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CHAPTER 5

SOLAR CONCENTRATOR APPLICATIONS IN AGRICULTURE

ABSTRACT

We have developed several prototypes of solar concentrators that are compact, light, and inexpensive. As an example of solar concentrators, we selected parabolic solar concentrators with plane mirrors that approximate the parabolic surface. A methodology is proposed for the evaluation of the impact of combinations of solar concentrators together with certain agricultural crops. The proposed mathematical model is simple and applicable for different cases of combination of solar concentrators and agricultural fields. This study is dedicated to renewable energy on the example of two countries, Mexico and Azerbaijan. The relief and climate of both countries have many common features, which are expressed particularly in the abundance of solar radiation, the predominance of mountainous regions with remote and hard-to-reach settlements that need to create autonomous life support systems. The main problem for proposed solar concentrators is the automatization of the assembly process of these solar concentrators. We proposed two methods of assembly that is, using a parabolic rule and using a robotic arm with a stereoscopic vision system. Both methods are described in this chapter.

KEYWORDS

Agricultural crops, mathematical model, solar concentrator, Micro Equipment Technology (MET), flat triangular mirrors, assembly, automatization.

The global climate change and its negative impact on the stable economic development of countries around the world have created a real danger to humanity in recent decades. It is well known that the active consumption of traditional energy sources (e.g., coal, oil, gas) is the main cause of environmental imbalance and climate change. This requires vigorous decisions and actions from the world community, scientists and politicians to hamper the global warming, reduce carbon dioxide emissions (CO_2) caused by anthropogenic factors. Scientists and experts on climate change estimate that even a 1.5 °C increase in temperature will lead to irreversible changes in the environment. Therefore, it is necessary to reduce greenhouse gas emissions (GHG) by 2030 by 45–60 %

compared to 2010, and by 2050 it is necessary to achieve a zero balance allowing ecosystems to absorb all anthropogenic emissions [1].

To date, all UN member countries have ratified the Paris Agreement, which sets the goal of preventing global temperatures from rising by more than 2 °C [2]. Each country has committed to Nationally Determined Contributions (NDCs) to reduce greenhouse gas emissions. In this regard, the ever-growing demand for energy in the world is accelerating the gradual transition of nation-states to green energy. The implementation of NDCs includes commitments to reduce greenhouse gases in the energy, agriculture, transport, and other sectors.

Agriculture is a critical component of the economy and plays a vital role in food security [3]. This area also stimulates the employment of the able-bodied population living in rural settlements, and provides a certain contribution to the achievement of sustainable development goals [4].

Along with this, agriculture is the most vulnerable segment of the economy to climate change, which manifests itself in the amount and distribution of precipitation, drought, land pollution, reduced water supply, changing seasons, etc. [5–7].

One way to meet the growing demand for food is to increase agricultural productivity and reduce the cost of agricultural production. Addressing this issue is of particular importance given the demographic trends that contribute to some extent to increased emissions and lead to an increase in per capita consumption of agricultural products. According to the new UN forecasts, by mid-November 2022, the world's population is estimated to increase to 8 billion people, and humanity to reach 8.5 billion people by 2035, 9.7 billion people by 2050, and 10.4 billion people by 2100. Back in 2011, the world population reached 7 billion people [8].

The development of agricultural production is largely determined by the technological modernization of the industry, the development of new intensive agricultural methods that increase the harvest and diversity of crops while protecting the soil through the use of environment-friendly renewable energy sources, conservation of water resources, etc. [9, 10]. Currently, many countries specify the transition to green energy as their national priorities. To implement this complex task, various concepts, numerous applied developments, technological solutions and equipment for the modernization of energy supply systems based on various renewable energy sources have already been proposed [11, 12].

One of the cleanest energy sources is solar energy, which is safe for the environment and does not cause global warming. Solar photovoltaic stations, which are the basis for the development of low-cost autonomous power supply systems, are now used to generate energy in many countries. A significant large area of roofs and walls of houses, including business buildings, as well as the availability of free territories may contribute to getting and collecting large amounts of free energy.

In the context of agriculture, technologies of solar energy are applicable in every sector of the agro-industrial complex and may address many problems in this field of activity.

In the modern practice of crop growing, one of the innovative, but promising applications of solar energy is the combination of plants and solar energy production on one piece of land. The idea of integrating solar devices into agro-ecosystems, namely agrovoltaic, provides the possibility of dual use of land, i.e. growing plants while generating electricity on the same land. Agro-electric systems are particularly effective in agriculture in countries that suffer from land scarcity and lack of areas for crops, as well as those with dry areas and high solar potential.

Various approaches to the implementation of the technology of combining solar energy and land use require a precise calculation of the features of shadows, taking into account the risks negatively affecting the growth and development of plants, the crop size, etc.

Many researchers around the world are now focusing on these studies, aimed at both the development of agriculture and the improvement of solar devices, including the development of alternative energy [13–20]. According to the results of studies and experiments, the combination of solar energy with crops, with the right scientific approach, may increase crop yields on the one hand, and generate environmentally friendly energy on the other [21].

In another study [19], the objective was to examine the performance of agrovoltaic systems, which produce crops and electricity simultaneously based on the installation of stilt-mounted PV panels on farmlands (**Fig. 5.1**).

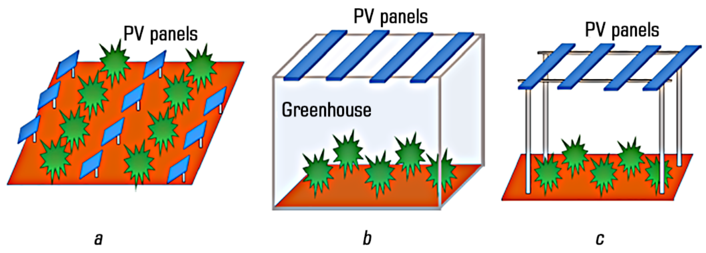


Fig. 5.1 Three different agrovoltaic system types: *a* – using the space between PV panels for crops; *b* – a PV greenhouse; *c* – a stilt-mounted system [19]

The abovementioned studies consider three principles for the application of solar devices in agroecosystems:

1) emphasis on the agricultural crops that make up the agroecosystem;

2) emphasis on the solar energy production;

3) emphasis on the integration of solar panels into agroecosystems.

The first principle is aimed to maximize biomass production by minimizing changes in production systems. Devices for electricity production are installed on available lands and do not severely change agricultural production. The second principle attempts to maximize the generation of solar energy and minimize the changes in standard technologies in solar energy receiving, contributing to the agricultural growth around renewable energy facilities. The third principle efforts to merge both cases and benefit from the increase in biomass and energy capacity of solar devices.

In this study, implemented within the framework of the third principle, we have made an effort to preserve and upsurge the productivity of agricultural crops while guaranteeing the highest power generation.

5.1 OUR APPROACH

This article explores the reasons for the transition of countries to a green economy through the prism of global climate change. An analysis of the state of development of environmentally friendly energy sources is performed on the example of two countries, i.e., Azerbaijan and Mexico, the energy sectors of which are mainly based on natural fuel. These countries, taking into account the values of their basic economic indicators, have upper-middle-income economies (4,046–12,535 USD) being referred to the group of developing countries and are gradually approaching the category of developed countries and also have a number of similar climatic, agrobiological and geographic relief features. More than 77 % of the world's population lives in developing countries, which make up about 4/5 of all countries in the world [22].

The main factors determining the relevance of the development of renewable energy sources in these countries are identified, with an emphasis on the use of the latter in agro-complexes. As the main segment of agriculture, crop production is considered, which is the leading field in ensuring food security and exports in both countries.

Taking into account the prospects of introducing agrovoltaics into crop production, this study considers the issues of creating integrated systems for electricity production and growing crops in one field through the use of solar energy.

Analysis of approaches to solving the problem of merging solar energy and agriculture, which makes it possible to identify two main problems when choosing a model for combining concentrators with certain types of plants. The first problem is related to the selection or development of solar concentrators that are most suitable for certain crops. The second factor is related to the choice of the mathematical model proposed to evaluate the most efficient placement of solar concentrators in the field in the combination with plants.

In **Fig. 5.2** we demonstrate flowchart of our model work. The model is subject to requirements of ease of use and versatility, providing simulation of various combinations of solar concentrators and agricultural fields. Another important point when choosing a model is to provide the ability to simulate various combinations of solar concentrators and plants without the need for empirical studies directly in the field. We can describe the general objective and specific objectives in the following way.

General objective is investigate the possibility of solar concentrator collocation between plants in agricultural fields.

Specific objectives:

1. Development of solar concentrators that are compact, light, and inexpensive. We selected parabolic solar concentrators with plane mirrors that approximate the parabolic surface.

2. A methodology is proposed for the evaluation of the impact of combinations of solar concentrators together with certain agricultural crops. The proposed mathematical model is simple and can be implemented for different cases of a combination of solar concentrators and agricultural fields.

3. Parameter selection for solar concentrators (the characteristics taken into account in solar concentrators include their dimensions, weight, plate width or dish diameter, shade produced, mounting structure, the material of construction, quantity and distribution of solar concentrators).

4. Parameter selection for agricultural fields (the field area, its slope, soil type, humidity, spacing between the rows, crop type, crop density, maximum plant width, and plant height).

5. Creation of a computer program to realize the mathematical model.

6. Comparative analysis of Mexico and Azerbaijan and their possibilities to develop green energy.

7. Development of methods of automatic assembly of solar concentrators.

This article substantiates the expediency of choosing a linear model with two objective functions that make it possible to satisfy the specified requirements. Such a model can be effectively used in crop production in the countries with analogous characteristics and high solar radiation potential.

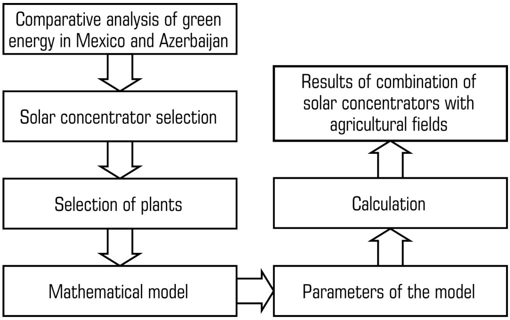


Fig. 5.2 Flowchart of our model

5.2 AZERBAIJAN AND MEXICO: DRIVERS FOR DEVELOPMENT OF GREEN ECONOMY

The main factors determining the need for the development of a green economy in Azerbaijan and Mexico may include:

1) global trend towards the decarbonization of energy and the need to fulfill obligations to reduce greenhouse gases;

2) climate policy of countries;

3) geographical location and landscape;

4) climatic conditions;

5) along with traditional energy resources, presence of high potential of renewable energy sources;

6) priorities of social and economic development policy.

A comparative analysis of Azerbaijan and Mexico through the prism of factors that determine the relevance of the development of new types of renewable energy makes it possible to identify a number of similar features of these countries, which are listed below.

5.2.1 OIL AND GAS INDUSTRY

Azerbaijan and Mexico are the countries with a developed hydrocarbon industry. Huge reserves of oil and gas resources, which are produced on land and under the sea, have contributed to the attraction of large investments to these countries ensuring energy security, and became the main driving force of national economies, the most important source of foreign exchange earnings and a growth factor of the population's well-being.

However, as mentioned above, the extraction and refining of traditional energy resources are associated with environmental problems, and furthermore, fossil fuels are among the main sources of environmental pollution and global climate change. Therefore, in recent years, the importance of the transition to low-hydrogen and carbon-free energy sources has become specifically relevant. In this regard, Azerbaijan and Mexico, despite the large reserves of oil and gas, focus on the transfer of their energy systems to alternative, mainly renewable energy sources.

Currently, electricity generation in Azerbaijan and Mexico is mainly based on hydrocarbon resources. In recent years, both countries have been intensively converting traditional oil power plants into natural gas with cleaner burning.

Thus, in Azerbaijan, the share of gas in electricity production in early 2020 was estimated at 92 %. As of 2020, the country's share of electricity generation from environmentally friendly sources (mainly through the generation of energy from hydroelectric power plants) in the total amount of energy produced in the country amounted for 17 %.

In accordance with the Paris climate agreement, Azerbaijan has committed to reduce the level of gas emissions and a thermal effect by 35 % by 2030 compared to the base year 1990 [23]. In November 2021, at the COP26 conference held in Glasgow, Azerbaijan made a new commitment to reduce emissions by 40 % by 2050 and create a "Net Zero Emissions" zone in the territories liberated from occupation [24].

Positive demographic and economic trends played an important role in the growth of annual emissions in Mexico between 1990 and 2010, increasing by 33 %, and led to an increase in energy demand [25]. To prevent unsafe climate change and the development of low-carbon energy, the Mexican government has adopted a series of climate measures, due to which, in early 2020, 70.1 % of the installed net power capacity in Mexico came from thermal gas power plants. Energy production from low-carbon nuclear power plants in Mexico accounted for 2.1 %, while electricity generation from clean renewable sources accounted for 27.8 % of the total electricity produced in the country [26].

Under the Paris Climate Agreement, Mexico's greenhouse gas reduction commitments are among the most ambitious in the world, compared to those of many developed countries and most other Latin American countries. Thus, Mexico's national greenhouse gas (GHG) emission reduction goals are to provide for bringing electricity generation from environmentally friendly sources to 35 % by 2024, and by 2035 to achieve a share in electricity generation with zero or low emissions up to 40 %. In the long term, it is planned to continue increasing the capacity of the energy sector by up to 50 % by 2050, including both renewable energy sources and low-carbon nuclear and fossil fuels [25].

Fig. 5.3, based on the BP Statistical Review of World Energy, shows the results of various types of energy consumption in Azerbaijan and Mexico. To concern from primary direct energy consumption, an inefficient factor has been applied or fossil fuels (i.e. the "substitution method") [27].

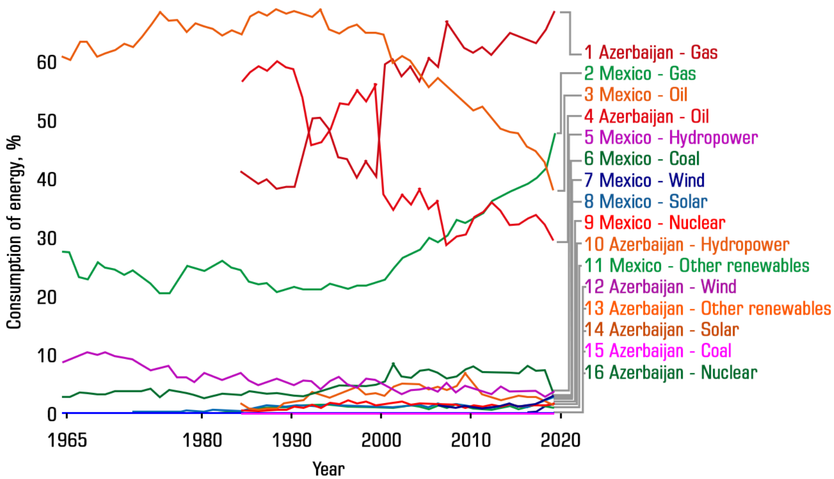


Fig. 5.3 Consumption of various types of energy (in Azerbaijan and Mexico in 2021 [27])

5.2.2 CLIMATE CHANGE POLICY

The growth of the renewable energy sector necessitates the enhancement of the policy and institutional environment in this field. Therefore, both countries have recently adopted relevant laws and regulations.

It should be mentioned that the establishment of the Azerbaijan Renewable Energy Agency under the Ministry of Energy of the Republic of Azerbaijan in 2020 [28], as well as the adoption of the law of the Republic of Azerbaijan "On the use of renewable energy sources in the production of electricity, in 2021 [29], significantly contributed to the growth of renewable energy.

The institutional and programme framework for national climate change mitigation policy in Mexico is specified in the 2012 General Law on Climate Change. Mexico [30] and the National Climate Change Strategy adopted in 2013. In 2021, the Mexican Ministry of Energy (Secretaría de Energía, SENER) prepared the Law on New Electric Industry in Mexico and the National Electricity System Development Programme for 2022–2036 [31].

5.2.3 GEOGRAPHICAL POSITION AND RELIEF DIVERSITY OF THE COUNTRIES

The territories of Azerbaijan and Mexico are characterized by a unique geographical position and diversity of relief.

The Republic of Azerbaijan is located in the east of the South Caucasus, to the southwest of the Caspian Sea. The total area of the country is 86,600 km^2. The population of Azerbaijan as of March 1, 2022 reached 10,164,464 people, the population density is 117 people per km^2 [32].

Azerbaijan has a unique geographical position, being at the crossroads of Europe and Asia, which gives it certain advantages and shapes the relief. Up to 60 % of the total area of the country is occupied by mountains, of which 43 % have a height of more than 1000 m, and 17 % of the area is occupied by low mountains and foothills. The rest of the country's territory, i.e., 40 % of the area, covers plains and lowlands with high mountains, intermountain depressions, valleys, and volcanic highlands. At the same time, 18 % of flats and lowlands are located 28 m below sea level [33].

Given the complexity of the landscape and suitability for agriculture, Azerbaijan refers to the category of land-poor countries in the world. According to the State Committee on Property Issues of the Republic of Azerbaijan, only 55.2 % of the country's land fund is suitable for agriculture, of which only 44.4 % of arable land is used for agriculture and perennial crops. The situation with arable land has become even more complicated by the fact that 20 % of the territories of Azerbaijan were under occupation for almost 30 years. Ecocide of agricultural lands as a result of burning land and forests, destruction of flora and fauna, widespread contamination of liberated territories with mines and other illegal actions led to the degradation of fertile lands in Karabakh.

Mexico is located in the south of North America and occupies most of Central America. To the west and south, the country is washed by the Pacific Ocean and to the east by the Gulf of Mexico and the Caribbean Sea. Mexico is the northern part of Latin America and the most populous country.

Mexico covers an area of 1,972,550 km^2 and is the 13th largest country in the world. The population of the country is 132,838,093 people, and the population density in Mexico is 67.6 per km^2 [34]. The relief of the country is made up of high mountain ranges, low coastal plains, high mountain plateaus, and deserts. Most of the territory of Mexico lies 1000 m above sea level.

Mountainous regions and highlands occupy almost 2/3 of the country's area. At the same time, the highlands, which occupy most of Mexico, in places rise above 3000 m or consist of vast depressions with gentle slopes. The lowlands and plains account for only 25 % of the country's territory. Thus, Mexico is also characterized by a lack of land and the predominance of remote mountainous regions with hard-to-reach settlements [35].

According to the World Bank's set of development indicators, generated from officially renowned sources, agricultural land (% of land area) in Mexico was 54.99 % in 2018 [36]. Agricultural lands are the territories which are arable, and occupied by permanent crops and permanent pastures.

5.2.4 THE CLIMATE

The characteristic topographical features and the main landscape types determined the diversity of climatic conditions in Azerbaijan and Mexico.

Azerbaijan, being a predominantly mountainous country, at the same time has vast lowlands, valleys, sea and other water resources that shape the country's climate. The country is protected from the invasion of cold air masses from the north by the main Caucasian ridge. Depending on the height above the level, several types of climate, namely semi-desert and dry steppe climate types are observed in Azerbaijan, which are characterized by hot summers and mild winters with little precipitation due to intense evaporation; humid subtropical type with warm-temperate climate and dry summers; cold climate with ample rainfall, which is distinctive for the Alpine zone of the greater and Lesser Caucasus, and others. Northern winds observed on the Absheron Peninsula sometimes even reach the strength of a hurricane [37, 38].

Mexico is also distinguished by its diverse landscape and unique geographical position, being a mountainous country, and possessing significant marine and other water resources that shape the country's climate. In the north of Mexico, the climate is subtropical, in the rest of the country it is predominantly tropical, on the coastal plains it is humid and hot [35, 39].

On the Pacific coast, daytime temperatures throughout the year do not fall below +30 °C degrees, and nighttime temperatures range from 21 to 24 °C. Temperatures are cooler on the Caribbean coast. In the winter months, during the day, the air warms up to +24 °C, and in the summer – up to +31 °C, at night, about 19 °C of heat is observed in winter and 25 degrees of heat in summer.

In the central highlands of Mexico, the climate is sharply continental, with a maximum temperature in April and May (+27 °C), and at night in the same months the air cools down to +11 or +13 °C. In winter, daytime air temperatures rise to +21 °C, at night it is about 7 °C.

In Mexico, an altitudinal zone is well expressed. Thus, in the northern part of the country, which is the driest region of the country, at the altitudes in winter, the temperature can drop below 0 degrees. The rainy season lasts from May to October, when powerful tropical cyclones often occur. The greatest amount of rainfall is observed in the southern regions of the country.

The geographical positions and climates of Azerbaijan and Mexico cause abundant solar radiation and heat, creating an opportunity for the cultivation of many crops and the production of solar electricity. Vegetation in both countries is distributed in altitudinal steps depending on the zonal changes in climate and soil.

5.2.5 NON-OIL SECTOR

The main priorities of the policy of both Azerbaijan and Mexico in the socio-economic sphere are aimed at diversifying the economy through the development of the non-oil sector. Alternative energy, agriculture, and "green economy" successfully fit this concept.

Today, a significant part of the remote highlands of Mexico does not have a centralized electricity supply. The population of these areas lives in the rural areas and most of them are engaged in subsistence farming. Connecting rural settlements to the centralized electrical systems is complicated due to the high capital costs for laying expensive heating networks and the construction of power lines, as well as the complexity of the terrain and the lack of infrastructure. Under these conditions, solutions for the autonomous power supply to the residents of remote and hard-to-reach areas of Mexico are uncontested.

The program adopted and implemented by the government of Mexico to provide modern clean energy to almost three million people in remote rural areas of the country without access to electricity, as well as to reduce the use of traditional biomass for domestic purposes, will certainly play an important role in improving the quality of life of villagers, increasing the productivity of rural economy, development of the regional economy, and achievement of the country's goals in the field of clean energy [26, 31].

The pace of "green energy" development in Mexico has enabled the country's energy companies to offer the lowest prices for solar energy. This allows for increasing access to electricity to all segments of the population [40]. In recent years, Azerbaijan has been focusing on the development of the "green economy" in agriculture, the second most important sector of the country after the oil industry. "Clean Environment and Green Growth" has been propagated as one of the top five national priorities [41]. The territories of the country liberated from occupation were declared a "green energy" zone [42] and an action plan for the establishment of a "green zone" in the territories of the Republic of Azerbaijan liberated from occupation in 2022–2026 was approved [43].

Furthermore, a number of factors have been taken into account. Consequently, firstly, the liberated territories, declared "green" energy zones, are predominantly agricultural. Secondly, in the process of reintegration of 1,670.3 thousand hectares of territories liberated from occupation into the country's economy, the area of agricultural land is estimated to increase by 680.8 thousand hectares of suitable arable land and 10.7 thousand hectares of household land, 247.3 thousand hectares of forests [44]. Thirdly, the policy of agricultural development in the liberated territories of Azerbaijan is based on the use of environmentally friendly and safe technologies. The country has already initiated a number of projects in the field of solar and wind energy production in the liberated territories with the involvement of investors.

5.2.6 SOLAR ENERGY

Currently, the technical potential of solar energy is estimated to be the highest among renewable energy sources, particularly in the countries with significant annual solar radiation resources.

The Mexican Republic has a huge and diverse renewable energy resource base that can provide a significant increase in clean energy capacity. Mexico's national renewable technical potential includes 24,918 GW of solar Photovoltaic power, 3,669 GW of wind power, 2.5 GW of conventional geothermal power, and 1.2 GW of additional capacity from existing hydropower facilities [45]. There are about 3126.3 solar hours during the year [35]. The level of solar radiation is 5.2 kWh/m^2 [46]. Mexico receives high levels of solar radiation over much of its territory (**Fig. 5.4**).

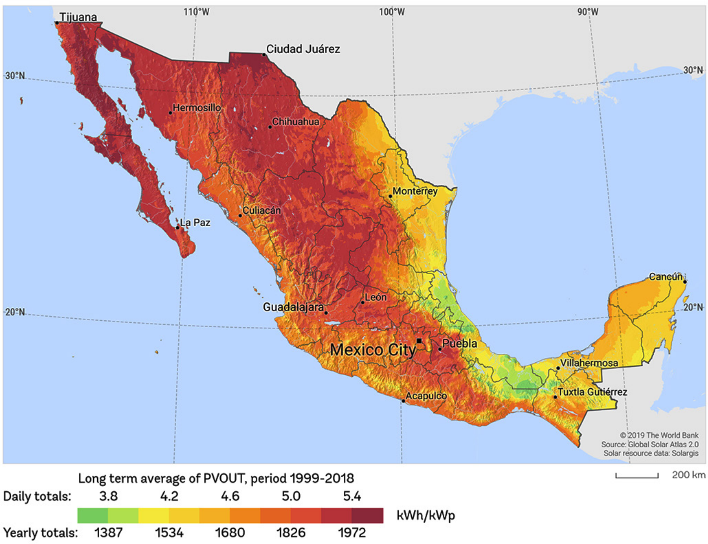


Fig. 5.4 Solar map of Mexico [47]

The Ministry of Energy of the Republic of Azerbaijan estimates the potential of economically practical and technically reasonable renewable energy sources in the country as 27,000 MW, including 23,000 MW of solar power, 3,000 MW of wind power, 380 MW of bioenergy potential, 520 MW of mountain river potential [24, 48]. Solar radiation in Azerbaijan is 2400–3200 hours per year and is well comparable with the international indicators. The sunshine duration on the Absheron Peninsula and in the coastal areas of the Caspian Sea is about 2500 hours, and in the Nakhchivan Autonomous Republic – about 2900 hours [49]. **Fig. 5.5** demonstrates the solar radiation high level in these areas.

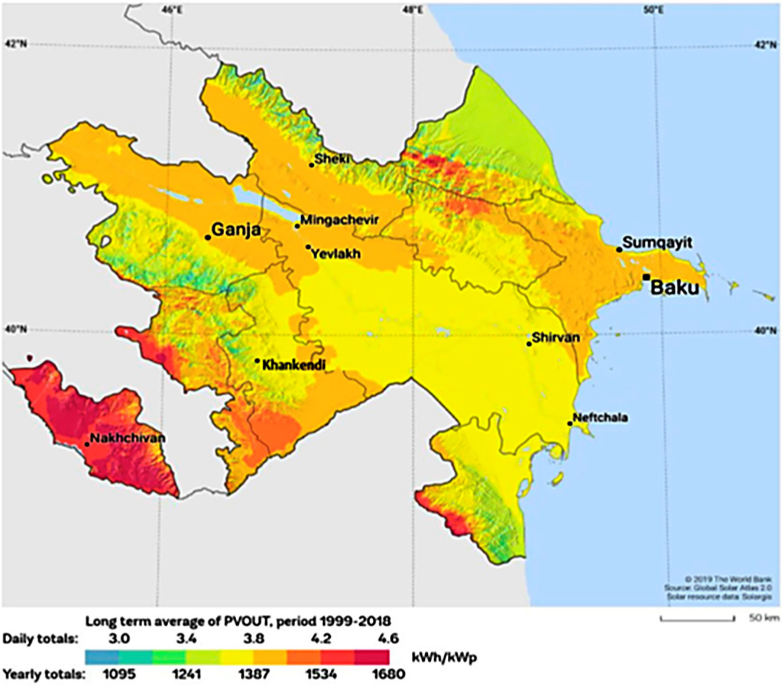


Fig. 5.5 The photovoltaic power potential of Azerbaijan [49]

With sufficient investment and improved regulatory frameworks, Mexico and Azerbaijan are capable to rapidly realize this potential in short term, meet the country's electricity needs, and achieve their energy goals in the field of clean energy production. The use of solar energy is the most cost-effective way to solve the problems associated with the energy supply of rural settlements, remote and hard-to-reach areas of both Azerbaijan and Mexico, which have complex landscapes suffering from the lack of land. Along with power generation, solar installations may assist to improve agricultural systems by reducing wind erosion as well as saving water.

5.2.7 PRACTICAL EXAMPLES

The company "Gecko Logic Mexico" offers renewable energy systems that can be interconnected to the Mexican electrical net system now available in Mexico [46]. The solar panel systems are designed to capture energy from the sun (**Fig. 5.6**). The hypothesis is based on the idea of placing solar devices in areas occupied by crops in such a way that the mutual influence between them is minimal, and thus one could benefit from solar devices for crops.

Fig. 5.6 Solar farm [46]

Azerbaijan has favorable climatic conditions, sufficient amount of heat and light, which enable growing and harvesting some agricultural crops twice a year. The main trends of agricultural production in the country include crop production, as well as grain-growing, vegetable-growing, fodder crops, tea-growing, potato-growing and various types of fruits [38].

Crop production is also the leading branch of Mexican agriculture, and the main crops grown include wheat, corn, soybeans, rice, beans, coffee, tomatoes, fruits, and cotton [50].

For the first time in Azerbaijan, as part of the "Agrovoltaics" pilot project, various agricultural plants were sown on a plot with solar panels in the village of Sarygamysh, Samukh region. Vegetables (peas, onions, red beets, carrots) were sown in the inter-panel space on an area of 1.2 hectares [51].

A group of Stanford University researchers recommends using solar-panels in agricultural fields that cultivate agave (**Fig. 5.7**), the plant that is used to make tequila [50]. Solar panels have to be washed to keep off the dust in the desert and maintain efficient electricity production. From this point of view, it seems that water is wasted. However, agave plants need water, and co-locating them together proves beneficial. One of the major issues is that most of the food crops do not grow in deserts because of low water availability, and soil not being very fertile. But agave and aloe are adapted to desert landscapes.

Azerbaijan and Mexico already have experience in installing and operating solar power plants. Thus, in Azerbaijan, solar power plants operate in Gobustan, in the villages of Surakhani and Sahil (**Fig. 5.8**), on the island of Pirallahi, in the regions Samukh and Garadagh, Sumgayit and Nakhchivan.

A wide network of solar power plants installed in various regions of Mexico is available [52]. Many of the proposed solar installations consist of large photovoltaic systems [18].

Fig. 5.7 Agave for production of tequila [50]

Fig. 5.8 Surakhani, Azerbaijan

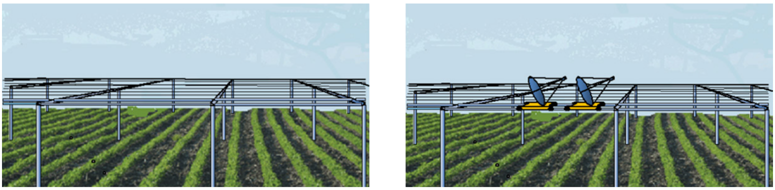
5.3 CHALLENGES OF COMBINING SOLAR ENERGY AND AGRICULTURE

As photovoltaic plants continue to grow, the use of land for solar farms upsurges the competition for land resources between food production and clean energy [53]. Although photovoltaic systems require less land than other renewable energy options [54], in fact, commercial photovoltaic power plants can occupy a significant area of land locally.

One of the first experiments recorded and described in the literature to develop an agro-power plant on a farm was the system in Montpellier, France, in 2013 [55]. The system grew lettuce in combination with a system consisting of photovoltaic modules mounted on 0.8 m wide piles. The same piece of land was used for electricity and food production. The results of the experiments showed that the shades of the PV matrices had no significant effect on lettuce yield.

To date, three types of agro-electric systems have been proposed for the simultaneous growth of crops and electricity production on agricultural lands. The first type was proposed in the early 1980s using photovoltaic panels in the spaces between crop rows [56]. The second type is the photovoltaic greenhouse, in which a part of the transparent roof is replaced by photovoltaic panels [57]. The third type is the photovoltaic systems mounted on poles above the crops, which consist of pipes and rows of photovoltaic panels. They are installed on the ground and located at regular intervals allowing enough sunlight to reach the plants for photosynthesis.

An example of the placement of solar concentrators is described in [58, 59]. In 2019–2020 we have proposed to collocate our solar concentrators with different types of plants [58, 59]. In **Fig. 5.9** we demonstrate the proposed structure.



a *b*

Fig. 5.9 Structure of collocation of solar concentrators with agricultural fields: *a* – Structure; *b* – Structure with solar concentrators [58]

In 2018, Amaducci and Colauzzi [60] proposed an agro-electric system, solar tracking, mounted on suspended structures (piles). The horizontal main axle is mounted on frames, on which the secondary axles supporting the solar panels are pivotally connected. The two shafts rotate driven by interconnected electric motors through an innovative wireless communication and control system.

To simulate the growth and production of crops in the shade of the Agro voltaic system, Scilab [61] develops a software platform combining the radiation and shading model with the universal plant growth simulator GECROS [62]. The GECROS agricultural crop model predicts biomass and yield depending on climatic factors (radiation, temperature, wind speed and humidity) and available water and nitrogen amount in the soil.

We propose using the solar concentrators in the fields of Mexico and Azerbaijan. For Mexico, these can be systems together with common crops such as beans, corn, and agave. For Azerbaijan, these can be plantations of early vegetables, fields of potatoes or beets. The spaces between plant rows can be used to install solar concentrators. Moreover, the parabolic surface dimensions do not affect the plants at all.

Global demand for energy leads to an increase in the need for the use of green energy for irrigation, domestic purposes, etc. The studies [13–19, 53–55] describe the solar concentrators installed in combination with an agricultural field infrastructure. They show the economic feasibility of these systems in some rural areas and their opportunities for the electrification of the latter, while stimulating their economic growth.

The first problem required to be solved for combining solar energy with agriculture is the choice of solar concentrators and the most suitable crops for such concentrators.

The need for solar energy varies for different crops depending on their metabolism and the timing of sunlight use. The design of solar concentrators and the mounting methods (distance and height of frames) can generate different amounts of energy according to the requirements of selected crops.

One of the motivating options can be obtained using parabolic dish solar concentrators covered with flat triangular or square mirrors. For example, the studies [63–67] present the development of such concentrators. The cost of such a solar concentrator is low due to the modeling of a parabolic surface by flat mirrors, and small dimensions (from 2 to 3 meters in diameter). Such a concentrator operates in two modes:

1) capturing solar energy, when the parabolic dish axis is directed towards the sun;

2) in the minimum shadow, when the parabolic dish axis is fixed perpendicular to the sun's direction.

The hypothesis is based on the idea of placing solar devices in areas occupied by crops, so that the interaction between them is minimal, thus, benefitting from solar devices for crops.

5.4 SOLAR CONCENTRATOR PROTOTYPES

Before discussing the mathematical model for the evaluation of solar concentrators and agricultural plants we present several prototypes of solar concentrators and discuss the existing problems.

We have developed several prototypes of solar concentrators. As an example of solar concentrators, we selected parabolic solar concentrators with plane mirrors that approximate the parabolic surface. This decision is based on our experience in developing new solar concentrator prototypes that are compact, light, and inexpensive.

During the last decades we have developed several variants of solar concentrators with parabolic surfaces. To decrease their cost, we propose to approximate the parabolic surface using flat triangular or square mirrors. For this purpose, a special support frame was developed. **Fig. 5.10** shows the support frame simulated using SolidWorks [68]. The structure consists of bars and nodes [69–71].

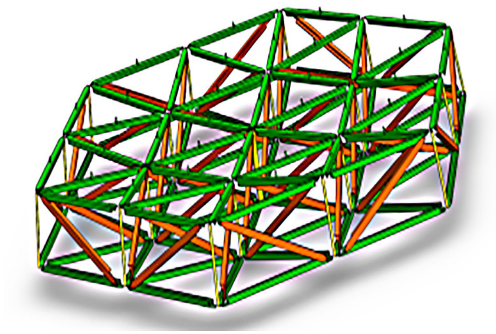
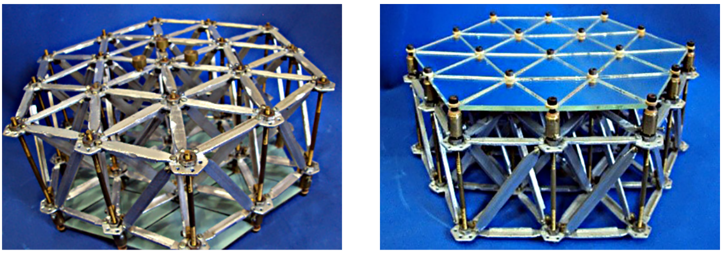


Fig. 5.10 Support structure of the solar concentrator with triangular mirrors

The bars are made from aluminum angles that are connected by screws (**Fig. 5.11**).



a *b*

Fig. 5.11 Structure of the first prototype: *a* – backside of the concentrator; *b* – right side of the concentrator with flat triangular mirrors

Prototype of a solar concentrator

The first solar concentrator prototype was developed, as shown in **Fig. 5.11**. It contains 24 triangular flat mirrors. ***Fig. 5.11, a*** displays the backside of the solar concentrator. The structure of the support frame is clearly presented in this figure. The aluminum bars are connected to each other by screws and form a triangular structure where it is possible to collocate the flat triangular mirrors, as exhibited in **Fig. 5.11, *b***. This prototype was made manually. It is a labor-intensive assembly. Therefore, it is very important to automatize this process.

We propose prototypes of solar concentrators with flat triangular or square mirrors. These concentrators have a support frame from bars and nodes. To automatize the structural construction process, we propose an automatic assembly system that can be used for the construction of the solar concentrator support frame. The first step is to simulate the structure and the two main modules (manipulator and computer vision) using SolidWorks. The results of the simulation will be used to fabricate real prototypes in the future.

5.5 MATHEMATICAL MODEL FOR EVALUATION OF SOLAR CONCENTRATORS AND AGRICULTURAL PLANTS

The main aim of this study is to develop a methodology for evaluating the effectiveness of possible models for combining solar concentrators with a certain type of plant. The methodology we propose in solving two tasks. The first task is to develop a mathematical model, which includes two important steps. The first step implies the development of an analytical model with the parameters characterizing agricultural fields. The second step is to evaluate the characteristics of the solar concentrator.

The second task implies the computer implementation of the developed model and virtualizes the interaction process of crops on an agricultural field and the placement of solar concentrators on it to obtain the maximum productivity of both.

The hypothesis is based on the idea of placing solar devices in areas occupied by crops, so that the interaction between them is minimal, thus, benefitting from solar devices for crops (**Fig. 5.12**).

Detailed implementation of the first task is described below.

The parameters taken into account in the fields include the field area, its slope, soil type, humidity, spacing between the rows, crop type, crop density, maximum plant width, and plant height. Irritability of plants to external agents (light, temperature, humidity, etc.) and plant development are determinable by the timing of sowing, germination, growth and harvesting.

The objective function may include all of these parameters or some of the most important in a particular situation. The simplest model is the linear model. In this case, the objective function has the following form:

$$f_1(x)=\sum_{i=1}^{N}a_i x_i, \tag{5.1}$$

where x_i – the selected parameters for the field and plants; a_i – the coefficients obtained by calculation or experiment for a specific task; $i=1,\ldots, N$.

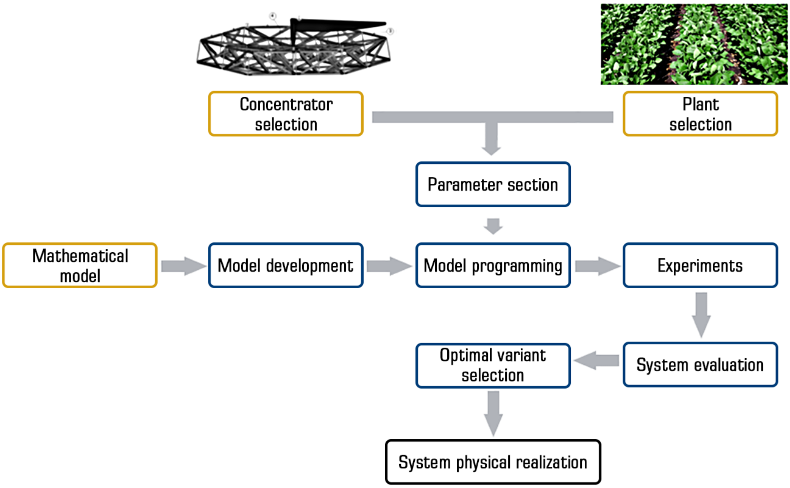


Fig. 5.12 The scheme of combining solar energy with agricultural plant

The characteristics taken into account in solar concentrators include their dimensions, weight, plate width or dish diameter, shade produced, mounting structure, material of construction, quantity and distribution of solar concentrators. The type of objective function is selected depending on the specific task. In this case, the objective function can be presented as follows:

$$f_2(y) = \sum_{j=1}^{M} b_j y_j, \tag{5.2}$$

where y_j – the selected parameters of the characteristics of solar concentrators; b_j – the coefficients obtained by calculation or experiment; $j=1,\dots,M$.

Some of these parameters can be obtained from various statistical tables, for example, the yield rate of certain crops. Certain parameters require additional mathematical calculations, for example, how many concentrators can be placed on a field with a predetermined distance between the poles (supports), etc. Some values can be obtained during the operation of the first real prototype of the combined system.

The efficiency of the system functioning is evaluated by two main criteria. The first criterion is the maximization of yield per field, and the second criterion is the maximum number of solar concentrators distributed per field.

Based on these goals, the first objective functions and models are constructed. Taking into account these functions and the ratio of the parameters of solar concentrators and cultivation fields, secondary goals can be obtained.

Based on these objective functions, new functions will be defined to determine the relationship between field parameters and concentrators' characteristics. For example, determination of the stability of solar concentrator support on the ground or the amount of shadow by solar concentrators on plants throughout the day. The computer system can be developed by model developers, or available software systems can be used, for example, software modules described in [66].

5.6 DISCUSSION OF POSSIBLE OPTIONS FOR THE MODEL IMPLEMENTATION

A holistic system combining renewable energy sources and agricultural fields may use new designs of solar concentrators. **Fig. 5.13** shows several prototypes of solar concentrators developed and patented in Mexico, Spain and the United States of America [17, 63–67]. The developed prototypes are 1 meter in diameter. Since the support structure is made of aluminum poles, it is not heavy. The cost of prototype materials is low. For example, flat mirrors are now available on market for about 3 USD per square meter. The only expensive and time-consuming step is assembling. This stage is estimated to require automation in the future, which will significantly reduce the cost of the assembling process.

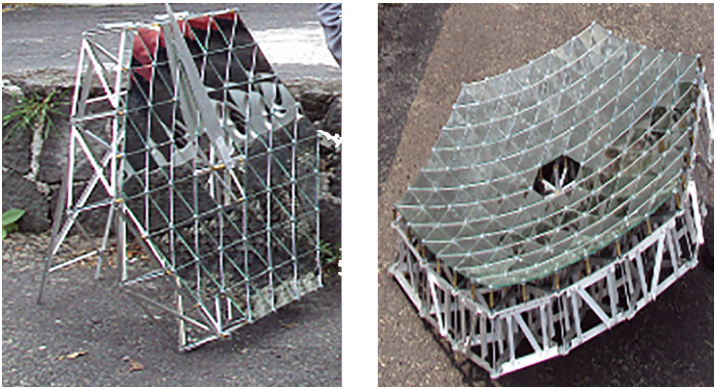


Fig. 5.13 Prototypes of flat mirror solar concentrators

Equipment technology (MET) has been developed over the past few years [72]. The task of manufacturing solar concentrators was chosen as an application of MET. Various types of solar concentrators with flat mirrors and their prototypes have been developed so far. These concentrators can be installed on the horizontal roofs of buildings, as are in many cities and towns in Mexico. Installing solar concentrators in agricultural fields is a new trend. This study proposes, as an example, to use these solar concentrators in potato fields in Azerbaijan and agave fields in Mexico to achieve dual benefits such as power generation and minimal crop losses.

The main problem is the automatization of the assembly process of these solar concentrators. Thus, we propose two methods of assembly, which is, using a parabolic rule and using a robotic arm with a stereoscopic vision system. Both methods are described in this article.

Parabolic surface adjustment

The concept of easily constructing a parabolic surface was patented in the USA, Mexico, and Spain [69–71]. The tool used is the parabolic rule, as illustrated in **Fig. 5.14** (the parabolic rule is colored red). This rule is installed on the center of the support structure (central tube) and can rotate over the surface. In the screw location, the screw must be rotated until it contacts the parabolic rule. This procedure is performed for all screws of the support frame structure. Thus, the screw heads will have different heights and the screw heights will approximate the parabolic surface.

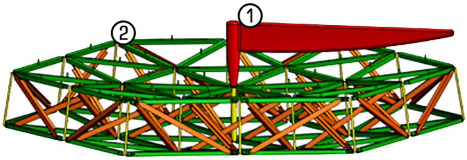


Fig. 5.14 Adjustment of the parabolic surface:
1 – parabolic rule; 2 – solar concentrator

The parabolic rule can also be used to prepare the structure of a solar concentrator to collocate the flat mirrors.

Manipulator and computer vision system

To automatize the process, it is proposed to use a robot manipulator with a computer vision system. The proposed robot manipulator is depicted in **Fig. 5.15**.

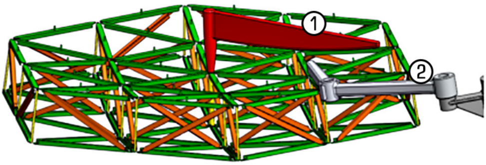


Fig. 5.15 Adjustment of parabolic surface using:
1 – the parabolic rule; 2 – the manipulator

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The second task implies the computer implementation of the developed model and virtualizes the interaction process of crops on an agricultural field and the placement of solar concentrators on it to obtain the maximum productivity of both.

Another variant of the system for an automatic adjustment that we propose is displayed in **Fig. 5.16**. In this system, a central tube is installed as a guide for a special type of manipulator.

Fig. 5.16 Variant of the automatic adjustment system

Components of the system for automatic adjustment

A more detailed view of the guide showing the different components is presented in **Fig. 5.17**. This guide contains two important components: the manipulator and the computer vision block.

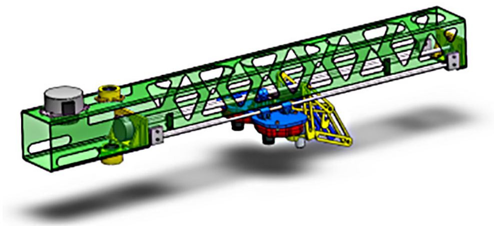

Fig. 5.17 Components of the system for automatic adjustment

The computer vision system contains two cameras to implement a stereoscopic vision, which is used to evaluate the distance to the point of the screw position. A stereoscopic kit with two digital cameras is depicted in **Fig. 5.18**.

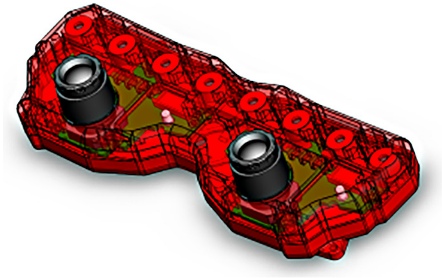

Fig. 5.18 Stereoscopic kit with two digital cameras

To recognize better the position of the screw, we propose to use a mark, as indicated in **Fig. 5.19**.

Fig. 5.19 Example of a mark for screw detection

Another variant of the system for an automatic adjustment we propose is displayed in **Fig. 5.15**. In this system, a central tube is installed as a guide for a special type of manipulator.

The prototypes of solar concentrators with flat triangular or square mirrors have the support frame from bars and nodes. The goal is to automatize the structural construction process. We propose an automatic assembly system that can be used for the construction of the solar concentrator support frame. The first step is to simulate the structure and the two main modules (manipulator and computer vision) using SolidWorks. The results of the simulation will be used to fabricate real prototypes in the future.

In Azerbaijan, the period of active agricultural activity, for example, for planting potatoes or beets, depending on the region, starts from late February to April. Potato varieties are distinguished depending on how many days after planting the tubes are dug out: early – after 50–65 days; medium early – after 65–80 days; mid-season – after 80–95 days; medium-late – after 95–110 days; late – after 110 or more days. Planting rows are often wide enough to install solar concentrators.

In Mexico, cultivation starts in April and ends in October or November [55]. Solar concentrators can be used during this 7-month period. In early May, plants do not consume much solar energy, and during this period, the solar concentrators can be placed easily. However, by the end of the second month, the plants are fully grown and need more sunlight. In this case, solar concentrators can be removed from the field and put into storage. In the period from November to April, concentrators can be installed throughout the field.

Fig. 5.20 shows the extent of agricultural activity during the twelve months of the year in Mexico. It is possible to compare the season in Mexico with season in Azerbaijan (**Fig. 5.21, *a***). The harvest periods correspond to the grayscale rectangles in **Fig. 5.21, *a***.

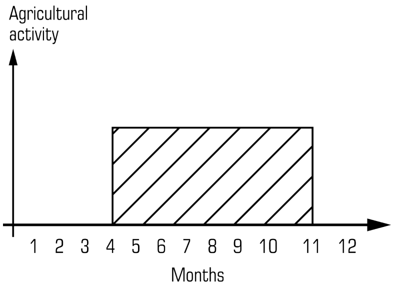

Fig. 5.20 Extent of agricultural activity

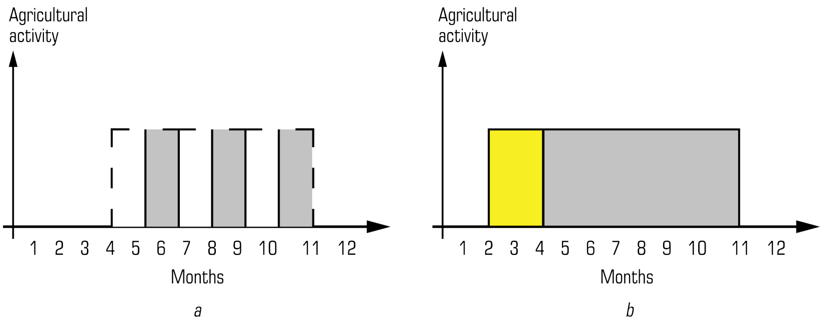

Fig. 5.21 Agricultural activity: *a* – three harvests over a 12-month period in Mexico; *b* – one harvest period in Azerbaijan

The maximum number of solar collectors could be placed in the field during the November-April period (**Fig. 5.20**). 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. 5.21, *a***).

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 Azerbaijan, characterized by only one harvest period per year is shown in **Fig. 5.21, *b***.

CONCLUSIONS

We have developed several prototypes of solar concentrators that are compact, light, and inexpensive. We selected parabolic solar concentrators with plane mirrors that approximate the parabolic surface.

We proposed the creation of integrated systems for electricity generation and agricultural products on one field of land through the use of solar energy. The proposed models, without any need for empirical studies directly on the field, made it possible to evaluate the distribution of solar concentrators, to avoid their assembly in the field, and to obtain results without conducting experiments on real sowing and harvesting cycles.

The next stage of the study includes the development of an optimal strategy for placing solar concentrators among crops and the production of new prototypes of solar concentrators with the parameters obtained after experimental trials. The proposed system includes a dual source of income for farmers, employment opportunities for both solar and crop production, rural electrification, and the availability of electricity for local agricultural processing.

Due to the geospatial positions of Azerbaijan and Mexico located in privileged regions of solar radiation, they have many opportunities for the practical use of solar energy.

The main problem of the proposed solar concentrators is the automatization of their assembly. We analyzed two approaches for the assembly automatization of solar concentrator frames. The both methods can be further realized and do inexpensive the solar concentrator manufacturing.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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