

Combinations of Solar Concentrators with Agricultural Plants

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Abstract: A new trend involving the combination of solar concentrators and agricultural plants on the same piece of land offers the possibility of realizing both electricity generation and a good crop harvest. Authors analyze this situation for different countries, including Mexico, and based on authors' experience regarding the development of new solar concentrator prototypes, authors' primary objective was to describe the development of compact, light, and inexpensive solar concentrator prototypes that can be collocated on horizontal roofs. Authors' second objective was to investigate the combination of such solar concentrator prototypes with agricultural plants on the same field. Thus, several studies related to the combination of renewable energy generation and agricultural crops were reviewed. Many such systems involving the combination of PV (Photovoltaic) panels with different types of vegetables exist in the USA, France (lettuce production), Japan (tomato production), India (aloe and corn), northern Italy (maize), Spain and México.

Key words: Solar concentrator, agricultural plant, flat triangular mirror.

1. Introduction

Studies that explored the possibility of installing solar infrastructure in combination with agricultural infrastructure were reviewed. LCA (Life Cycle Assessment) in these studies showed that such systems are economically viable in some rural areas and can provide opportunities for rural electrification, while stimulating economic growth [1-5].

Globally, energy demand is increasing rapidly, and the use of green energy for irrigation, domestic purposes, etc., is also on the rise.

Most proposed solar installations consist of large PV (Photovoltaic) systems [2]. The construction and operation of such systems in deserts can add additional disturbance to desert soils and increase dust emissions. One possibility that is being evaluated in the United States is the installation of solar infrastructure alongside vegetation (agricultural crops), which provides additional benefits, including a double

income source for farmers, employment opportunities in crop management solar facilities, rural electrification, and the availability of electricity for the local processing of agricultural products.

Most solar installations are located in arid and semi-arid regions, which are characterized by low rainfall and poor soils that make them unsuitable for most crops. However, there is growing interest in the cultivation of high-value xerophytic plants, including Agave, Aloe and Opuntia, which in arid and semi-arid regions, can be cultivated without competition for soil and water resources. Aloe and succulent evergreen xerophytic plants, which are ecologically and physiologically adapted to arid and semi-arid lands, have the potential for cultivation alongside solar infrastructure installations. Aloes, which include more than 300 species, have been used for economic and medicinal purposes for centuries [2], and their cultivation alongside solar installations could maximize the efficiency of water use in arid areas by using water meant for panel cleaning for irrigation as well, thereby minimizing dust generation given that increasing soil moisture minimizes impacts on soils

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through the deployment of crops. This stimulates economic returns, which improve life in rural areas.

2. Examples of PV Solar Systems

LCA is a commonly used tool that can be employed to explore the economic feasibility and environmental impacts of new technologies. In this previous study, the analysis was based on a detailed assessment of the life cycle of a PV solar system [2] and an aloe gel production system, which are two emerging technologies in northwestern India.

2.1 LCA of the Aloe Gel Production System

The data needed for the LCA of the aloe culture and gel processing system were obtained from existing literature and from field observations of aloe farms and gel processing facilities in northwestern India. The stages of the aloe gel production life cycle included: aloe cultivation, aloe leaf harvesting and transportation, and aloe gel production. In this scheme, aloe leaves were periodically harvested and processed to obtain aloe gel, and the greenhouse gas emissions resulting from direct energy consumption, material supply, as well as machinery and building use were considered.

2.2 LCA of PV Solar Panel System

It is considered a PV solar installation. The PV solar installation was located in a desert environment that is characteristic of northwestern India, where the annual rainfall and solar insolation are 300 mm and 2,000 kWh/m²/year, respectively. The LCA stages considered in Ref. [2] are the manufacture of PV modules and the balance of system components, the construction and operation of the system, as well as dismantling and recycling, assuming a life cycle of 30 years.

2.3 Integrated Solar-Aloe Energy Systems

Based on the LCA of the autonomous PV solar system and aloe cultivation, the possibility of integrating these two emerging land use systems in

northwestern India was investigated to identify the synergies and compensations of the installation.

2.4 Sensitivity and Uncertainty Analysis

A sensitivity analysis of the PV solar installation in combination with aloe cultivation was performed, taking base parameters into consideration. A range of uncertainties (minimum to maximum) were identified for each parameter, and the effect of changing each parameter on energy input/output and greenhouse gas emissions/offsets was investigated. Module efficiency, irradiation, performance ratio, and the number of PV modules as well as the general conversion rate of aloe leaves to gel and the number of plants in the gel production system, were used as the input parameters.

2.5 Economic Analysis

An economic assessment was performed to compare returns based on single land use with those based on combined land use, for both networked and off-grid cases. During the assessment, five project designs or land use scenarios were considered, and each of them was used to assess the economic performance of a 5 ha plot in Rajasthan. The land use scenarios considered included: (a) aloe only, (b) PV only, (c) PV only connected to the network, (d) combined, and (e) combined connected to the network.

During the economic assessment, it was assumed that the land was owned by an individual, rather than a business; thus, it was not necessary to capture tax-related incentive cash benefits, such as accelerated depreciation.

2.6 Assumptions regarding PV Solar Energy

The system design specifications were developed using HOMER, which is a cost optimization tool (model) that was used to optimize the system design such that the PV capacity of the system was kept constant for all scenarios, thus providing a basis for meaningful comparisons. The results obtained took into account the capital costs of the PV technologies,

batteries, and inverters. It also considered a diesel generator to ensure consistent production, total production costs, and annualized values for replacement costs as well as operation and maintenance costs.

The results of the economic assessment showed that for network-linked cases, the owner received more benefits when the combined land use scenario was employed given that there was no decrease in PV capacity when aloe was grown in the same area, considering the space restrictions between the installed PV panels. The sensitivity analysis revealed that changes in input parameters, including module efficiency and number of PV modules as well as the general efficiency of sugar utilization and the number of aloe plants, significantly affected the total energy output as well as gel production. During the analysis, it was observed that the synergy between the PV system and aloe cultivation resulted from the fact that the water inflows needed to clean the solar panels were similar to that required for annual aloe production, suggesting the possibility of integrating the two systems on the same plot of land to maximize the efficiency of land and water use. The LCA showed that in some cases, the installed systems were economically viable, and could provide opportunities for rural electrification, while stimulating economic growth. The LCA of a hypothetical system in northwestern India indicated greater economic returns per m³ of water used than any of the other systems, an important finding to consider in arid areas.

Installed systems can provide several collateral benefits. In rural areas that are not connected to an electricity grid, the integration of aloe cultivation with independent solar infrastructures can potentially stimulate economic growth by facilitating rural electrification and creating stable employment opportunities for agricultural workers [2]. The integration of the solar infrastructure and aloe cultivation could:

(a) Ensure efficient land and water use by maintaining agricultural production on marginal lands

and maximizing energy production from PV solar installations.

(b) Increase the area of high-value crop-cultivated land, and thereby minimize the socio-economic and environmental problems associated with high-value non-food crop cultivation (e.g., aloe) on first-level agricultural land.

(c) Stimulate rural economies by creating employment and providing opportunities for rural electrification.

(d) Improve regional air quality by reducing soil erosion and dust emissions from large PV solar infrastructures.

In another study [3], the objective was to examine the performance of agrivoltaic systems, which produce crops and electricity simultaneously based on the installation of stilt-mounted PV panels on farmlands (Fig. 1).

As the number of PV plants continues to increase, land occupation for solar farms has intensified the competition for land resources for the purpose of food and clean energy production [4]. Although PV systems require less land than other renewable energy options [5], in reality, commercial PV power plants can occupy considerable amounts of land at the local scale.

However, this competition could be reduced via the application of agrivoltaic systems, which produce crops and electricity simultaneously by installing compact solar panels on farmlands. Even though previous studies have indicated that such systems can effectively produce electricity and shade-tolerant crops simultaneously [6], more studies are required to evaluate its practical applications. Particularly, the performance of shade-intolerant crops, which are expected to grow poorly in low-light settings, has not yet been fully explored for agrivoltaic systems.

To date, three agrivoltaic system types, which allow the simultaneous production of crops and the generation of electricity on farmlands have been proposed. The first type, which uses the space between PV rows for

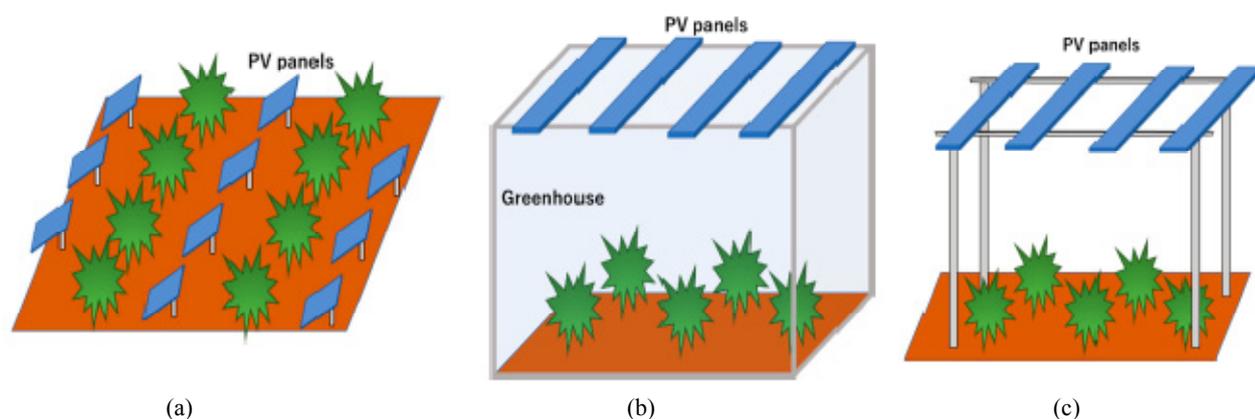


Fig. 1 Three different agrivoltaic system types: (a) using the space between PV panels for crops, (b) a PV greenhouse, and (c) a stilt-mounted system [3].

crop cultivation, was proposed in the early 1980s [7], and the second type, a PV greenhouse, consists of a transparent cover, part of which have been replaced by PV modules. The use of PV energy in greenhouses is a promising solution to the competition for land resources between food and energy production, given that it allows the continuous production of food and the generation of electricity throughout the year [8]. The third type consists of PV modules mounted on poles above the crops, i.e., stilt-mounted agrivoltaic systems, which were originally invented in 2005 [9]. The structure consists of pipes and rows of PV panels mounted on the ground, and arranged at certain intervals to allow enough sunlight for photosynthesis to reach the ground. The system is designed to ensure the adequate supply of sunlight for crops and enough space for agricultural machinery. Furthermore, the structure does not have a concrete base; thus, it can be easily disassembled.

The first reported agrivoltaic farm experiment, which involved the cultivation of lettuce in a system consisting of PV modules mounted on 0.80-m wide stilts, was conducted in Montpellier, France in 2013 [6], i.e., the same piece of land was used to successfully produce both electricity and food. The results showed that the shading created by the PV matrices did not have a significant effect on lettuce yield, i.e., there was no decrease in the growth rate of

the crops under the PV panels, except during the juvenile phase of cultivation.

Interestingly, field experiments by Dupraz, et al. [10] revealed that agrivoltaic systems could even result in a 35%-72% increase in soil productivity for durum wheat [10]. They used equivalent land proportions to compare conventional options (agriculture only and energy harvesting only) with two agrivoltaic systems with different PV panel densities. The study only showed that the agrivoltaics were effective for shade-tolerant plants [11]. However, it is important to study the possibility of coupling PV systems with shade-intolerant crops. Additionally, it is also important to investigate whether an overall increase in land productivity can be achieved even with crops that need a lot of sunlight.

The size of the experimental farm, which contained three sub-configurations, including no modules (control), low module-density, and high module-density, was 100 m² [3]. The PV solar modules were mounted on the ground, and the area under the stilts, which was large enough to accommodate agricultural equipment, was used for agriculture, and the total output capacity of the PV system was 4.5 kW.

This system consisted of 72 PV modules (1,354 mm × 345 mm) mounted at a height of 2.7 m, and inclined at an angle of 30°. Regarding the high-density configuration, there were eight sets of PV modules (48

modules) installed at 0.71-m intervals, and in the low-density configuration, there were four sets of PV modules (24 modules) installed at 1.67-m intervals. Both stilt-mounted PV panel configurations cast shade on the crops.

In this study, sweet corn, which is a typical shade-intolerant crop and a major global product that has a growth period of 90 days and grows to a height of 2 m, was planted on the experimental farm in early April, 2018, and harvested in late July. In each configuration, there were nine stems within 1-m² areas separated by 0.5-m spaces. The sensitivity of the corn yield per square meter with respect to changes in shading level was investigated, and if the biomass of the corn plants grown on an agrivoltaic farm was greater than 90% of separately grown corn plants, the corn could be said to grow well under the shade of agrivoltaic PV panels.

This study showed that it is possible to grow corn, which is a typical shade-intolerant crop, under the shade of agrivoltaic PV panels. The biomass of the ear of corn grown under shades of PV modules installed at 0.71-m intervals was not less than 96.9% of corn cultivated without the PV modules. Additionally, the biomass of the cob of the corn grown under the PV modules installed at 1.67-m intervals was even 4.9% higher than that of corn cultivated without the PV modules. Actually, the corn yield per square meter of the low-density configuration was 3.54 kg, which is not only higher than that of the high-density configuration, but also 5.6% higher than that of the corn cultivated on the piece of land that served as the control configuration, i.e., without PV modules.

This study also revealed that the annual income from PV power generation and corn cultivation on an agricultural farm could be higher than that based on a traditional corn field. Actually, the total income resulting from the high-density configuration was 8.3-fold greater than that resulting from the control configuration, while that of the low-density configuration was 4.7-fold greater than that of the

control configuration. Although existing studies have reported that agrivoltaics work well only for shade-tolerant crops, the results of this study showed that growing corn, which is a typical shade-intolerant crop in the shade of agrivoltaic PV panels, is a possibility. This study also showed that an increase in overall land productivity could be achieved even with crops that require a lot of sunlight, indicating that stilt-mounted agrivoltaic systems can be applied to a wider range of commercially important crops. Thus, the practical availability of stilt-mounted agrivoltaic systems is very promising; however, they are associated with several disadvantages. Like traditional PV power generation, agrivoltaics cannot reliably generate constant power, and the system cannot function properly when sunlight is unavailable, particularly at night or on cloudy days.

Other examples of agrivoltaic systems have been analyzed [12]. The PV panels were mounted on the ground, between the crops as a partial replacement of the greenhouse or placed under or on top of the greenhouse cover film. Such strategies can provide solutions regarding land use competition as well as climate change mitigation. These systems had certain additional functions, namely, sunlight and land sharing, as well as energy generation, compared with conventional agricultural production systems. During agricultural LCA, these new functions are not adequately exhibited by traditionally used FUs (Functional Units), such as mass or area based FUs.

The objective of this study was to propose two new agrivoltaic system FUs, one based on the modified area, and another that is a monetary FU. As a case study, new and traditional FUs (i.e., mass- and area-based FUs) were applied to a tomato greenhouse in Japan, with and without OPV (Organic Photovoltaic) panels.

The LCA was performed such that the unique functions of the agricultural system were addressed, and particular attention was paid to the FU choice, which in turn, was related to the notification of the LCA results. The FU was defined based on the

objective of the study. It normalized the environmental impacts and allowed the comparison of the environmental impacts of different systems. In most agricultural strokes, mass, energy, protein content, area or livestock unit were considered as FU [13].

The LCA was performed in compliance with the guidelines of the ISO (International Organization for Standardization) 14040 and 14044 and the methodological guidelines for PV LCA [14]. The objective was to compare the LC-CO₂ emissions of an agrivoltaic system with that of a conventional system with respect to tomato production. Agrivoltaic systems did not require additional land for power generation given that the PV modules were mounted on the ground between the crops, replacing a section of the greenhouse or placed under or above the greenhouse cover film as a two-floor building.

This FU was obtained by adding the area covered by the PV modules and that covered by the crops. In this study, the area covered by the OPV modules was 66 m², while the cultivated area was 162 m²; thus, the areas covered by the agrivoltaic system and the conventional system were 228 (66 + 162) m² and 162 m², respectively.

The monetary FU was derived by adding crop prices to the financial value of the generated energy. The price of the crops was obtained from the 10-year average of its wholesale price, and the monetary value of the generated energy was derived based on the price of electricity. Additionally, it was assumed that the energy generated using the OPV module was used by the farmer in the field.

Inventory data for tomato production was obtained from the experimental greenhouse at Kyoto University. In both the agrivoltaic and conventional systems, the tomatoes were harvested twice, leaving the land fallow after the harvest. Planting was started in July 2016 or March 2017, and the transplant was completed in September 2016 or May 2017, respectively. Thereafter, harvesting began from mid-October to late February for the fall-winter growing period, and from late June

to early August for the spring-summer growing period. A sensitivity analysis was then performed to assess the effect of the choice of the OPV-related stroke on the stroke outcomes.

Electricity consumption for heating in the agrivoltaic system was less than (30 kWh) that of the conventional system. However, the agrivoltaic system showed a 9% decrease in tomato yield (i.e., 1,513 and 1,669 kg for the agrivoltaic and conventional systems, respectively).

Total LC-CO₂ emissions in the agrivoltaic system were lower compared with the conventional system for both area-based and traditional FUs, and this could be attributed to the reduced LC-CO₂ emissions owing to energy generation. Similar results were obtained using the proposed new FUs.

In the agrivoltaic system, the area-based FU was used to reflect the role of the agricultural production systems as producers of non-commercial goods [15] and shared solar energy given that the same sunlight was shared between crop cultivation and energy generation on the same land. To address the land-sharing function, an FU based on the modified area that could be used to express efficiency with respect to the reduction of the environmental load compared with the conventional system, was proposed. The monetary FU addressed the role of the agrivoltaic systems as a means of producing market goods (i.e., crops and electricity). The mass-based FU focused only on crop production; however, the monetary FU represented market goods that are valued differently.

An agrivoltaic system is one in which energy generation using PV modules and crop production is performed on the same piece of land. In such a system, certain functions, including sunlight and land sharing, as well as energy generation exist in addition to the conventional functions of agricultural production systems. To address the unique functions of the agrivoltaic system, two new FUs were proposed in this study: a modified area-based FU and a money-based FU. These new FUs were intended to enhance understanding

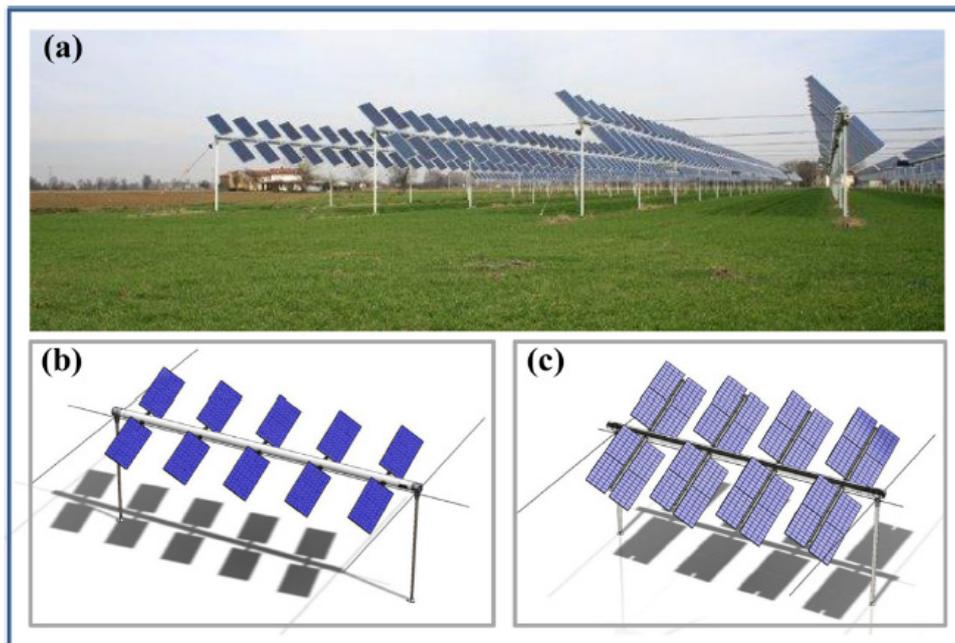


Fig. 2 View of an agrivoltaic® plant. Reprinted from [16] with permission from Elsevier.

regarding the environmental impacts of the system. Particularly, combinations of various FUs can help maintain focus on crop production as the primary function of agricultural land [12].

To avoid soil consumption, landscape impact, and competition with food production, the installation of the soil-mounted PV in agricultural land has been restricted by governments and local authorities (Fig. 2) [16].

It has been proposed that the advantages of agrivoltaic systems could be related to their similarity with agroforestry systems [17]. PV panels protect crops from excessive heat and provide mitigation against high soil temperatures, possibly implying that agrivoltaic systems are more resistant to climate change than monoculture systems [17].

Majudmar and Pasqualetti [18] proposed the implementation of agrivoltaic systems as a sustainable strategy to generate carbon-free electricity in peri-urban areas, while preserving agricultural land by providing boundaries for urban growth and increasing the value of land as well as farmers benefits.

Agrivoltaic systems built on suspended structures (stilts) can also be used as solar tracking systems. On

stilts, the mounted horizontal axis serves as the main axis on which the secondary axes that supports the solar panels is mounted. Powered by interconnected electric motors through an innovative wireless communication and control system, the two axes can be rotated.

To simulate the growth and production of crops grown under the shade of an agrivoltaic system, a software platform, within which a radiation and shading model are coupled to a generic crop growth simulator, was developed. The platform was designed to maintain and manage large sets of climate data and different environmental conditions using a free software relational database.

The model could be used to calculate direct and diffuse radiation at ground level with a time step, $t_s = 0.5$ h and a spatial resolution of 0.12 m. These parameters were chosen to achieve the best compromise between computing time and resolution in time and space. In this study, the mathematical model, which has already been discussed in detail in a previous study [16] is not described. Additionally, the estimation of electrical energy and the equivalent ground ratio are presented.

The electricity production using the PV panels was calculated for all the simulations (4 scenarios within a 39-year period) during the crop cultivation period (April-September), using the same meteorological database that was employed during the simulation of crop growth, but with a time step of 1 h. Electricity production was calculated per m² of the PV panel; however, it was thereafter converted to and presented in per m² of cultivated soil using the ratio of the number of PV panels to the cultivated area. Dupraz [17] proposed to use the LER (Land Equivalent Ratio), which was developed as an indicator of land productivity in agrivoltaic systems, to estimate land productivity under crop mixing conditions. In the study, the LER was used to compare agrivoltaic scenarios with the monoculture of corn obtained in full light.

With the crop model, it was possible to predict biomass and crop yield under the influence of climatic factors (radiation, temperature, wind speed, and partial vapor pressure) as well as the amount of water and soil nitrogen available. The model represented the responses of the individual physiological processes of the crops to environmental variables. Thus, it incorporated mechanisms that drive crop dynamics, and generated emergent feedback characteristics.

The simulation study was divided into three main steps as follows:

(1) The calculation of shading and radiation at a resolution of 0.12 m for the agrivoltaic scenarios. The scenarios involved different panel management schemes, e.g., static management with the solar panel at a fixed-tilt angle of 30° and a two-axe configuration, which differed in the number of panels mounted on the secondary axis. A shadowless full light simulation scenario was also included as a baseline scenario.

(2) The preparation of input files was characterized by a wider resolution range (0.12 to 0.48 m) alongside the calculation of the average radiation value obtained from 16 high-resolution pixels. To simulate the entire area within a reasonable calculation time, without significantly affecting the results, the model was run

at a lower resolution.

(3) The model was run taking into consideration the study area (144 m² or 625 pixels). Steps 1, 2 and 3 were then repeated over the 39-year period.

The crop cycle was divided into the three main development phases: the lag phase (i.e., the period between emergence and the start of exponential growth); the crop establishment phase (i.e., the period between exponential growth and the formation of grains) and the crop maturity phase (the period between grain filling and crop senescence).

The simulation of an agrivoltaic culture system requires a culture model that is capable of capturing the multiple feedback processes triggered by a fluctuating radiation regime as well their consequences on the microclimate. Thus, the use of the proposed model was considered to be very appropriate. Actually, the coupling of photosynthesis and transpiration allowed a dynamic response to external stresses via the calculation of the energy balance. This feature was particularly relevant when simulating a culture grown in an agrivoltaic system because the temporal radiation patterns were simulated at a high time resolution.

In a previous study, an innovative platform was designed and implemented to run simulations aimed at optimizing agrivoltaic systems, in which electrical energy production is combined with arable crop production (northern Italy, Emilia Romagna Region, PC) [16]. A long-term simulation, in which the corn yield of an agrivoltaic system and that of an open field were compared, highlighted that although the yield of the agrivoltaic system was slightly lower when water was not the limiting parameter, it was higher under drought stress conditions. Furthermore, with respect to the cultivation of maize under rainy conditions, the average maize yield of the agrivoltaic system was higher and more stable than that obtained under full light conditions, indicating that agrivoltaic systems, which enhance crop yields, clean energy production, and water savings, can play an important role in the energy-food-water nexus.

3. Passive Solar Concentrator

Other examples of combinations of solar concentrators and irrigation systems in agricultural fields have been previously described [19].

In 1996, Paton and Davies [20] established the first greenhouse in Tenerife with a humidification and dehumidification system and they called it “the seawater greenhouse”. The results of their study showed that the system had a good water production performance, and basically could satisfy the growth requirements of the crops.

In their study, they proposed a fully passive solar energy still powered by a CPC-SS (Composite Parabolic Concentrator) that could be used for direct irrigation using seawater. Compared with other hubs, the CPC showed better optical performance, including a higher acceptance angle [21]. Thus, it has been extensively used in solar energy applications [22]. The device [19] combines CPC, seawater desalination, and agricultural seeding, so that fresh solar-energy desalinated water can be transported directly to plant roots. It avoids the large area required for traditional solar desalination systems and eliminates traditional

agricultural drip irrigation facilities, thereby greatly reducing costs.

The structure of this fully passive CPC-SS that can be employed for direct irrigation using seawater is shown in Fig. 3. It consists primarily of four subsystems, including a transparent cover, a concentrator system, a seawater channel, and a freshwater outlet pipe. Given its simple structure, it can be made from transparent plastic. Thus, it is low cost, and it is very suitable for use in agricultural engineering.

The advantage is that the entire system is completely passive and requires no power components. Additionally, it can be placed directly in seawater or brackish water to produce fresh water, which is then transported directly to the roots of soil plants, eliminating the traditional drip irrigation system.

Fig. 3 represents the experimental CPC-SS system that was used to supply the plants with water. Its operating principle can be explained as follows: after passing through a transparent cover plate placed obliquely on top, sunlight enters the CPC-SS and reaches its reflective surface, where it is reflected into

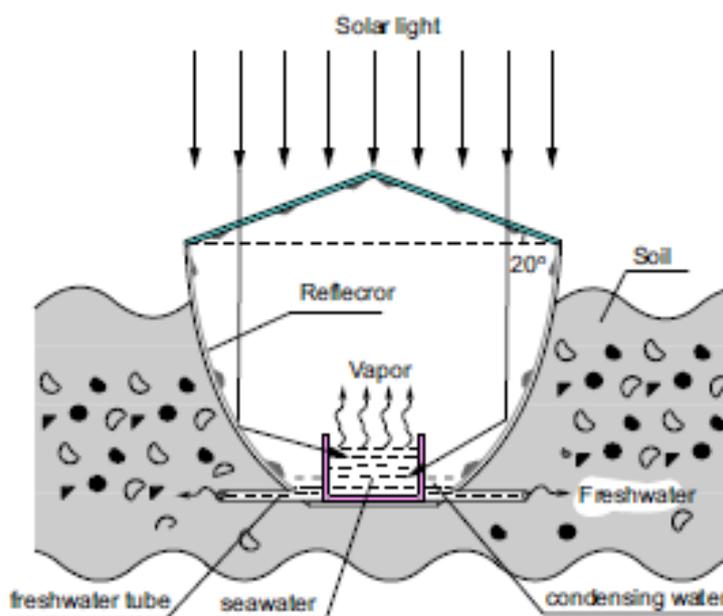


Fig. 3 Structure of experimental system [19]. Reprinted from [19] with permission from ASME.

the seawater channel and is absorbed by the black absorption layer within the channel. After the sunlight absorption, the temperature of the black absorption layer increases. Thus, the seawater in the channel is heated to evaporate, and given that water vapor is lighter than air, it rises until it finally reaches the transparent cover and exchanges heat with it. Moist air then releases moisture and condenses on the surface of the clear cover. The condensed fresh water then flows through the inner surface of the transparent cover and the reflective surface, and collects at the bottom of the CPC-SS. Finally, the water produced water is supplied to the soil at the root of the plants through the freshwater pipe [19].

The following assumptions were made during the simulation:

(1) The transparent top cover was assumed to show 100% transmission, i.e., it does not affect the concentration properties of the system.

(2) Given that the black absorbent layer of the seawater channel was placed on the inner surface of the groove, which was in contact with seawater, and that the material of the groove was transparent, the reflection was considered to be effective as long as light was reflected off the wall of the slot.

(3) The reflector had a reflectance of 100%.

(4) The total number of incident lightning strikes was 500.

Regarding the light path, when the angle of inclination of the solar rays ranged from 0° to 30° , the sun's rays could be focused effectively. The energy analysis included the energy of sunlight (Q_1) that enters the device, the energy to the transparent cover (Q_2), the heat loss resulting from the reflection on the ground surface and the surroundings (Q_3), the heat lost to the ground at the bottom of the device (Q_4), the heat lost by the seawater via evaporation and convection in the evaporation-condensation chamber (Q_5), and the heat lost to the ground through the fresh water (Q_6).

To test the performance of the system under real weather conditions, the freshwater production

performance and operating temperatures of the system were investigated, and on the experiment days, the curves of solar irradiance as a function of time were recorded. During the experiments, the device was placed in an east-west direction, and its performance was tested experimentally to determine its efficiency. The main conclusions arrived at after the experiments were as follows:

(1) The results of the optical simulation showed that the angle of reception of the device without tracking can reach approximately 35° .

(2) On sunny days, the fresh water production performance of the device was approximately 850 g/day, and in the seawater channel, the temperature of the seawater could exceed 60°C .

(3) The efficiency of the device was approximately 22%; however, it could be improved in future studies.

4. Our Solar Concentrator Prototype and Its Collocation

In authors' previous study [23], new solar concentrator prototypes, which have flat mirrors, were proposed. The idea was developed, and solar concentrator prototypes were fabricated as previously described [24-27].

The parabolic surface is approximated by triangle flat mirrors. The structure of one meter of diameter is constructed from bars and nodes from aluminum.

In 2019, authors published the book dedicated to the solar concentrators and intelligent automation of their production [28].

The structure of solar concentrator and method of its manufacture are patented in USA, Mexico and Spain [29-31].

The primary objective of the study was to describe the collocation of solar concentrators on horizontal roofs in Mexico, then with bean fields in Mexico and potato fields in Canada [32]. The type of solar concentrators that were employed has been previously described in detail [23-27]. In Fig. 4a, the design of one of the prototypes developed for this purpose is

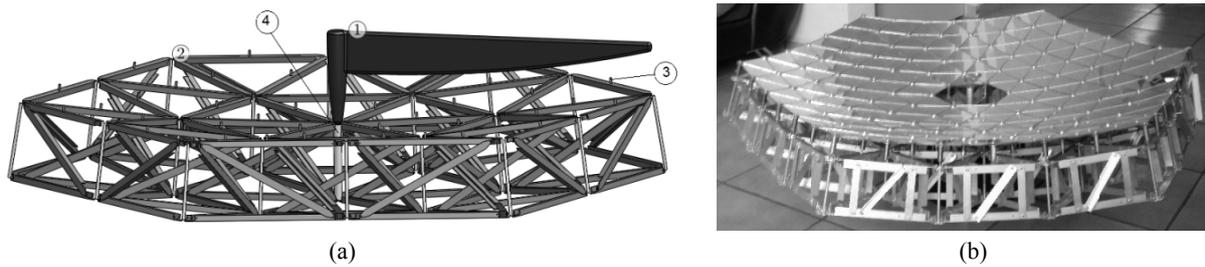


Fig. 4 (a) Design and (b) solar concentrator [32].

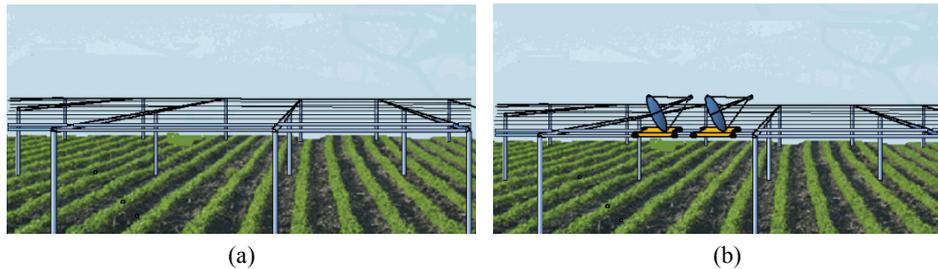


Fig. 5 Structure of collocation of solar concentrators with agricultural fields. (a) Structure, and (b) Structure with solar concentrators [32].

presented [32]. In Fig. 4b, the solar concentrator prototype with one meter of diameter is presented.

The cost of materials (aluminum bars for the support frame and flat mirrors for the parabolic surface) was low, and the size of the solar concentrator was in the order of 1-2 m of diameter. Thus, it was possible to collocate them on the horizontal roofs of buildings or in agricultural fields as shown in Fig. 5.

In Mexico, agricultural activities begin in April, and end in October or November. Thus, during this 7-month period, solar concentrators can be used. However, it is during the first five months that the solar concentrators can easily be used between the rows of crops because the plants are absent; thus, there is no demand for sunlight. Within the final two months, the plants are fully grown, and need sunlight. Thus, the solar concentrators must be removed from the field and stored nearby, and from November to April, solar concentrators can be installed in the entire field [32].

Fig. 6 shows the extent of agricultural activity during the twelve months of the year.

The harvest periods correspond to the grayscale rectangles in Fig. 7a.

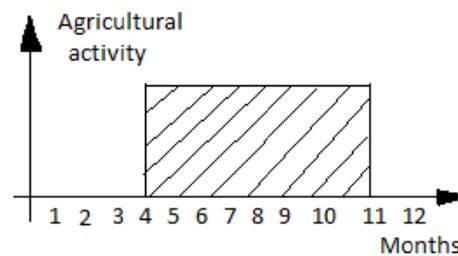


Fig. 6 Extent of agricultural activity.

The maximum number of solar collectors could be placed in the field during the November-April period (Fig. 6). The crop is harvested two or three times during the April-November period when agricultural activity recommences; thus, three harvests were considered in the present study (Fig. 7a).

Each harvest was divided into two periods. The first period corresponded to when the plants are small and solar concentrators can be used, while the second period corresponded to when the plants are mature, during which all concentrators are removed.

Secondly, the situation with potato fields in Canada, which is a northern country characterized by only one harvest period per year is shown in Fig. 7b, while Fig. 8 shows one of the potato fields that was considered [33].

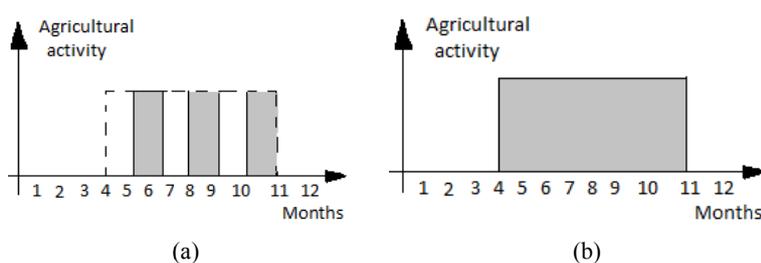


Fig. 7 (a) Three harvests over a 12-month period in Mexico; (b) One harvest period in Canada.



Fig. 8 Initial stage of potato field [33].

The agricultural activity lasted from April to September, and from October till April, no agricultural activities were performed; this period is characterized by rain and snow, which are weather conditions that do not favor the generation of electricity using solar concentrators. Although it was possible to use the solar concentrators; however, the efficiency will be not very high. Thus, the best period for the installation of the solar concentrators in Canada is from March to November (Fig. 7b). For example, in Ontario, the potato planting season begins in April-May [30], while the harvest season begins in July and runs through fall [34].

Authors also proposed the use of MET (MicroEquipment Technology) for the manufacture of solar concentrators given that this technology allows the production of different types of microcomponents [35]. The solar concentrators can be collocated with agricultural fields, especially bean fields in Mexico and to realize the dual advantages of electricity generation and crop production at a minimal loss of agricultural harvest, their use in potato fields in Canada has also been suggested. Additionally, the main results of microequipment development for solar

concentrator production as well as the results of studies related to collocation methods aimed at ensuring minimal loss of agricultural harvest are described.

5. Conclusions

The combination of solar concentrators and agricultural plants on the same piece of land is a new trend in environmental science and engineering. Authors analyze this situation for different countries, including Mexico. Several studies related to the combination of renewable energy generation and agricultural crops were reviewed. Many such systems involving the combination of PV panels with different types of vegetables exist in the USA, France, Japan, India, Northern Italy, Spain, and México. Our objective was to describe the development of compact, light, and inexpensive solar concentrator prototypes that can be collocated on horizontal roofs or in agricultural fields.

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