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. The green energy is very important in modern world because of global climate change, which has caused disproportion in the ecological balance, population growth rates, an increase in demand for food and electricity against the backdrop of a decrease in arable land. They are now the main challenges to the development of agriculture and ensuring sustainable food security of many countries. In this paper, as one of the ways to address these challenges, the problems of combining crops with agrivoltaics are studied using the example of two countries – Mexico and Azerbaijan. The economy of both countries is based on oil production, relief and climate 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. 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. 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 article. The simulation of these processes was made with using software of SolidWorks

Keywords: agricultural crops, mathematical model, solar concentrator, flat triangular mirrors, assembly

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DEVELOPMENT OF A MODEL OF COMBINATION OF SOLAR CONCENTRATORS AND AGRICULTURAL FIELDS

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1. Introduction

In recent decades, the world has faced a number of global challenges. First of all, this is the increase in the population of the world. According to the new UN forecasts, by mid-November 2022, the world's population is estimated to increase to 8 billion people, and the 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 [1].

Positive demographic trends lead to an increase in demand for food, electricity and the need for a continuous increase in agricultural production. However, the provision of food to the population is complicated by the decrease in arable land due to degradation, loss of crops or low productivity due to sudden changes in temperature, excess rainfall and natural disasters. Other reasons for the currently observed shortage of food and the aggravation of the problem of food security are the urbanization, increased population density and increased emissions in large cities, population migration due to lack of land, lack of water resources, and armed conflicts [2].

Today, the global climate change, which provokes most of the above factors, causes great damage to agriculture and is recognized by the entire world community as another key challenge of our time [3].

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 [4].

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. [2, 3, 5].

Therefore, the issues of ensuring the sustainability of the agricultural sector and the adaptation of agricultural ecosystems to climate change are the current priorities of the policy of many countries [2, 5]. The development and implementation of measures to switch to alternative energy sources (GHG) and to increase food production can contribute to solving another global problem, i.e., ensuring sustainable food security of the world's population.

The ever-growing demand for energy in the world is accelerating the gradual transition of nation-states to green energy. This area also stimulates the employment of the human resources living in rural settlements, and provides a certain contribution to the achievement of sustainable development goals [6–8].

The development of agricultural production is largely determined by the technological modernization of the industry, the development of new climate-adapted 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].

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 [9–11].

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 agroecosystems, namely agrivoltaic, provides the possibility of dual use of land, i.e. growing plants while generating electricity on the same land [12–15]. Photovoltaic panels are mounted at a certain height in this regard, allowing crops to grow under them.

Presently, many researchers consider agrivoltaics a concept ensuring the resilience of the agricultural industry to climate change. As a result of the research, scientists have identified the following advantages of combined land use:

1) economical use of land (elimination of the main disadvantage of solar energy – idle land on large areas for solar farms);

2) an increase in the yield of areas – from 20 % up to 70 %;

3) the best growth of many vegetable and berry crops is not under the open sun, but in partial shade;

4) reduction in the level of evaporation of moisture in the soil, which can reach up to 30 %;

5) ensuring the energy independence of farmers [12–16].

Researchers have mentioned the necessity of continuing study for identifying the best feature of the behavior of various crops in a combination with green energy equipment, especially solar concentrators.

2. Literature review and problem statement

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.

The concept of agrivoltaics was proposed by Goetzberger and Zastrow in 1982 [17]. However, this idea was put into practice in pilot agrivoltaic plants 30 years later. To date, three types of agro-electric systems have been proposed for the simultaneous growth of crops and electricity production on agricultural lands [17, 18]. Commercial photovoltaic power plants can occupy a significant area of land locally. As photovoltaic plants continue to grow, the use of fertile land for solar farms upsurges the competition for land resources between food production and clean energy [19, 20]. Against the backdrop of growing populations and increased demand for food, especially in land-poor countries, new technological solutions are needed to effectively combine solar devices and crops in the same field [10, 12].

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 [21]. 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.

An example of the placement of solar concentrators is described in [22]. 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, 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. The configuration of the placement of photovoltaic panels, which is a suspended placement at a height of 3–4 meters above the various crops, made it possible to free up significant space for the passage of agricultural machinery or workers, as well as a large amount of sunlight falling at an angle. The results of the experiments showed that the shades of the panels did not have a significant effect on the lettuce yield. However, a significant disadvantage of this method of placement is the inevitable shading of crops, which negatively affects the amount of light reaching the plants during the day, and, accordingly, the yield. This is due to the fact that many plants are affected by the reduction in received solar radiation and are not always able to adapt to changing growing conditions. This predetermines the need to identify plants that can adapt to the conditions of joint placement. To solve this problem, field experiments are usually carried out, the results of which take a long time to obtain. In this regard, modeling various combinations of solar devices and agricultural crops, taking into account the specifics of the latter, will seem to be an urgent solution to the problem.

Studies conducted by scientists and practitioners in recent years have revealed the following advantages of combined land use:

1) economical use of land (elimination of the main drawback of solar energy – idle land on large areas of solar farms);

2) increasing the overall efficiency of land use and increasing the yield of areas – from 20 % up to 70 %;

3) the best growth of many vegetable and berry crops is not under the open sun, but in partial shade;

4) reduction in the level of evaporation of moisture in the soil, which can reach up to 30 %;

5) ensuring the energy independence of farmers [5, 10, 12–15].

At the same time, they note the need to continue and expand research to identify optimal models for the combination of different crops and types of solar devices [5, 6, 10, 11].

A new trend is associated with a combination of solar concentrators and agricultural plants on one piece of land. The works [22–24] describe strategies and examples of a combined approach that makes it possible to simultaneously produce electricity and get a good harvest. Authors analyze this situation for different countries, 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. The authors analyze the main trends in developments in the field of solar energy, in particular, solar concentrators, aimed at solving such problems as modularity, autonomy, compactness, ease of installation, cost, simplification of the positioning system, and extension of service life. The devices used to generate solar radiation are described; their advantages and disadvantages are shown [22–24].

In [25] 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.

To simulate the growth and production of crops in the shade of the Agrivoltaic system, in [26] develops a software platform combining the radiation and shading model with the universal plant growth simulator GECROS. 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.

The shading of the crop on the photovoltaic panels is studied in [27]. In the design and development of green energy, the context of the country, covering the potential of renewable energy, energy policy, relief and climate, initiatives in this area is very important. Agroenergy systems are particularly effective in agriculture in countries with dense populations, suffering from land scarcity and lack of crop areas, as well as in countries with dry areas and high solar potential. In India agriculture is the main occupation of the majority of people [28]. Solar photovoltaic stations, which are the basis for the development of low-cost autonomous power supply systems, are currently used to generate energy in many countries, including India. Solar energy technologies are applicable in any branch of the agro-industrial complex and can solve many problems in this field of activity. Due to the suitable solar potential available in India, the deployment of solar energy has been more as compared to other renewable resources. The authors discussed various agricultural applications of solar energy, such as solar water desalination system, solar water pumping system, solar crop dryer system for food safety, etc. as a means to promote solar-based technology. The issues of providing electricity and fresh water to almost 600,000 Indian villages, the possibility of reducing poverty through the development of agrivoltaics remained out of sight in the work.

Potential of agrivoltaic system in Turkey is evaluated in [13]. It is shown that geographical location and grown agricultural products provides to Turkey lot of advantage for applying agrivoltaic system. However, in term of usage of the agrivoltaic systems in Turkey are still at an early stage. To evaluate this, up-to-date policies should be developed and opportunities should be used. To evolve the agrivoltaic system in the country, it is necessary to develop a modern energy policy aimed at supporting the green economy.

A brief review of the literature allows to conclude that the problem of combining solar concentrators or photovoltaics panels and agricultural crops is multifactorial and multicriteria and that there is currently no perfect model for their interaction. The few research prototypes of such systems, along with encouraging results regarding the strengthening of the «immunity» of agricultural systems to climate change, also reveal certain gaps that require clarification. In this regard, it seems appropriate to conduct further research, taking into account different climatic conditions, types and varieties of agricultural crops, new technological solutions using mathematical models. Our main interest is the development of new prototypes of solar concentrators and the technology of the automatic assembly of these solar concentrators.

In this study, implemented within the framework of the third principle, it is made an effort to preserve and upsurge the productivity of agricultural crops while guaranteeing the highest power generation. In this regard, it seems appropriate to conduct further research, taking into account regional characteristics, geographical location and landscape, climatic conditions, types and varieties of crops, new technological solutions using mathematical models.

3. The aim and objectives of the study

The aim of the study is to develop the mathematical model of combination of solar concentrators and agricultural fields. From the practical point of view the mathematical model will make it possible to calculate and evaluate how many concentrators it is possible to collocate in special condition, with what kind of plants it is possible to work, etc. before doing it in practice.

To achieve this aim, the following objectives are accomplished:

– to do comparative analysis of Mexico and Azerbaijan and their possibilities to develop green energy;

– to develop the solar concentrators that are compact, light, and inexpensive. To develop methods of automatic assembly of solar concentrators;

– to propose and justify the structure a mathematical model for the evaluation of the impact of combinations of solar concentrators together with certain agricultural crops. Let's discuss how to select parameters for solar concentrators in this model and what parameters it is possible to select for agricultural fields.

4. Materials and methods

Before developing the mathematical model of combination of solar concentrators and agricultural fields we study possibility to apply for this purpose parabolic dish solar concentrators were parabolic surface is approximated by triangular flat mirrors.

The way the research was carried out includes both theoretical method (mathematical model), and solar concentrator prototyping. Two countries were selected for comparison their possibilities to develop green energy in combination with agriculture.

Assumptions accepted in the work are connected with 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. 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 agrivoltaics 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 collected by solar concentrators.

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.

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. It is possible to describe the general objective and specific objectives in the following way.

Simplifications adopted in the work are connected with mathematical model selected for the work. 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.

5. Analysis of green energy in Mexico and Azerbaijan and of solar concentrator development and their combinations with agricultural fields

5. 1. Comparative analysis of Mexico and Azerbaijan in green energy

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

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

2) geographical location and landscape,

3) climatic conditions,

4) along with traditional energy resources, presence of high potential of renewable energy. 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. 1. 1. Oil and gas industry

Azerbaijan and Mexico are the countries with a developed hydrocarbon industry. Huge reserves of oil and gas resources 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.

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 and by 40 % by 2050 [29, 30].

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 % percent by 2050, including both renewable energy sources and low-carbon nuclear and fossil fuels [31, 32].

5. 1. 2. 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.

Azerbaijan is located in the east of the South Caucasus, to the southwest of the Caspian Sea. 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 [30]. Given the complexity of the landscape and suitability for agriculture, Azerbaijan refers to the category of land-poor countries in the world.

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. 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. Thus, Mexico is also characterized by a lack of land and the predominance of remote mountainous regions with hard-to-reach settlements [32].

5. 1. 3. The climate

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. Depending on the height above the sea 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 [29, 30].

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 [33, 34]. 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.

5. 1. 4. 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 [34]. There are about 3126.3 solar hours during the year. The level of solar radiation is 5.2 kWh/m^2.

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 [29, 35]. 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.

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.

It is proposed to use 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.

5. 2. Solar concentrators and methods of their automatic assembly

The solar concentrators are developed. They are compact, light, and inexpensive. Parabolic solar concentrators with plane mirrors are selected. It approximates the parabolic surface.

Global demand for energy leads to an increase in the need for the use of green energy for irrigation, domestic purposes, etc. [10, 15]. The studies 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 [36–39] 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.

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.

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.

Several prototypes of solar concentrators are developed. 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, it is proposed to approximate the parabolic surface using flat triangular or square mirrors. For this purpose, a special support frame was developed. Fig. 1 shows the support frame simulated using SolidWorks. The structure consists of bars and nodes [37–39].

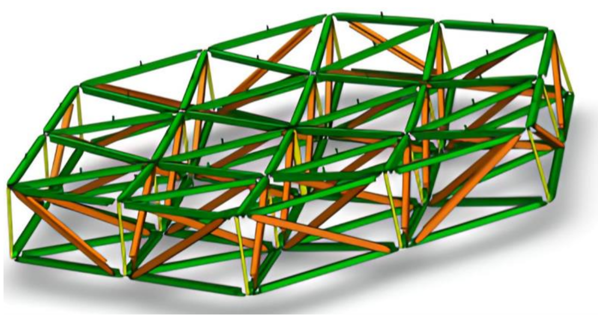


Fig. 1. Support structure of the solar concentrator with triangular mirrors

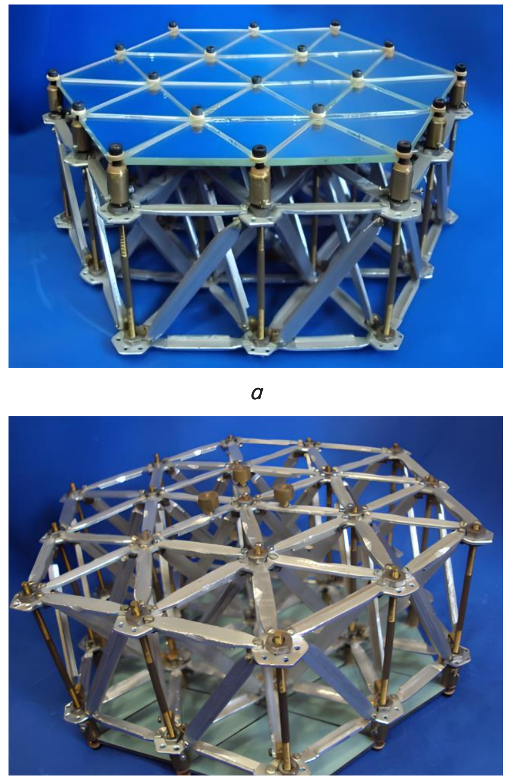
The bars are made from aluminum angles that are connected by screws (Fig. 2).

The first solar concentrator prototype was developed, as shown in Fig. 2. It contains 24 triangular flat mirrors. Fig. 2, *a* displays the backside of the solar concentrator. The structure of the support frame is clearly presented in Fig. 2, *a*. 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. 2, *b*. This prototype was made manually. It is a labor-intensive assembly. Therefore, it is very important to automatize this process.

Let's 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, let's 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.

A holistic system combining renewable energy sources and agricultural fields may use new designs of solar concentrators. Fig. 2 shows prototype of solar concentrators developed and patented in Mexico, Spain and the United States of America. 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.



a

b

Fig. 2. Structure of the first prototype: *a* — backside of the concentrator; *b* — right side of the concentrator with flat triangular mirrors

Equipment technology (MET) has been developed over the past few years [40]. 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, let's 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.

The concept of easily constructing a parabolic surface was patented in the USA, Mexico, and Spain. The tool used is the parabolic rule, as illustrated in Fig. 3 (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.

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

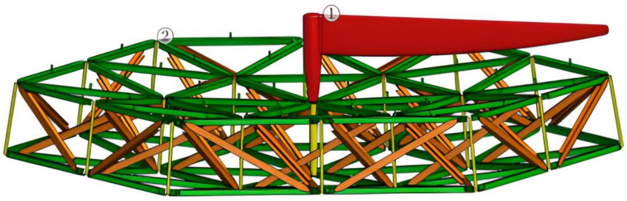


Fig. 3. Adjustment of the parabolic surface:
1 – parabolic rule; 2 – solar concentrator

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. 4.

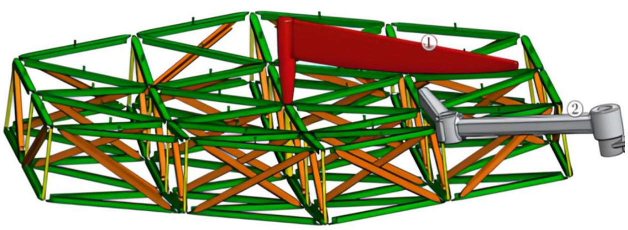


Fig. 4. Adjustment of parabolic surface using:
1 – the parabolic rule and 2 – the manipulator

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 proposed system for an automatic adjustment is displayed in Fig. 5. In this system, a central tube is installed as a guide for a special type of manipulator.

Fig. 5. Variant of the automatic adjustment system

Components of the system for automatic adjustment include the guide. This guide contains two important components: the manipulator and the computer vision block.

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. To recognize better the position of the screw, let's propose to use a special mark.

Another variant of the proposed system for an automatic adjustment is displayed in Fig. 4. 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. An automatic assembly system is proposed. It 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. 3. The structure a mathematical model of combination of solar concentrators with agricultural fields

The proposed structure a mathematical model is simple and can be implemented for different cases of a combination of solar concentrators and agricultural fields.

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 can permit to obtain the maximum productivity of both. Detailed implementation of the first task is described below.

The first task is to evaluate the parameters of solar concentrators. 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:

$$f_1(y)=\sum_{j=1}^{M} b_j y_j, \tag{1}$$

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

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 second task is the selection of agricultural field parameters. 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:

$$f_2(x)=\sum_{i=1}^{M} a_i x_i, \tag{2}$$

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

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 [24].

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 [22]. 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.

6. Discussion of the results of the study of green energy in Mexico and Azerbaijan, of the solar concentrator development and their combination with agricultural fields

The scope of the results is the following. The comparative analysis of Azerbaijan and Mexico was carried out, taking into account regional and geographical features, politics, etc., especially green energetic.

The development of solar concentrator prototypes with plane triangular flat mirrors which approximate the parabolic surface is described. Two methods of automatic assembly of this type of concentrators are proposed in this article. The limitation is connected that these methods were simulated with Solid Works. In future the prototypes of these assembly systems will be developed. In comparison with methods described in section 2 developed and simulated methods permit to reduce the cost of solar concentrators' production and their applications. As example of applications of solar concentrators Azerbaijan and Mexico can be chosen.

One result more is the development of mathematical model to evaluate the combination of solar concentrators with agricultural fields to get double benefits from energy generation and harvesting on the same lands.

This study is dedicated to renewable energy on the example of two countries, Mexico and Azerbaijan. A comparative analysis of the economic situation, green energy development, climate, relief, etc. of these two countries is not done. 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 economy of the both countries is petroleum oriented. So, to decrease in future the contamination it is necessary to develop green energy.

It is proposed to use the solar concentrators developed last years instead of photovoltaic system. The cost of these concentrators is low because flat triangular mirrors instead of concave mirrors with high price are used. It is proposed to do them with diameter of one or two meters.

The mathematical model is developed to calculate how many solar concentrators it is necessary to collocate in agricultural fields. It is included parameters of solar concentrators and agricultural field parameters.

The limitations of this study is that all prototypes of solar concentrators were manual assembled. It is very important to develop the methods of automatic assembling. So two approaches of automatic solar concentrator are described.

Conditions for applying the results are the development of prototypes of automatic systems for solar concentrator assembly. Now it is presented only their simulation with SolidWorks. Potentially expected effects from the use of parabolic solar concentrators with flat triangular mirrors together with agricultural fields at a qualitative level are decreasing of the cost of the developed system.

7. Conclusions

1. The comparative analysis of two countries, Azerbaijan and Mexico, was made from the point of view of green energy. 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. Similar geographic, climatic and others conditions will make it possible to apply the proposed concentrators and developed mathematical models in these countries, quantitatively calculate plant parameters and select the most suitable plants, etc. The result obtained in accordance with the task is the firm belief that green energy, especially combination of solar concentrators and agricultural fields is very important for these countries and for the world in total.

2. It is proposed to apply in integrated systems the parabolic solar concentrators that are compact, light, and inexpensive. Every farmer can afford this device. Solar concentrators with plane triangular mirrors that approximate the parabolic surface are selected. The main problem of the proposed solar concentrators is the automatization of their assembly. Two approaches for the assembly automatization of solar concentrator frames are analyzed and simulated in SolidWorks. The both methods can be further realized and do inexpensive the solar concentrator manufacturing in massive production.

3. The structure a mathematical model of integrated systems for electricity generation (with solar concentrators) and agricultural products is proposed. The proposed methodology permits to evaluate the impact of combinations of solar concentrators together with certain agricultural crops, for example, calculate the number and the distribution of solar concentrators. The mathematical model includes two blocks. The first based on evaluation of solar concentrators features. And the second block is connected with evaluation of agricultural fields. The mathematical model can include more blocks and be more complicated. It is only the first approximation. In future it is more important to propose methodology of their mutual coordination. So this model opens up new opportunities to simulate different situation before its physical realization.

Conflict of interests

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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Data availability

Manuscript has no associated data.

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