’Cunha, 2018). A reliable power supply can be achieved with the use of renewable sources, which play a vital role. Most of the rural areas are rich in renewable resources, which include biomass, hydro, wind, and solar energy. An additional economic benefit provided by these resources could be selling excess power generation to the grid (Mishra et al., 2023b). One of the sources that can be used in agriculture is the photovoltaic (PV) technology, which has potential benefits to generate electricity to power the greenhouse load (Stallknecht et al., 2023). Using renewable energies on a large scale allows reducing greenhouse effects and these have been improved and implemented by researchers and include solar energy, wind energy, wave energy, geothermal energy, and tidal energy (Bermel et al., 2016). A particularly interesting renewable energy technology is solar, which generates electricity by using Photovoltaic materials (PV). Over the long term, despite their initial high investments, they require little maintenance (Allardyce *et al.,* 2017). However, the site selection for installing solar systems to generate electricity, causes biodiversity loss, ecosystem conservation issues and because of the limited land area capacity also soil loss. Solar parks require more land area than fossil fuel or nuclear plants because of its comparatively low energy production density, thus, solar PVs systems modify land use and land cover, altering the microclimatic conditions, hydrological process and seed bank survival (Yoon *et al.,* 2021). The integration of PVs systems in agriculture is called “agrivoltaics” or “agrienergy”. PV technology is commonly found on the roof of domestic and industrial buildings (Allardyce et al., 2017) such as in greenhouses roofs (Schallenberg-Rodriguez *et al.,* 2023). Indeed, one type of agrivoltaic system is Greenhouse-mounted PV arrays with panels which cover the greenhouse roof alongside with Interspersed PV arrays (panels installed between the rows of cultivated crops) and mounting the panels on an open-air structure (Toledo and Scognamiglio, 2021). Dupraz et al. (2011) investigated the best strategies to convert solar radiation into both, energy and food, comparing two agrivoltaic systems with different densities of solar panels and modelling the light transmission at crop level (durum wheat). The first agrivoltaic system was with full density (FD), the second one with half density (HD). The prototype of agrivoltaic system had an area of 820 m^2 with panels tilted at 25°slope and spaced every 1.64 m. The results have shown that during the wheat cropping season (November to June), the average simulated radiation under FD and HD of panels were 43% and 71% of the incident radiation, respectively. The STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) crop model has predicted that durum wheat yields are reduced in the shade of panels: dry matter (DM) and yield (Y) were reduced by 29 and 19% respectively at FD density and at HD only 11% and 8% for DM and Y, respectively. The LER (land equivalent ratio) was calculated and based on dry matter was 1.64 and 1.32 for FD and HD densities, respectively, suggesting that agrivoltaic systems are efficient. At the end, there was an increase in global land productivity by 35 and 73% for FD and HD, respectively. Mouhib et al. (2024) examined the performance of an agrivoltaic system with three different olive cultivars. They modelled the amount of solar radiation that reaches the trees and the PV modules using SMART tool. The outcomes have shown that the highest energy yield of PV modules was achieved with an inclination near the site's latitude, while vertically-oriented modules lead to the greatest olive yield. Furthermore, they investigated the land equivalent ratio (LER) which provides insights into the land efficiency of an agrivoltaic system. The results indicated the LER remains >1, suggesting that the combined yield on the same land is higher than what each system would produce individually if implemented separately on the same area. Ciocia et al. (2022) simulated a PV plant of 10 hectare in Southern Italy with two different layouts to evaluate the energy and crop production performance of an agrivoltaic system. The crops cultivated were the olive Arbequina trees. The two configurations regarded the distance between two trackers of PV modules, the first was 6 m and second 7.5 m, with the nominal power of 7.13 MW and 5.68 MW, respectively. The findings have shown that the first PV field configuration modelled produced 13.7 GWh/year, while the second 11.2 GWh/year and LER for first and second configurations were 1.34 and 1.2 respectively. The whole land saving estimated for 10 hectar with agrivoltaic was ≈3.4 hectares for each hectare of terrain used for the agrivoltaic plant, 0.34 ha is saved, demonstrating that the combination in PV plant with crops can save land. In 2019, solar-powered systems had a 98 GW overall capacity growth, which equals to 60% of other renewables (Alami et al., 2022). Anyway, in the review of Widmer et al., (2024),they proposed a contribution to development possibilities of agrivoltaics in term of agronomic knowledge. From literature review they found that PV installations can satisfy energy requirements, but it is of great importance to note that crops growth and their quality are affected by shading, and to date, the research is focused on vegetable production, such as tomato and lettuce. There is no a defined general threshold limit of shading which plants can tolerate but, can be considered the amount of PAR (Photosyntetically active radiation) for yield and production. In such a way, also the type of solar panels can be considered. In addition, insular or inaccessible areas have the main constrains of limited land, food and electricity transportation challenges due to the distance, storage and costs. Hence, the potential development of solar greenhouses directly in these areas, can contribute to solve both problems in agrienergy field. Meanwhile, agrivoltaic systems can sell generated electricity and fed the power grid (Schallenberg-Rodriguez et al., 2023; Guerrero Hernández and Ramos de Arruda, 2022; Heyat Jilani et al., 2023). Furthermore, also wind power is a reliable and proven technology that can provide electricity. Wind power has become another commercialized prospect of renewable energy technologies which has increased in recent years thanks to its mature, high-level technology, abundant reserves, flexible installation, and other characteristics. However, as the wind power penetration grows, its inherent volatility and uncertainty pose challenges to the power system stability (Wang J. et al., 2022). As a result, it is possible to design a combined power generation system, such as a wind-energy storage hybrid power plant. Many Chinese provinces have issued corresponding policies to encourage the construction of a certain proportion of energy storage facilities in new wind farms. Thus, the combined operation system of wind farms with energy storage can be a new research object in the energy field (Wang W. et al., 2022).

The aim of this paper is to reviewing and evaluating the literature about innovative energy technologies integrated with agricultural systems to produce and utilize energy with sustainable and eco-friendly methods. This can help to conceive new eco-friendly projects, in accordance with European Green Deal policy, to increase energy production with renewable sources in developing countries, as well as food production for self-sustenance. Moreover, developed countries can achieve total decarbonisation in agriculture. The paper is divided into five sections. The first part provides a general overview of the Green Deal, of its objectives, the scope of the policies in which it can be applied, and the areas that are covered in this paper, alongside with other agricultural policies. The second part concerns an overview agrivoltaic systems for energy production in agriculture,the benefits and the possibility to be integrated with livestock . The third part presents the different photovoltaic systems integrated into greenhouses to produce and use energy on a small scale in such a way that they are energy self-sufficient and can also be a solution to the possibility of generating excess energy to be stored and sold into the grid. The fourth section provides a framework of the main greenhouse covering materials and presents a new one that can also generate electricity, splitting spectral covering (SSC). The fifth section analyses PV systems to provide electricity to energy communities or greenhouses, and the possibility, through local electrification systems, *e.g.* microgrids, of providing energy through energy sharing.

Sustainability in EU towards the Green Deal and agricultural policies

The European Green Deal (EGD) is the EU’s sustainable and inclusive growth strategy which, in the agricultural field, is supported by the Common Agricultural Policy (CAP). The aim of the EGD is to boost the economy, improve people’s health and quality of life, and take care of nature. It is a global standard for sustainability, including a package of measures adopted by the European Commission in July 2023 for the sustainable use of key natural resources, to strengthen the resilience of European food systems and agriculture. The EU’s aims include:

-ensuring food security in the face of geopolitical uncertainties, climate change and biodiversity loss;

-reducing the environmental and climate footprint of the European food system and strengthening its resilience;

-leading a global transition towards competitive sustainability from farm to fork (European Commission, 2023b).

In order to obtain the above-mentioned objectives, the CAP reform introduces a more flexible, performance-based approach that considers local condition and needs, while increasing EU level ambitions in terms of sustainability (European Commission, 2020a) (Figure 1).

The following are the CAP’s objectives:

1) to ensure a fair income for farmers;
2) to increase competitiveness;
3) to improve the position of farmers in the food chain;
4) climate change;
5) environmental care;
6) to preserve landscapes and biodiversity;
7) to support generational renewal;

8) vibrant rural areas;
9) to protect food and health quality;
10) to foster knowledge and innovation.

Agriculture is highly exposed to climate change and the increase of temperature, due to the seasonal fluctuations that disrupt farming cycles. Climate change and environmental pollution are closely related. The main sources of global warming—the extraction and burning of fossil fuels—are not the only key drivers of climate change, but are also major sources of air pollution.

As a part of the EGD, the Farm to Fork strategy leads towards a sustainable food system, in which farmers can satisfy society's demand for food security while at the same time protecting the climate. Baquedano and Scott (2020) performed policy simulations to examine the economic implications of the targets of European policies such as Farm to Fork strategies. The latter impose restrictions on EU agriculture through targeted reductions in the use of land, fertilizers and pesticides and EU would to expand these targets beyond EU. These targets, have shown that the input reductions decrease the agricultural production of the farmers by 7 to 12% and furthermore, this worldwide adoption could increase the global food prices by 9% (EU adoption) to 89% (global). Anyway, as aforementioned in the introduction by Widmer et al. (2024), Ciocia et al. (2022) and Mouhib et al. (2024), the agrivoltaics, despite a little decrease in agricultural production, can save the land use, optimizing the energy and food production in the same land area.

CAP is the key tool to support farmers in this transition to rural development, in order to promote the efficient use of resources and support the shift towards a low-carbon and climate resilient economy in the agricultural field. In their rural development programmes, EU countries intend to contribute through the supply and use of renewable energy sources; the reduction of greenhouse gas and ammonia emissions; and the promotion of carbon conservation and sequestration in agriculture and forestry (European Commission, 2023a). The new EU strategy involves existing and emerging technologies, processes and business models, such as smart grids, energy communities, meters and flexible markets. The integration of the sector will allow various energy carriers - electricity, heat, gas, solid and liquid fuels – to be linked with each other and with the end-use sectors, such as construction, transport or industry, to optimize the energy system as a whole (European Commission, 2020b) (Figure 2).

Renewable energy communities can restore our energy systems by harnessing energy and enabling citizens to actively participate in the energy transition. They can provide potential direct benefits to citizens, such as increasing energy efficiency by taking action regarding energy production and fostering social acceptance of renewable energy; reducing electricity bills; reducing carbon emissions; and increasing economic income (European Commission, 2019a). New market players, such as aggregators and energy service companies can offer new services to consumers, enabling them to regulate their own consumption and take advantage of the flexibility provided by the grid through smart grids. The decisions of energy communities, or electricity-intensive industries, will be influenced by market prices, and this can help strengthen competition in the retail market, incentivize the reduction of greenhouse gas emissions, while providing an opportunity for economic growth and EU leadership in global technology (European Commission, 2019b). In November 2023, under the EU State aid rules, the European Commission approved funding for an Italian scheme made available in part through the Recovery and Resilience Facility ('RRF') to support the production and self-consumption of renewable electricity. The scheme supports the construction of renewable power generation installations, as well as the expansion of existing ones. Furthermore, it will align with important EU objectives and targets set out in the European Green Deal and with other recent regulatory changes in the energy and environmental areas and will cater for the increased importance of climate protection. The beneficiaries will be small projects, with a capacity of up to 1 MW (European Commission, 2023c). Promoting the sustainable development depends by the amount of funds and adoption rate of the environmental measures, thus, Mgomezulu et al. (2023) noted that dis-adoption rates of agricultural measure range from 20 to 27% so, Canessa et al. (2024) provided insights about the variables that determine the adoption of farmers of agri-environmental-climate measures. The farmers decision depends on different stage-specific constructs, grouped into "alignment", "opportunity", "engagement" and "contracting". Alignment is referred to the compatibility of the measure with farmer values, past experiences and needs; the opportunity is related to the advantage to adopt the measure; the engagement concerns the process of information exchange and contracting is linked to the alignment and opportunity participation. For example, in the alignment construct was observed that the adoption of such measures for farmers with lower household and farm-related income can make participation more attractive, as income support enabled by lower opportunity costs and in addition, commercial farms are more likely to adopt measures, which can face the increased transaction costs due to participation. Likewise, in opportunity category, the role of tenure on adoption decision is related to the level of investment required by the measure. For engagement and contractual framework, receiving information directly from public organisations or funding agency, significantly increase the adoption and also, with bureaucratic simplification, increased fairness and flexibility. The agrivoltaic systems could play an important role because it could supply a lot of clean energy. This funded action will contribute to climate protection, but it will also represent an integrative income for small farmers who will install new renewable plants that will integrate agricultural production with clean energy production. In this context, Pascaris *et al.* (2021)investigated in U.S. about solar development from participant experiences to deep what were the factors which affect the industry perspective focusing on market, community and socio-political dimensions. Findings have shown that alignment among all three dimensions of acceptance will determine successful adoption of agrivoltaics for example, community support can lead to advocacy and implementation of socio-political conditions like favourable policies that promote profitable development. Participants agreed that agrivoltaic projects may stimulate community acceptance of solar, easing the development process, by retaining local values- local acceptance, the lowest levels of acceptance are observed during the siting phase of RE development. So,_the market dimension of agrivoltaics is the most relevant and complicated, being inclusive of community and socio-political factors and consequential for successful technology adoption among developers. In addition, research, innovation and knowledge are instruments which enhance competitiveness and sustainability in agriculture, indeed, Suárez *et al.* (2024) analised the effect that changes in the structure of CAP subsidies have on the research and development objectives using a multivariant model. There are different types of subsidies: coupled, decoupled. For Research and Development, the specific CAP subsidies are: production oriented (to increase production objective), input oriented (cost efficiency, the second objective) and for environment protection (third objective). Specific subsidies discourage the production increase and environmental protection objectives and increase the cost efficiency goal, while decoupled subsidies jointly improve the three objectives. Thus, research should develop and improve a new smart and efficient integrated system and last modifications applied to CAP enhance the equality distribution of funds among farms with the aim to foster their quality by growing in size, export capacity and to promote a collaboration networks.

Energy integrated systems in agriculture

Worldwide, about 0.8 billion people are going hungry and 1 billion do not have access to electricity (FAO, 2021). Sustainable Development Goals underline that about 2.8 billion people depend directly on agriculture for a living and encourages to take urgent actions to mitigate climate change and to achieve the goal to ensure affordable, reliable, sustainable, and modern energy access for all by 2030 (United Nations, 2021). In this context, developed and developing countries with sustained economic growth and energy food production make a pressure on energy and agricultural sources. Aboagye et al. (2022) highlighted the issue of how the design, installation, the type of solar PV, operation and maintenance issues of 16 installed PV systems in different climatic zones in Ghana, have an impact on the performance and degradation of installed PV systems. They discovered that the installers disregarded the PV system design procedures, leading to undersized systems against the desire demand and consequently, 69% of PV systems were improperly sized with a lower power output than expected and failure of some systems. In this regard, Adeh et al. (2019) proposed a model for solar panel efficiency that incorporates the influence of the panel's microclimate to study what kind of environmental factors influence photovoltaic (PV) panel function. For this reason, also the site to install a PV plant is important to take in account. Findings confirmed that PV panel efficiency is affected by the insolation, air temperature, wind speed and relative humidity and in addition, solar power production potential is influenced by croplands with the greatest median solar potential approximately 28 W/m^2.

Agrivoltaic systems

In recent years, agrivoltaic system utilization has become dramatically widespread, with a global installed capacity of 2.8 GW by 2020, up from 5 MW in 2012 (Gorjian et al., 2022). Figure 3 shows a typical agrivoltaic system. Co-production has received a huge attention by global research, and several studies were conducted. One of these investigated a suitable configuration for space utilization under the PV panels to promote power production. The threeconfigurations, in the 25-kW PV farm at the Asian Development College for Community Economy and Technology, under PV panels were the following: building a pond, planting chilies and grass (control), and were monitored sunlight intensity, air temperature, PV panels temperature, electric current, and voltage.

Findings showed that the first configuration (the pond under PV panels) and second one (chilies cultivated under PV) produced a solar power generation average of 1.6 kW, and this implied that planting under PV panels can potentially produce adequate yields and electricity (Kumpanalaisatit et al., 2019). Another study consideredwhat kind of agronomic aspects and structural safety along with an analysis of design criteria are important to design an Agrivoltaic system (AVS) by conducting a design method. Agronomic aspects that authors considered to design the AVS system were: LER to maximise land use, shading ratio of PV on crops which can decrease the yield, crop planting distance, the columns spaces and height to allow machineries to work on field, instead for AVS structure they considered: foundation of ground-mounted PV systems, snow load and wind load and modelled on Midas Gen software (MIDAS Information Technology Co.) with 2 scenarios. The first scenario was with a distance between the columns of 5,1 m; the second with a 4,5 m of distance. In addition, safety standards for disaster resistance and trade-offs among shading ratio, power generation capacity, and quantity of structural members were analysed. Safety assessment showed that wind loads damage the columns of AVSs, and, depending on the adjusted column spacing, the narrower the column design, the more advantageous the safety and power generation and the more disadvantageous the crop cultivation environment and installation cost. Moreover, PV panels at 5 m generated 3.5% more solar energy than those at 4 m. Conversely, mounting the modules at a 4 m distance, the structural safety was slightly reduced, and more solar radiation and economic feasibility were achieved (Lee et al., 2023). The increase in efficiency of solar power generation can be achieved by lowering the temperature of solar panels (Roy and Ghosh, 2017) coating them, for example, with aluminium oxide and tantalum pentoxide, chilling the PV panels with ice,(Peng *et al.,* 2017) allowing to decrease the temperature by 2.9-5°C while increasing PV panel efficiency by 14-47%. Global electricity demand can be satisfied by solar power as a renewable energy source which can replace the fossil-fuelled electricity production, improving national energy security and self-sufficiency (Kumpanalaisatit *et al.,* 2022). For instance, a multi-disciplinary assessment framework by integrating Geographic Information System (GIS), biogeochemical simulation, and solar power simulation was conducted in Shenzen city to reveal that an urban rooftop agrivoltaic system (e.g., planting lettuce under photovoltaic panels) on the 854,000 number of rooftops (i.e., 105 km^2 identified), offers a sustainable solution to achieve cities with clean energy. Findings have shown thatsolar PV installed capacity can reach 1899 GWh/year generated electricity corresponding to 0.2% of the whole city's electricity demand and indicating a great contribution to SDGs goals (Jing *et al*., 2022b). Jing *et al.* (2022a) proposed an economic analysis framework by coupling Monte Carlo based global sensitivity analysis, Sobol index method, potential assessment, and SDG assessment to fill the gap which exists in benchmarking the economic feasibility of the emerging agrivoltaics and aquavoltaics systems in Zhejiang Province, China. This framework was applied for benchmarking the project's economic performance across China. Findings have shown that considering spatial variations in China, the average simple payback period ranges between 6.2~6.6 years for agrivoltaics projects, and 9.5~10.1 years for aquavoltaics, respectively. Furthermore, capital cost of PV, solar resource, income from farming or fishing, are the main factors for the profitability of these systems and the national implementing potential of agrivoltaics would be up to 112 GW and 564 GW for aquavoltaics. From these outcomes they derived that comparing only PV systems, aquavoltaics and agrivoltaics contribute more to SDGs goals to achieve energy and food sustainability. Moreover, it has been demonstrated that an agrivoltaic system results in a large offset in GHG emissions if it is compared to the same-scale diesel power generation or grid supply (Choi *et al.,* 2021). Agrivoltaic systems can provide a cash flow for agriculturist and entrepreneurs (Havrysh *et al.,* 2022; Chae et al., 2022) who may also minimise the expenses by using the electricity generated on their farms, saving money for energy (Bhandari et al., 2021). By selling the electricity generated by agrivoltaic systems and agricultural products, entrepreneurs and farmers can obtain income streams (Guerrero Hernández and de Arruda, 2022). Thompson *et al.* (2020) demonstrated that the income from selling electricity with basil and spinach increased the production values by 18% and 113%, respectively. In India, an experimental investigation was conducted with a portable and adjustable agrivoltaic system of 0.675 kWp capacity to study the enhancement of land productivity and revenue of farmers or/and investors. This system has provided an underneath farming of 1.5 kg turmeric as a shadow tolerant medicinal crop. Findings demonstrated that the major performance indicators of the project, such as land equivalent ratio, benefit-cost ratio, price-performance ratio, and payback period, were 1.73, 1.71, 0.79, and 9.49 years respectively. Furthermore, there was an improvement of the energy generation in the system because the temperature level decreased by 1-1.5°C. A slight improvement of 1120 kWh was observed in the annual average energy generation capacity of the 0.675 kWp AVS, while, in the absence of crops, it stood at 1024 kWh. There was also a slight sacrifice in turmeric production as the 1.5 kg food production capacity of turmeric stood at about 16 kg with SPV and 18.5 without, respectively, and the average annual energy and turmeric revenue in the year 2021 were of US$ 51.52 and US$ 31.36, respectively (Giri and Mohanty, 2022). Trommsdorff *et al.* (2021a) assessed the technical feasibility of agrivoltaic (APV). Furthermore, they analysed the electrical yield and the behavior and productivity of four crops grown in Germany's largest agrivoltaic research facility compared to a ground mounted PV system with the same size. The APV facility size was width x length of used area 25.3 × 136.3 m. The findings indicated that LER increased between 56% and 70% in 2017, while in the summer the agrivoltaic system could increase land productivity by nearly 90%. The total amount of electricity produced during the first year of operation was 246 MWh compared to the standard PV plant (monofacial PV modules) which have generated approximately 295.4 MWh during the same period. Therefore, the electrical yield of the APV system was about 17% lower than the electrical yield of PV plant. Electricity selling prices were lower than consumer prices to improve economic performance and increase self-consumption for which the local farming community used 41% of the electricity generated (101.2 MWh) in the first year of operation. Increased employment and generation of money for the farming community, then, are due to the development of agricultural plots, solar plants only generating electricity, or abandoned land for agri-voltaic plant (Trommsdorff et *al.,* 2021b) . Junedi *et al.* (2022) discussed three different configurations of ground-mounted PV farms: PV-wind, building integrated- or applied- PV (BIPV/BAPV) and agrophotovoltaic (agroPV) to generate electricity. The PV-wind system generates electricity from two energy sources, while BIPV/BAPV systems use existing building space. The agroPV system combines the advantages of energy production and utilization of the free land under PV panels through cultivation with an energy payback time (EPBT) of 6.3 years and an emission rate of 0.02 kg CO_2eq/kWh. This is comparable to that of GMPV systems and lower than that of other integrated systems in terms of emissions; yet the levelized cost of energy is higher than that of GMPV systems, which showed an EPBT of 0.5 years due to the system's high power production that allows immediate payback of the primary energy consumed. The BIPV system has the lowest emission rate, with a range of - 0.906-0.071 kg CO_2 eq/kWh. By employing more community members in food processing industries, more agrivoltaic crops can be sustained.

Through the generation of energy by agrivoltaic plants and other activities, entrepreneurs can sell energy to electricity authorities, thus earning money. Thanks to the installation of agrivoltaic plants in areas without electricity, or at the end of a transmission line, an increase in electric capacity in those areas can be achieved and help electric authorities reduce transmission line expansion costs (Bhandari et al., 2021). There is also the possibility of integrating agri-voltaics with animal husbandry. Handler and Pearce (2022) in U.S. investigated the environmental performance of sheep-based agrivoltaics system by using LCA method (Ecoinvent profile) compared to a conventional PV system. They found that Global Warming potential was 3.9% better than conventional PV system and sheep grazing separately. Furthermore, shifting sheep to PV farms for grazing, U.S. could save 5.73E8 kg CO_2 eq per year from sheep raising. Maia *et al.,* (2020) investigated the potential of co-generation of PV system to generate electricity and provide shade for sheep managed in a paddock. Two types of shade structures were used: ten PV panels each one with 335 Wp and efficiency of 17% and shade cloths. Results have shown that the sheep spent less than 1% of their time under the shade cloths while the 38% of their time they were under PV panels, demonstrating that they were thermally comfortable because most of them were lying down. In one year, the PV shading system generated 5.19 MWh reducing the emission of 2.77 ton CO_2 to the atmosphere.

Renewable energies integrated with greenhouses

One third of greenhouse gas emissions are produced by the agricultural sector, contributing significantly to climate change (Gilbert, 2012). Increasing world populations and economies play a major role in increasing the demand for energy and food, so a few issues have arisen concerning the management of energy demand and its consumption (Bahiraei et al., 2022) . Renewable energy sources have become a global trend (Ma and Yuan, 2023) and with the rapid development and wide use of PV systems the basic assessments of the actual capacity, emission reductions, and economic benefits of PV panels are required (Wang P. *et al.,* 2022). Solar energy is a promising and renewable energy that is developed and used by countries (Ma and

Yuan, 2023). In this context, solar photovoltaic (PV) systems are a promising alternative for future energy supply, for increasing the energy independence in green buildings (Marocco et al., 2023). Thanks to European energy policies, and especially to favourable subsidy policies for their installation, the photovoltaic (PV) industry has spread rapidly over the last few years (Bigerna *et al.,* 2017). There has been a move towards using greenhouses in a sustainable way, integrating renewable energy systems (e.g. using solar radiation to produce energy and heat). Therefore, a new sustainable profile of agriculture can be achieved by placing photovoltaic (PV) systems on the roofs of greenhouse structures (Marucci *et al.,* 2012).

Silicon mono and poly-crystalline modules

Solar cells were discovered for the first time in 1839 using photovoltaic effects, which could convert solar light into electrical energy. This important discovery did not attract researchers until 1954 when modern silicon cells were developed, though their efficiency was very low. Solar PV systems are formed by small opto-electrical devices converting solar radiation directly into electricity (Alami *et al*., 2022). Conventional solar cells are fabricated with silicon crystalline cells, the efficiency of which is approximately 26.3%. Crystalline Si includes monocrystalline silicon and polycrystalline silicon, and the efficiency of monocrystalline silicon cells is higher (Tang *et al.,* 2023). Marucci *et al*. (2018) conducted a study in Viterbo to investigate the evolution of PV panels on the roof during several Energy counts (E.C.). Furthermore, they wanted to examine the effect of shading of PV panels with an efficiency of 18%, and manufactured with mono-crystalline cells, on a prototype greenhouse to allow its environmental adaptation to the intrinsic characteristics. One of the major limits to use the PV panels is the shading on crops, which affects their growth.

They were installed in a checkboard pattern. Findings showed that, throughout the year, the shading percentage was never over 40%. A new approach to deploying a highly efficient photovoltaic hydroponic greenhouse was developed by Bouadila *et al.* (2023). Simulations and experiments were performed to obtain information on the performance and control strategies of a greenhouse acting as zero-energy housing. The system included evacuated tube solar collectors (vacuum system), a solar air heater with latent storage energy and a PV array to ensure the electrification and air conditioning of the greenhouse. The lighting, ventilation, irrigation, and solar systems were powered by the greenhouse's 2.1 kWh photovoltaic system. The results showed that the discounted payback time and return time were 13 and 10.9 years, respectively. The levelized cost of energy produced was 0.198 of the price of electricity at distribution. The heat demand of the greenhouse was covered by the photovoltaic system for 92.25% of the operating hours and the excess energy could supply approximately 1421 kWh_{el} per year to the grid (Bouadila *et al.,* 2023).

Another study was conducted to develop coupled optical-electrical-thermal models to assess the energy performance of the PV greenhouse with different PV roof coverage ratios during the summer months. In order to evaluate the response of crops to the interior climate conditions and validate the models, some experiments were conducted in a PV greenhouse in Kunming also considering photosynthetically active radiation (PAR) and net photosynthetic rate (PN) based on the irradiance and temperature of the PV greenhouse. The energy systems included PV modules (3.285 kWp), a battery bank (24 kWh), an air–water heat pump, and spray combined with fan cooling and strawberry cultivation. Two cooling scenarios were analysed by varying the PV module coverage ratio: Scenario 1 (S.1) was AWHP cooling, and scenario 2 (S.2) was spray combined with fan cooling. The results showed that optimal PAR and interior temperature of the greenhouse were 300 $\mu mol \cdot m^{-2} \cdot s^{-1}$ and 22°C, respectively; the proportion of the PV layout on the greenhouse roof was greater than 20%; and the year-round PAR inside the greenhouse was below the threshold value of 550 $\mu mol \cdot m^{-2} \cdot s^{-1}$, at which the strawberry

PN (net photosynthesis) was saturated. At the same time, an increase of 10% of the cover ratio of the PV modules of on the roof showed a decrease of the interior air temperature and a daily cooling load reduction of 0,45-1,02 kWh/ d. PV generation increased of 1.7-3.19 kWh/d and the maximum electricity consumption of S.1 and S.2 dropped by 0.66 kWh/d and 0.52 kWh/d, respectively. The lowest levelized costs of electricity (LCOE) and the levelized costs of cooling (LCOC) showed a coverage of 40% in Scenario.1 with PV modules; while in S.2 , the lowest LCOE and LCOC showed a coverage of 30% (Peng *et al.,* 2023). A typical Mediterranean greenhouse with good climate control requires approximately 90,000 kWhe/ha/a of electrical power compared to one with low technological development requiring 20,000 kWhe/ha. A feasibility analysis was performed with photovoltaic (PV) technology integrated on the cover of an east-west oriented greenhouse to assess their energy potential and the economic convenience of the investment. The maximum power to be installed was between 94 and 188kWp/ha, corresponding to a shading level of 10 and 19%, respectively. Of the two photovoltaic plants of 188 and 94 kWp/ha, the first showed the best economic results, with a Net Present Value (NPV) of €/ha 1,112, far exceeding the investment cost (€832,000). In contrast, the payback time of the investment ranged from 10 to 13 years, for the 188 kWp and 94kWp plants (Cossu et al., 2010). Another study analysed agrivoltaic systems (APV) in greenhouses in terms of energy yield on a global scale. The study was conducted in four locations with a high crop cultivation greenhouse implantation, *i.e.,* El Ejido (Spain), Pachino (Italy), Antalya (Turkey) and Vicente Guerrero (Mexico), and with different plant cultivars (*i.e.*, Cucurbitaceae, Fabaceae, Solanacae, Poaceae, Rosaceae). Semi-transparent c-Si PV modules were used for the study. The results showed that APV systems had a transparency factor of around 68% without much influence on the photosynthetic rate of the crops, producing an average annual energy of around 135 kWh/m^2 and, in a favourable scenario, around 200 kWh/m^2. The representative contribution to the total market share would be between 2.3% and 6% for Mexico and Turkey respectively, and up to 100% of the consumption demand of greenhouses equipped with heating and cooling and lighting (Fernández *et al.,* 2022). Al-Naemi and Al-Otoom (2023) conducted a study about a smart sustainable greenhouse concept model to demonstrate the effectiveness and the profitability of using renewable energy and smart control systems in closed agriculture environment. Solar polycrystalline panels with an efficiency of 16.5% were installed on the roof of the greenhouse. A hybrid inverter was used to invert the solar photovoltaic energy and convert it into AC power used to drive the air conditioning system and irrigation pumping system. In addition, excess energy during peak hours was stored in battery systems. The photovoltaic capacity installed with the storage system could support the energy required by the greenhouse, and the greenhouse's water requirements were reduced by 40 % compared to a conventional system. 65% of the water used for irrigation came from condensation from the air conditioner. The total energy produced by the installed photovoltaic system was constant, averaging 678 kWh as shown in Table 1.

Different photovoltaic systems and integrated structures

The development of solar cells has allowed investigating different structures over time, with the main materials including crystalline Si (c-Si), amorphous Si (a-Si), cadmium telluride (CdTe) or copper indium gallium (di) selenide (CIGS). The last three types of materials are commonly used in thin-film solar cells, which can use low-cost ceramics, graphite, metals, and other different materials. New generation of DSSC devices can be fabricated with an electron acceptor semiconductor oxide film, which is coated with a liquid iodide/triiodide electrolyte and a layer of a charge-transfer dye, also taking advantage of features of abundance, strong chemical stability, high dielectric constant, and fewer defect states with TiO_2 (Tang *et al.*, 2023). A study investigated the performance comparison of 5 different types of photovoltaic technologies (Mono, Multi, a-Si, CdTe, CIGS) subjected to five distinct proportions of temperature and humidity in a controlled environment under biasing conditions. CIGS (Copper Indium Gallium Selenide) perform with best efficiency at 60°C, 60% RH (relative humidity), while CdTe (Cadmium Telluride) performs with best efficiency at 85 °C, 85% RH. This study established the performance dominance of C-Si (Mono) over all the thin film technologies based on evaluation of maximum power, module, and cell efficiency (Siddiqui *et al.,* 2016). Silicon-based mono-crystalline and poly-crystalline modules, as well as thin film technologies based on non-silicon materials, were the most used and marketed PV panels with current commercial efficiencies in the range of 15% to 23% (Alami *et al*., 2022). Photovoltaic technologies had the potential to create multipurpose agricultural systems that generated income through conventional crop production as well as sustainable electrical energy (Stallknecht *et al.,* 2023). 70% of capital investment for PV systems was related to the module part. Photovoltaic cost effectiveness is gaining importance with the ongoing growth of PV market (Siddiqui *et al.,* 2016).

Thin solar cells

Thin-solar cells with a substrate film of only a few microns and energy conversion efficiency of up to 29.1% have been developed. For this reason, the applications of thin-film solar cells are very extensive and wide and can be found not only in planar devices but also in non-planar structures. In addition, thin-film technology can also be used in solar cells in series. Besides, they can commonly be combined with buildings or become part of buildings (Aberle, 2009). Photovoltaic modules can be utilized also to heat stores in collectors, to use in different domestic, residential, and industrial applications. Energy produced by PV can feed electricity into the grid. A study was conducted to design a greenhouse with an integrated thin-film photovoltaic system in a Quonset greenhouse (polyethylene tunnel) (GiTPV) to facilitate plant growth in cold and harsh climatic conditions. An earth-to-air heat exchanger (EAHE) utilising shallow geothermal energy to enhance the self-sustainability of the system was coupled to the system. The results showed that the EAHE system inside the GiTPV reduced air temperature fluctuations in the room, providing heating during non-sunny hours and thus improving thermal comfort. Greenhouse and plant air temperatures increased by 5°C and 4°C, respectively, with an air flow rate through the EAHE of 0.5 kg/s. The GiTPV system produced 15.3 kWh of electrical energy per day, proving to be self-sufficient (Jilani *et al.,* 2023).

Semi-transparent PV modules

Semi-transparent PV modules have higher light transmittance than Opaque PV. They have a long service life, and a low cost of power generation. Over 20% energy is saved than traditional PV modules. Semi-transparent PV (STPV) modules are a good choice for power generation (Zhang *et al.,* 2022)**.** In the review of Gorjian *et al*. (2022) they absorb photonic energy from the sunlight, and their characteristic transparency allows the photons to pass through their layers. The material used for PV cells encompasses both features of photon absorption for electron flow and light penetration. Transparency of PV cells varies on the average visible transmission (AVT) property. Unlike opaque conventional PV modules, the non-selective and ultraviolet/near-infrared (UV/NIR)-selective ones are based on the wavelength in which photoactive compounds absorb the photons from the selected wavelengths and transmit them as visible ones. The average visible transmission (AVT) of non-selective modules ranges between 0 and 50%, while, for the UV/NIR STPV type, it is in the range of 50-90%, following power conversion efficiency. Silicon and Perovskites modules are more suitable for STPV cells and for PV integrated products, such as sunroofs, windows, greenhouses, *etc*. The highest recorded efficiency, was observed for tandem Semi-Transparent perovskite solar cells, 12.7% (AVT is 77%), followed by the screen-printed DSSCs, 9.2% (AVT is 60%). There was a study about the effect of tinted a-Si STPV modules on the growth of basil and spinach with a nominal efficiency of 8% and power output of 66 W/m^2, which absorb light in the blue and green part of the spectrum and let a red light pass through (orange tint). There were morphological changes on crops, *i.e*., basil with larger leaves and spinach with larger stem; a redistribution of metabolic energy; and increased protein. Biomass yields were reduced for basil and spinach by 15% and 26%, respectively (Aira *et al*., 2021). Regarding the Mono-Si STPV modules installed on a greenhouse, a study was conducted to evaluate the energy power generation, with cultivated tomatoes inside. The c-Si STPV modules with a nominal power of 170 Wp for each one (size 1985 mm x 1038 mm), an efficiency of 8.25%, and a transparency of 47% were installed on top of a South-facing greenhouse. Crystalline silicon STPV had a power conversion efficiency of 26.6%; amorphous silicon had a PCE of 14%; perovskite an efficiency of 22.7%; and polymer 11.5% of efficiency. The electric performance of innovative modules was evaluated on a prototype Venetian-blind-type system underneath a greenhouse glass. Modules blocked 35-40% more light than the polyethylene cover and decreased the air temperature; no significant variations were found in the growth of tomatoes. Produced electricity was enough for the supplemental energy demands of the greenhouse, over a 9-year payback time. Inclination of the PV blind was controlled. During a period of 5 months, the system generated an annual surplus energy of 7.8 kWh/m^2/year (Hassanien et al., 2018).

Organic solar cells (OPV)

Different light spectrum bands have various effects on plant growth, which is achieved by the useful light spectrum in the PAR range of 400 to 700 nm. PAR allows the crops to do photosynthesis and peak rates are observed in response to light in the red and blue regions of the spectrum, whereas green light is poorly absorbed. In addition, UV and far-red light (near IR from 700-800 nm) are not used for photosynthesis, yet have profound effects on plant growth and development. They should be optimised sharing solar energy in order to not compromise the plant growth and to generate electricity, considering even the morphogenic and photosynthetic responses of the plants. To achieve this, incident light may be filtered through specifically coloured semi-transparent PVs, including DSSCs and organic PV (OPV) (Lau *et al.,* 2014). The components of DSSCs and OPVs can be tuned to allow only the wavebands of light important for plant growth to enter the greenhouse. Crops were successfully cultivated under blue-red diodes, and green light can be channelled into electricity production with no loss of biomass and without inducing shade responses. Furthermore, luminescent solar concentrators have been developed that absorb green light wavebands, re-emit energy as red light wavebands, and transmit blue and red-light wavebands. This system was observed to be suitable also for the algae growth without a decreasing growth rate or achievable mass density (Detweiler *et al.,* 2015). The green light waveband contains enough energy to take in account the integration of semi-transparent PVs as an option. Numerical modelling has demonstrated the compatibility of OPVs light absorption spectrum with a lot of herbaceous plants, including common greenhouse crops (Allardyce *et al*., 2017). Figure 4 shows different PV modules.

Organic solar cells are another class of thin-film solar cells. In addition to organic and inorganic solar cells, dye-sensitized solar cells (DSSCs) are another cost-effective type of solar cells whose overall conversion efficiency, under diffuse sunlight, is 12.5% (Tang *et al.,* 2023). DSSCs are flexible, lightweight, and are used as a rollable screen to keep the advantages of OPV. DSSCs employ a light-scattering layer to increase light absorption. A study was carried out about special DSSCs for greenhouse applications using novel Ruthenium (Ru) sensitizers to enhance the transmittance of the red and blue wavelengths. The transmittance was measured at 660 nm and at 440 nm, with values of 62% (red) and 18% (blue), respectively. The sunlight

conversion efficiency in electricity was of 4.96%. In DSSCs, TiO_2 as a semiconductor, with its good insulation properties, also make them suitable for use in greenhouses.
Transferring sunlight through photo-selective films and increasing the amount of diffuse light in the greenhouse improves the light penetration and homogeneity into the plant canopy (Kim *et al.,* 2014).
A study was conducted in Australia (Geraldton) to assess and analyse the potential for semi-transparent organic solar cells in agrophotovoltaic greenhouses. Organic semi-transparent cells with 9.4% power conversion efficiency and 24.6% AVT were employed to design the greenhouse, to simulate and to compare light interaction and tomato growth model with both traditional silicon and semi-transparent technologies. The results showed that the electrical revenue generated by the solar greenhouse with semi-transparent cells (STSC) was 36% of the Si greenhouse revenue. The overall revenues of the STSC were 26.77% less profitable than those of the Si technology as the lower energy production was due to 9.4% power conversion efficiency compared to 21% of the Si photovoltaic. This is only valid if the electricity price is deducted from what the farmer would pay for grid electricity. If the energy were sold to the grid, the profit would be lower. Furthermore, STOSCs are not yet commercially available due to their lower efficiency and shorter lifetime.
Therefore, considering the results and analysis, one might argue that there is limited potential for STOSCs in agrophotovoltaic greenhouses in the current market. Private companies are also exploring Semitransparent solar Cells in agrophotovoltaic, showing significant interest in this field (Dipta *et al.,* 2022). Another study investigated the energy production of semi-transparent organic photovoltaic modules integrated into a single-span gable-roof greenhouse.
The effect on PAR availability (radiation simulations) in a greenhouse in Greece was analyzed indirectly through computational fluid dynamics (CFD) . The OPV module had a 30% average PAR transmittance, and 3 different active material cover ratios were investigated, resulting in PAR transmittance of 30%, 45%, and 60%. The results were compared to a reference greenhouse covered with polyethylene and 89% PAR transmittance, resulting in considerable CO_2 savings. The simulations indicated that OPVs could cover the annual energy demand of the greenhouse in hot and mixed-humid climates with an annual PAR reduction of only 10% and 25%. With integration of OPVs, there was an energy demand load reduction. Opaque OPV modules offer smaller efficiencies than other modules. OPVs can potentially be the most efficient modules considering that transparency for AVT is over 40%. In laboratories, AVTs are in a range of 60–65% with PCEs in a range of 4-5% achieved for OPV cells (Baxevanou *et al*., 2020).

Wavelength selective photovoltaic system (WSPV)
In the photovoltaic field, there are also some technologies that can be integrated, such as a solar thermal system combining an LSC (luminescent solar concentrator) with conventional c-Si solar cells, named Wavelength Selective Photovoltaic System (WSPV). Cells are placed in front of the module for using direct sunlight and reducing the travelling distance of the light.
Luminescent dye absorbs some of the blue and green wavelengths, which are remitted as red wavelengths and allow the solar cells to produce electricity; the rest of sunlight is available for crops. Findings in this study observed that cover ratios of 21% led to a panel efficiency of 6.8%. The performance of various WSPVs panels covering a greenhouse was also compared to a reference case where c-Si cells of the same size were incorporated on clear glass, without luminescent material. A greenhouse fully covered with the WSPVs generated 57.4 kWh/m^2 /year and the 20-year reliability of the luminescent material was confirmed under the UV testing system (Gorjian *et al.,* 2022). The LSC can be embedded into greenhouses for different applications: 1) to improve the performance of PV panels; 2) to ensure a more evenly diffuse

light can reach the plants, 3) to modulate the solar spectrum and radiate through fluorescence (Costa, 2021).

Solar trackers
Other technologies are used to boost the energy output of a solar plant, e.g., solar trackers. Yet, they can potentially double the cost of installation if the area is big. As a matter of fact, it is cheaper to install more solar panels to boost the system's energy production. A solar tracking system can help generate more electricity in a smaller area and increase the amount of energy gained by PV panels in many conditions. Solar tracker rotates the solar panel in the direction of the sun maintaining an optimal angle of incidence of solar radiation, close to 90◦. They are classified in single-axis trackers or double-axis trackers (perpendicular to each other), and in passive and active positioning. The latter in closed loop or open loop. Passive positioning uses a heated liquid and the expansion of gas to make the panel turn, while active positioning uses a gear mechanism (El Hammoumi *et al.,* 2022).

Floating PV system (FPVSs)
PV systems need a lot of land (about 10 m^2 per kWp); however, these constraints can be overcome by deploying and installing PV systems on water bodies, such as ponds, dam reservoirs, canals, and rivers, in order to conserve land. This kind of PV systems is called floating PV systems (FPVSs) and allows solar panels to be cooled using the cooling action of water, hence enhancing their efficiency. Key components of FPVS are pontoon, mooring and anchoring system, PV panels, and electric cables and connectors. Besides PV panels, also combination boxes and central inverters can be floating on water. Connectors and cables transport electricity to the land or to the grid, or to be stored in batteries. The advantages of FPVs are that they do not require land area, which means significant cost savings in terms of land use; the floating structures offer shade on the water's surface, reducing algae blooming, improving water quality and preserving water losses by 25% to 70%; there is an increase in PV energy production. Nevertheless, there are some drawbacks: 1) decrease in sunlight penetration into bodies of water can spoil the growth of aquatic creatures living under floating structures, 2) FPVs are not resistant to severe wind gusts, thus, they are located on inland freshwater bodies because the anchoring and mooring system is less stressed by wind, waves and currents (El Hammoumi *et al.,* 2022). FSPV market is expected to reach from a valuation approximately $2 billion in 2021 to $27.7 billion by 2031 (Newswire, 2020). Off-shore FPVSs systems can be a suitable alternative solution to large-scale ground PV systems, which make rational use of water resource and as abovementioned decreasing the land use. The difference between PV land systems temperatures compared to FPVSs temperatures obtained by cooling wind effect were about 5 ◦C and 6 ◦C at wind speeds increasing from 0.5 to 10 m/s. Furthermore, to less stress the pontoons resistance, the material which can be used is the high density polyethylene. The latter thanks to its characteristics has good wear resistance, electrical insulation, toughness and cold resistance. It can resist acid, alkali and all kinds of salt corrosion and also are easy to install and transport. The deployment of FPVSs allow for potential development of offshore fish farming enhancing economic gains from marine activities (Huang *et al.,* 2023). Mishra et al. (2023a) presented a review which covers various aspects related to FPVSs to provide valuable insights into the design and integration of floating solar-based hybrid renewable energy systems. It is of great importance to take in account for example, critical design strategies to develop a FPVS such as site inspection, reservoir layout, water quality, solar irradiance, wind loading. Also, to promote the broadcast of FPVS systems, feasibility analysis involving the techno-economic and environmental assessment are made i.e. the location, structural design, and soft costs such as taxes and transportation, operating and maintenance costs, energy yield,

and environmental impact will impact the total system cost. Genetic algorithms can be used for sizing and economic analysis. For designing different simulation tools such as PVsyst, ANSYS, computational fluid dynamics (CFD) can be used. Thus, a potential concept is the development of floating farm that combines smart floating solar based system with farming to overcome future food shortages. Barreca, (2024) carried out an energy simulation with EnergyPlus and Energy analysis with Design Builder to compare the energy performance of two heating, ventilation, and air conditioning (HVAC) systems for a novel floating dome greenhouse, fixed on sea platform. The first HVAC system is equipped with a cooling tower system, while the second with seawater cooling system. The HVAC system uses only electric energy to maintain the inside temperature within the range of 15–23 ◦C and it is possible to supply the required electricity by integrated PV modules. Findings have shown that HVAC system saved a total annual energy about 14% of cooling and seawater cooling system about 20% of energy savings. A study was conducted to present a decentralised floating controlled environment agricultural system for vegetable production, which is self-sufficient in terms of energy and water, producing food all year-round in an environmentally benign manner. The system consists of a floating greenhouse and integrated photovoltaic solar panels to meet electricity needs, a plant's growing area, two heat exchangers (a primary and a secondary one), and several auxiliary equipment. Figure 5 shows the floating controlled system. Findings have shown that the integrated PV system produce sufficient electricity for both seasons to power the floating greenhouse.
The discount payback period (DPP) for determining economic viability is 13.5 years and the net present value (NPV) is $21,710, showing that the investment in the project is worth it. Table 2 shows the economic breakdown of the system (Luqman *et al.,* 2023).

Cladding materials and a novel covering material: the spectral splitting covering (SSC)
In addition to the various types of photovoltaic systems that increase energy production in greenhouses, it is also of great importance to consider the roofing materials of a smart greenhouse and the shapes of the roof. A smart greenhouse system provides monitoring and control capabilities that do not require human interactions, manages the cost reduction and energy consumption, finding the ideal solution to design (Gholami *et al.,* 2021). There are several shapes of a greenhouse roof: gable roof, arch roof, sawtooth roof, trussed roof, even span, gothic house, Quonset, uneven span (Badji *et al*., 2022). A study found that a greenhouse with an uneven-span design gathers the most solar radiation regardless of latitude, and the east-west orientation is suitable for year-round applications at all latitudes, since it can lead to higher winter solar gains and lower summer solar gains; while a Quonset shape is the worst in collecting solar light. Regarding cladding materials, their properties are the following: high transmittance for visible light and low for long-wave radiation, wind resistance and low light transmittance to extend lifespan (Briassoulis *et al.,* 1997). The main materials used are glass, polymers, such as polycarbonate, fiberglass reinforced plastics, low-density polyethylene, ethylene-vinyl acetate copolymer, PVC and ethylene tetrafluoroethylene copolymer (Lin, 2020). A study was carried out for the microclimate and energy assessment of two different cladding materials, three types of double polyethylene (PE) and single glass (SG). The differences in climate under different claddings are presented in terms of PAR transmission and humidity levels. The measured average PAR transmission during the winter months was 0.68, 0.62, 0.65 and 0.60 for glass, and other three different double PE claddings, respectively. In the summer months, the values were higher. The average vapour pressure deficit in the double PE was found lower than under single glass during the winter season, but no significant difference was observed between various anti-fog films (Zhang *et al.,* 1996). Another study demonstrated that polycarbonate could lower overall thermal energy consumption when compared to

polyethylene (Seshasayee and Savage, 2020) and others discovered that polycarbonate was more effective in blocking UV light (Kaschuk *et al*., 2022). A study was carried out to present a novel greenhouse covering structure named as the spectral splitting covering, which can transmit visible light and convert near-infrared light into electricity and letting only visible light through. Plants absorb the visible light spectrum between 400 and 700 nm for photosynthesis (PAR). The near-infrared spectrum between 780 nm and 2500 nm causes overheating in greenhouses. The simulated transmissivity and the experimental results were in line and the transmissivity to VIS (visible) light throughout the day was 40%, even reaching 57.7%. The electrical output of this coverage was at its highest at midday, with a value of 133.2 $W \cdot m^{-2}$, and the photovoltaic efficiency for the whole day was 6.88%. The near infrared was about 78% blocked, thus reducing the energy consumption for cooling. This new cover ensures plant growth by converting near-infrared sunlight into electricity and providing a new approach to improve the utilisation of full spectrum solar energy in the greenhouse (Ma *et al*., 2022).

PV systems for energy communities

Over the past few years, global energy demand has rapidly increased because of economic expansion and the growing population. Limitations of electricity delivery schemes are caused by the utility regulators, which aim to shorten end-user use in a variety of areas, including implementing elevated tariff rates. Energy authorities are now attempting to reduce fossil fuel dependence, due to exhaustion of fossil fuel reserves, market fluctuations, and detrimental environmental effects, such as CO_2 emissions (Zhang, *et al.,* 2013). Thereby, end users must reduce their energy consumption by modifying their energy usage patterns and utilizing energy-efficient appliances and tools. Other potential alternatives include energy and utility bills reduction by the development of effective photovoltaic (PV) systems, notification of consumers' energy use, use of energy-efficient appliances and the use of advanced power communications systems (Ali *et al.,* 2022). A power grid with bidirectional energy/data flow and integrated advanced information/communication technologies is called a smart grid (Yu and Xue, 2016). The concept of a modern grid was implemented by the need to: (1) improve efficiency of electricity production and distribution, and reliability, (2) make electricity users aware that they have information to control electricity use and costs, (3) mitigate the climatic impacts of the electrical power industry. These goals led to industrial, research and regulatory actions for the evolving smart grid (Zhang *et al.,* 2022). In Japan, the Government has targeted a 46% reduction in greenhouse gas emission by 2030 and a net-zero emission by 2050, including PV technology in the power grid which can help to decarbonize the energy system of the country. To reduce the amount of carbon emission associated with huge electrical energy production, and to provide an economically viable alternative to fossil fuels, PV technology and other renewable technologies play a key role (Renewable Energy Institute and Agora Energiewende, 2020). One of the concerns of this system is its impact on the stability of the power grid due to the weather fluctuations which affect the performance of renewable technologies and make the power supply from these technologies unstable (Komiyama and Fujii, 2021). The transmission frequency of the system have to be within tolerable ranges because small imbalances due to the load are normal. When these are excessive, they could lead to local or total system blackouts. The use of spare capacity could prevent the system frequency drop (Merk *et al.,* 2018). A study was conducted to analyse the potential value of large-scale integration of agrivoltaic technology in rural farming areas in Japan, assessing the effect of a storage battery system and expanded transmission line capacities using a temporal resolution of 8760 h for all regions in Japan. The output suppression was investigated in rice paddy areas or in equivalent land areas (35% of the total cultivated land; 35 TCL). A sensitivity analysis

was conducted with 0%, 5%, 10%, and 15% agrivoltaics to examine the impact on the energy mix, comparing scenarios for PV system capacity in the power grid, installed battery storage capacity, and capacity expansion of regional transmission lines, with a 15% introduction rate. The results suggest that by modelling a power grid, one can reduce the suppression of generation caused by agrivoltaics and become more efficient in reducing oversupply by up to 82% and CO_2 emissions by up to 8.14% compared to base cases using batteries and/or expansion of transmission lines at the same time. Agrivoltaic installation is more efficient in rice fields than 35 TCL because of the distribution of crops in all regions of the country and its proximity to high energy demand regions (Gonocruz, *et al.,* 2022).
As mentioned in the first section, the renewable projects that are usually installed (e.g., solar and wind power) are located in remote and impoverished areas in developing countries in order to alleviate energy poverty of people who would otherwise not have access to electricity (Ibrahim *et al*., 2021). A study was conducted in the Himalayan region to estimate energy demand and to improve food and nutrition security in areas with a hostile climate, such as the Himalayan region. Greenhouse aquaponics (GA) is a sustainable method that has the potential to achieve the above-mentioned food goals in such regions, but energy problems are one of the main issues in this area. Due to difficult topographical and climatic conditions, agricultural production is low; therefore, GA energy modelling was performed to provide information on energy consumption. To meet GA's energy needs, the most reliable and sufficient source of renewable energy in this area is solar energy through off-grid electrification methods using photovoltaic (PV) panels. The results obtained showed that the high energy demand was due to a considerable loss of heat quantity, and adjustments were made between energy and yield. Measures included decreasing the optimal internal temperature by choosing crops and fish with high growth potential in low T environments, utilising the greenhouse area by maximising the growth area. Passive heat reservoirs that store excess solar energy were also identified, *e.g.,* by channelling only about 20 % of the solar energy for passive heating through the heat reservoirs, the GA could operate for an average of 80 % of the year without the need for additional heating devices (Parajuli *et al.,* 2023).
In North Egypt, El Nemr *et al.* (2021) studied the sizing of stand-alone hybrid Photovoltaic-Wind-Storage system which could guarantee a proper state of stability in the power system and a minimum cost of energy system installation applied in rural areas to supply the different types of electrical loads. Three case studies were compared. The first was a hybrid PV/Wind system (case 1); the second was a system with only a Photovoltaic system (case 2); and the third was a wind system (case 3). Results showed that the hybrid system was cost-optimized and met the requirements for the probability of power loss. Moreover, it was recommended for the presence of two power sources and, thus, higher reliability. Another study, conducted by (Parreño-Rodriguez *et al.,* 2023) showed that the implementation of the energy community as a citizen initiative, with a shared self-consumption solar power system, led to significant savings in the electricity bills. An energy community in Getafe (Spain) was analysed to reduce the energy poverty of its participants. The energy community was designed and implemented as a collective PV solar self-consumption infrastructure. Several nearby public buildings were provided with photovoltaic systems (PV) on their roofs and then compared to buildings with fixed price rate without PV installation for domestic consumption. The results showed that the bill price of vulnerable households with a PV system was reduced by €15.69/month for two-person households and €16.40/month for four-person households, respectively.
Hybrid PV and wind systems can help generate electricity to power facilities in rural communities where there is no stable power grid. Another solution could be microgrids, which could also power agricultural facilities for year-round food production. (Zeyad *et al.,* 2023) presented a feasible community microgrid design in Dhaka (Bangladesh) of a photovoltaic

installation on the rooftop of a local community building with the lowest COE and a large renewable fraction using HOMER Pro software. A PV-microgrid was chosen to assess analysis of the system cost as shown in Table 3. Fossil fuel consumption was reduced, and the electricity supplied had a 52 % reduced tariff compared to Bangladesh's current electricity tariff, with a renewable fraction of 70 %. The project met the demand of the analysed area with a connected load of 1367.76 kWh/day and a peak load of 380.35 kW. Figure 6 shows the comparison of energy sold and purchase of the different case studies.

Farthing *et al.* (2023) estimated the end-use electricity demand for a range of agricultural productive uses of energy (PUE) in Sub-Saharan Africa to design a microgrid. Two case studies in Kenya and Zambia designed a microgrid incorporated with agricultural PUE to determine the cost and system sizing. The agricultural PUE were the following: irrigation, refrigeration, egg incubation, hammer milling, shelling, hulling, and oil pressing. The hourly electricity generation of a PV system of a given size to supply the microgrid for PUE was also estimated. The agricultural PUE demand was estimated for the above-mentioned activities and was 16.8 TWh/yr. Three scenarios were considered for each country. This analysis showed how the potential of PUE in the site-specific agricultural sector could affect the cost and sizing of microgrids that otherwise serve the load of local homes and communities. Hybrid microgrids in Kenya and Zambia showed an estimated median levelized cost of energy (LCOE) of the potentials of about \$0.80/kWh in Kenya and \$1.20/kWh in Zambia. These tariffs may not lead to high household adoption unless costs for these end users are reduced through innovative business models, policy alignment, and cross-subsidies from PUE end users. Serving a portion of total agricultural PUE demand, avoiding any further increase in demand, could reduce energy costs by 2-4% compared to serving only community load, and would require 15-20% larger solar and storage systems.

Another study presented a simulation of an urban centric greenhouse-retail complex and explored optimal building design parameters, integrating renewable energy technologies and exploring energy sharing strategies within both buildings of the complex. It was assumed that the complex had a bidirectional electricity meter to import electricity when renewable energy systems could not meet demand and to export power to the grid when excess generation occurred. The photovoltaic system was sized on Energy Plus. The results showed that a net reduction of 27 % of energy in the greenhouse-restaurant complex was achieved compared to a design that met the minimum requirements of the applicable energy codes. It was also possible to meet 21 % of the space heating and ventilation needs of the greenhouse by sharing waste heat recovered from the compressor racks of the retail refrigeration. It was found that sharing energy could lead to a reduction in the dependence on distribution networks and to the availability of a local source of food growth (Syed and Hachem, 2019). In Canary Islands, a research was conducted to establish how agrivoltaic could be relevant in terms of energy production at regional scale. Thus, a methodology was identified to detect greenhouses with cartographic information systems, and establish how many areas could be covered by solar photovoltaic panels without a reduction of crop yield. To that purpose, the optimal photovoltaic cover ratio for different types of crops was estimated, and the photovoltaic power and production were appraised. Results in this study found that energy production is high and is affected by the transmittance values. Installable PV power doubles when there are variations in the transmittance values (from 0.8 to 0.9), and so does the energy production. With a transmittance of 0.8 (τG: 0.8), the total power reaches about 1607 MW; while, with a 0.9 transmittance, it achieves 2940 MW of power produced. The annual energy production ranges from 2480 GWh/a (τG: 0.8) to 4497 GWh/a (τG: 0.9). At the regional level, the hourly photovoltaic production demonstrates that, using greenhouses with transmittance values (τG) of 0.7, all the PV production can be fed into the grid; while, with a lack of storage energy system, using transmittance values (τG) of 0.8, the PV production that can be fed into the grid can cover around 27% of the electricity demand; and, if the transmittance values (τG) are higher than 0.9, the PV production can cover around 41 % of the electricity demand, feeding into the grid (Schallenberg-Rodriguez*, et al.* 2023) . Temiz *et al.,* (2022) investigated an agrivoltaics system on a surgacane field whose leaves and tops were used to produce electricity alongside with the cow manure in a combined cycle, to fill the cooling and heating load for a community by using energy thermodynamic analysis. Bifacial PV modules were used that were more advantageous due to their transparency and each one had a 540 Wp of power. AV plant capacity was determined as 8 MWp, where 37 888 m^2 module area was needed. The outcomes have shown that the overall energy efficiency was 33.64% and the APV plant at 8 MWp capacity produced 143 694.3 MWh electricity in a year. The LCOE of PV system have one of the cheapest electricity among other electricity production options in 2022 because of the contribution of bifacial PV modules.

Discussion and Conclusions

Worldwide, governments are trying to raise awareness and encourage people to use less electricity offering benefits and implementing renewable energy solutions (Ali *et al.,* 2022). Policies and strategies have been introduced by the European Union to raise awareness of sustainable attitudes (Cossu *et al.,* 2010) All these studies can help implement the use of renewable energy in order to have energy savings, to be able to improve the quality of life of rural communities through more stable and reliable electricity supply, and to be able to produce energy for agricultural uses.

The European transition to renewable energy to achieve climate neutrality and make energy more affordable has increased in recent years. In 2022, approximately 11.8% of Europeans were still energy poor. Energy poverty has not shown a significant decrease, despite being linked to renewable energy sources and income. A study was carried out to investigate the impact of electricity and governance quality on energy poverty, using panel data from 27 EU countries from 2005 to 2018. Regulations and policies can influence the transition to green energy, so researchers identified a number of indicators to represent effective governance systems, including stability, socio-economics, corruption, law and order, efficiency of the bureaucracy, military in politics, *etc*. Thus, renewable energies, such as wind and solar can provide access to electricity in those developing countries and impoverished rural areas where electrification is poor. For RE projects, governments provide subsidies and incentives to power companies and these efforts are supported through policies, such as renewable portfolio standards and feed-in tariffs. Findings showed that, in the early transition stage, RE does not reduce energy poverty; on the contrary, it promotes a hike in energy prices. If RE lasts over time and permeates the system becoming a dominant energy supply source, it will help to reduce energy poverty, alongside the quality of governance (Muhammad *et al*., 2023). Campana *et al*. (2024) carried out an economic analysis to compare the profitability of an APV system versus a conventional ground mounted PV using a Monte Carlo Analysis in Sweden. The APV was designed with 60 bifacial PV modules, each one with a capacity of 22.8 kWp. The outcomes have shown that the LER was 1.27 in 2021 and 1.39 in 2022 respectively and the APV system had a lower NPV than the reference ground mounted PV system, (i.e., 46.2 k€ for the system combined with permanent ley grass compared to 107 k€, respectively). The NPV has shown to be 30 times more profitable than a conventional PV system. Agostini *et al.* (2021) carried out an environmental (LCA) and economic analysis of a new APV system, Agrivoltaico®, with tensile structure compared to ground-mounted or roof PV systems (reference). The GHG emission have show be similiar to those of reference (20 g CO2wq MJ-1 for APV system and 22.6 and 22.3 g CO_2eq MJ− 1 for ground monunted and roof PV system, respectively). Ground mounted systems were about 33% cheaper than Agrovoltaico systems and the cost for roof PV system were further reduced because there were no need of support structures. The LCOE of Agrovoltaico was similiar to those of ground mounted and roof PV systems thanks also to the materials used by mounting PV panels on tensile structures.

This review provides an overview of integrated technologies in the agri-voltaic sector for sustainable energy use and production. The origin of the discussed topic stems from two main questions: 1) What technologies for energy production are compatible with the agricultural sector? 2) How can these be integrated to simultaneously meet energy and food demand without the increased pressure on natural resource use?

The European Green Deal is a package of measures whose objectives include: ensuring food security, avoiding biodiversity loss, reducing the environmental impact of energy and food systems, and driving the global transition to farm to fork in a sustainable way. The agri-voltaic sector makes it possible to achieve the goals of the European Green Deal by enhancing the resilience of food and energy systems in the face of geopolitical uncertainties. The EGD promotes the farm to fork strategy to meet the global demand for food security through the use of renewable energy resources in order to decrease the carbon footprint while producing clean energy and safe food. In this sense, agricultural energy systems contribute to the global demand for electricity by enabling its production without limiting agricultural production, food security and the biodiversity of the natural environment, and overcoming the existing land use conflict for each. In agriculture, electricity production is mostly done by means of solar power plants consisting of photovoltaic panels. In fact, in 2020, installations reached a capacity of 2.8 GW worldwide. Many studies have been focused on the search of solutions to increase the capacity of energy production, such as the influence of the variation of the distance between the support columns of photovoltaic panels; the integration of different sources of renewable energy (the photovoltaic and wind); the study and comparison between different types of photovoltaic panels on the market for the realization of more efficient agrivoltaic systems. Among the various types of photovoltaic panels, those with high efficiency in converting solar energy into electricity are monocrystalline and polycrystalline silicon opaque panels, with efficiency ranging from 15 to 23 % but a higher cost compared to all the others. Several studies on photovoltaic greenhouses, however, have shown that semi-transparent panels increase both crop yields, because they let through more solar energy for photosynthesis, and economic and energy performance. This important feature makes them particularly efficient in agrivoltaics although further studies on improving conversion efficiency are needed. With this in mind, many multinational companies have begun to apply this technology to solar farms to power distribution networks (power grids). An important limitation of power grids powered by renewable energy is that of discontinuous distribution of electricity due to varying weather conditions. In the study of Gonocruz, Uchiyama and Yoshida (2022), in order to limit such electrical discontinuity, the integration of large-scale energy storage systems into electric transmission lines in some rural areas of Japan was proposed and evaluated. The study demonstrated the reliability of such a solution to prevent blackout situations. Though being efficient, this solution proves to be particularly costly; specific economic aid and financing policies would be necessary for its deployment. The application of hybrid systems, such as the integration of photovoltaics with wind power, also makes it possible to limit the variability from the variation in the intensity of solar irradiation by allowing it to supply electricity even to areas where there is no easy access to it. In the study by Farthing *et al*. (2023), microgrids (small-scale electrical distribution networks) were useful for powering rural communities and the energy loads of their agricultural facilities. The study proposed a PV-microgrid for various agricultural production uses, such as irrigation, refrigeration, egg incubation, hammer milling, shelling, hulling, and oil pressing. The analysis showed that integrated microgrid use with PUE in the site-specific agricultural sector did not particularly affect the community's energy cost. Future research could be focused on the development of integrated power distribution with power grids and microgrids, energetically interconnecting rural communities to large urban basins. Rural areas could then harness renewable energy to meet the energy loads of agricultural facilities, including greenhouses in such a way that they could become energy self-sufficient, growing plants for the production and use of local food resources and ensuring clean yet continuous power generation. Furthermore, they would have a way to integrate into society both economically and energetically, in line with international and European sustainability policies, as well as to ensure food security.

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Figure 1. CAP's objectives (European Commission, 2020a).

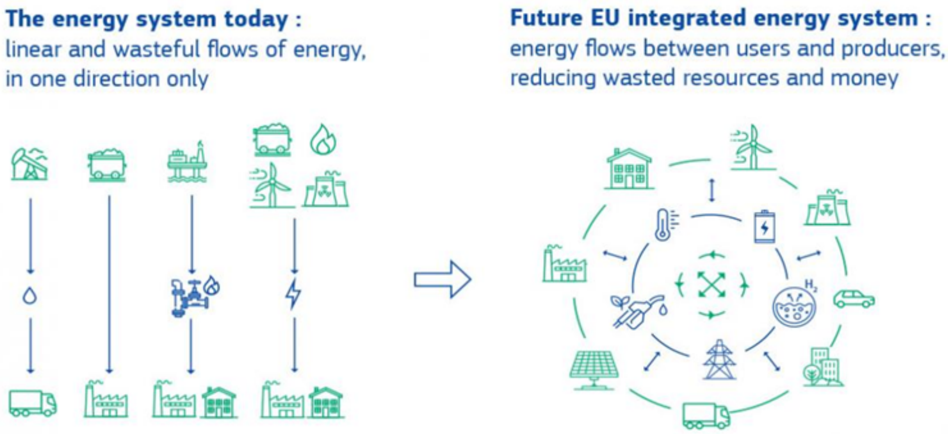

Figure 2. EU integrated sectors (European Commission, 2020b).

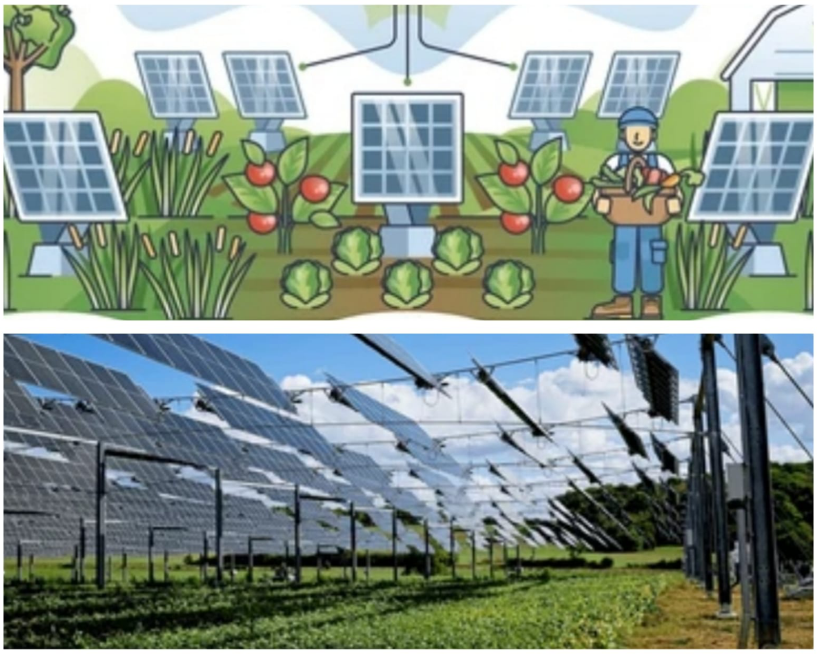

Figure 3. Typical agrivoltaic system.

Figure 4. Different PV modules, on the left non selective PV modules, in top right UV-NIR selective cells, and below opaque PV**.**

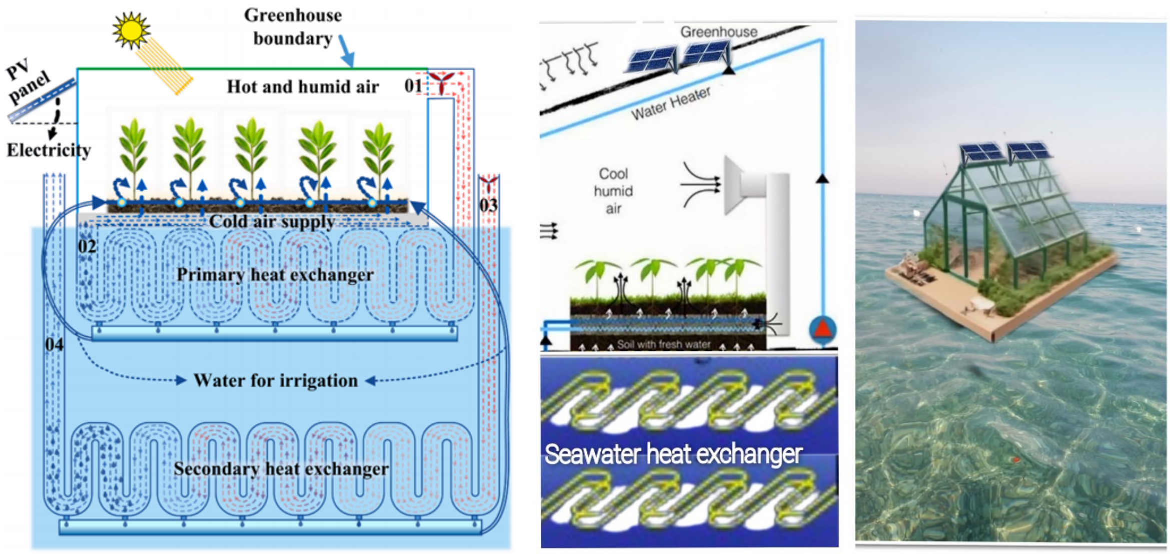

Figure 5. Left: floating systems proposed by Luqman et al. (Energ. Convers. Manage. 2023;277:116577; with permission). Right: representative floating system.

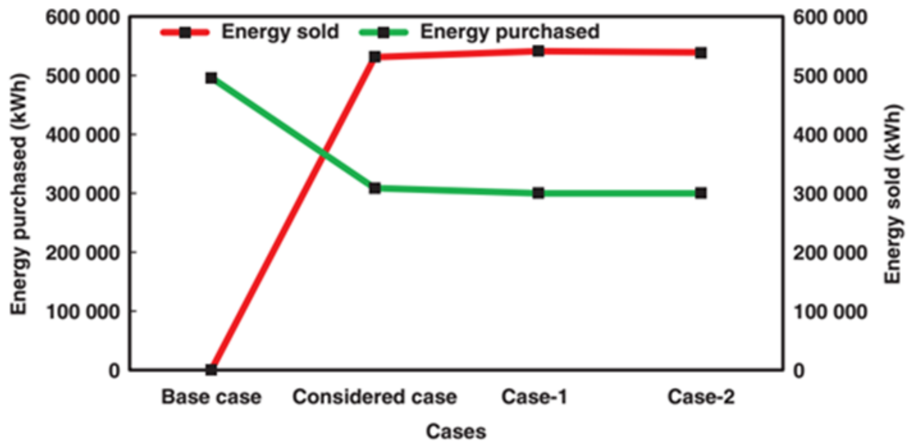

Figure 6. Chart of the energy sold and purchased for the case studies taken from Zeyad et al. (Clean Energy 2023;7:926-939; with permission).

Table 1. Total energy gathered in one year from PV panel, from greenhouse system and from the grid (reproduced from Al-Naemi S, Al-Otoom A. Results Engin. 2023;17:100889; with permission).

	Available energyfrom PV kWh	Energy used in theSSGHCM kWh	Energy drawn from the Grid kWh
January	**680**	**51**	**0**
February	**634**	**51**	**0**
March	**688**	**66**	**0**
April	**643**	**131**	**0**
May	**676**	**219**	**0**
June	**662**	**249**	**15**
July	**652**	**268**	**24**
August	**684**	**257**	**24**
September	**727**	**220**	**8**
October	**771**	**179**	**0**
November	**649**	**96**	**0**
December	**872**	**51**	**0**
Yearly total	**8138**	**612**	**69**

Table 2. Economic breakdown of the system by Luqman et al. (Energ. Convers. Manage. 2023;277:116577; with permission).

Component	Value	Unit cost	Economic cost ($)
Greenhouse construction	150 m^2	$ 25 m^{-2}	$ 3750
Labour	150 m^2	$ 20 m^{-2}	$ 3000
Fertilizer	135 m^2	$ 3.21 m^{-2}	$ 434
Floating platform	180 m^2	$ 376 m^{-2}	$ 67813.2
Mooring chain	50 m	$ 279.39 m^{-1}	$ 13969.5
Mooring wire	500 m	$ 51.75 m^{-1}	$ 25.875
Heat exchangers cost	8.94 m^2	$ 276.$(A_{HX})^{0.88}$	$ 1985.40
PV module	1000 W	$ 1,94 W^-	$ 1940
Battery	24 V, 220	$ 2.2 Ah^-	$ 484
Battery after 5 years			$ 420
Battery after 10 years			$ 463
Battery after 15 years			$ 487
Inverter		$ 0.31 W^-	$ 310
Controller		$ 3.5 A^-	$ 146
Installation		10% of PV cost	$ 194
Maintenance		2% of PV cost	$ 39

Table 3. Cases studies taken from Zeyad et al. (Clean Energy 2023;7:926-939; with permission).

Average values	Configuration
Grid	Base case
PV-grid	Considered case
PV-wind-grid	Case-1
PV-wind-grid-BESS	Case-2