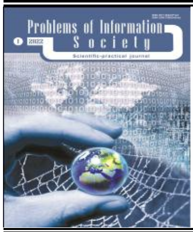

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Assessment of the impact of the combination of crops with solar concentrators on their productivity

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ABSTRACT

The main factors determining the need for the widespread development of the green economy and the growing need for the use of renewable energy sources are identified. The article highlights the possibility of using green energy devices in agricultural complexes and proposes a model for assessing the impact of using solar concentrators together with the agricultural crops on the productivity of the latter. The comparison is made for two countries – Azerbaijan and Mexico, in which economy the oil industry is leading. It is shown that the relief and climate of both countries have many common features, particularly expressed 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 problem of combining solar energy and agriculture is analyzed, examples of successful experiments in this area are given, objective functions and models are proposed to establish the relationship between the parameters of agricultural fields and the characteristics of concentrators.

1. Introduction

At present, humanity has particularly felt that the uncontrolled production and use of traditional energy, emissions of which account for 75% of all greenhouse gases polluting the atmosphere, are unavoidably leading the world to a catastrophe. Not by coincidence the issues of reducing the global climate change and the environmental problems, developing a "green economy" and clean energy, providing each inhabitant of the planet with the access to clean energy were the discussion topics at the annual general debate of the 76th Session of the UN General Assembly with the participation of leaders of states and governments of 193 member-countries, September 21-27, 2021, New York. The representatives of various countries expressed concern in their speeches over the current situation and specific commitments were made to reduce the hydrocarbon share and "decarbonization" of energy industry in the following ten years in order to implement the Paris Climate Agreement, which is a legal international treaty on climate change [1]. The goal of the Paris Agreement is to keep global warming below 1.5oC compared to pre-industrial levels by reducing greenhouse gas emissions, increasing the sources of renewable energy production, and cooperating with various countries to combat the climate change effects.

To achieve these goals, several technological solutions modernizing energy supply systems through the introduction of new equipment and the use of renewable energy sources (RES) are already available.

Solar photovoltaic stations today originate the development of low-cost and environmentally friendly power supply systems using solar energy in many countries. One of the promising and priority areas for the application of solar energy is agriculture, since it is a leading field of activity ensuring the food security of a country. Therefore, the idea of integrating solar devices into agroecosystems – Agrovoltaic systems is currently in the focus of researchers around the world. Various approaches and proposals in this area, aimed at the development of both agriculture and solar devices, are represented in the works of scientists from the USA, Italy, Spain, Mexico, India, etc. [2-6].

These studies highlight three principles for incorporating solar devices into agroecosystems: 1) focus on crops that make up the agroecosystem; 2) focus on the production of solar energy; 3) focus on the integration of solar panels into agroecosystems. In the first case, the goal is to maximize biomass production by minimizing changes in production systems. Devices for electricity generation are placed on existing fields and do not drastically change agricultural production. In the second approach, developers are trying to maximize solar energy production and minimize changes in standard technologies in obtaining solar energy, by promoting the development of agriculture around renewable energy facilities. The third case attempts to combine both approaches and take advantage of the increase in biomass and energy capacity of solar devices.

This study was carried out within the framework of the third approach and involves joint placement of solar devices and crops.

2. Azerbaijan and Mexico: drivers for the Development of a Green Economy

The main factors determining the need for the development of green economy in Azerbaijan and Mexico include the available traditional and alternative energy resources, global trends in environmental protection, geographical location, relief and climatic conditions, and the main priorities of the socio-economic development policy.

A comparative analysis of Azerbaijan and Mexico through the prism of factors determining the relevance of developing new types of renewable energy identifies a number of common features for these countries expressed as follows:

1. The oil industry is the leading sector of the economy, and oil extraction and export are the most important source of foreign exchange earnings and a factor in the growth of the population's welfare. However, as noted above, the extraction and processing of traditional energy resources are associated with environmental problems and considered one of the causes of environmental pollution and global climate change.

Electricity generation in Azerbaijan and Mexico is mainly based on hydrocarbon resources. Both countries have traditionally relied on oil-fired power plants rather than gas-fired ones with relatively cleaner natural gas combustion. The report for 2018, the net generation capacity of power plants in Azerbaijan was 7829 MW, including 84.3% of thermal power plants burning fossil fuels (TPPs), and 15.7% of renewable energy sources (RES) [7]. As of 2020, the share of electricity generation from environmentally friendly sources in the total volume of energy produced in the country accounted for 17%. By 2030, this figure is estimated to be increased to 30%. Azerbaijan has ratified the Paris climate agreement voluntarily undertaking a commitment to reduce the level of gases' emissions by 2030 that create a thermal effect by 35% compared to the base year 1990. Within the framework of the climate agreement, the country's capabilities are studied to determine conditional goals for 2050 [8].

According to the statistics of 2018, in Mexico, the net generation capacity of power plants accounted for 76,921 MW, of which 70.7% accounted for the share of TPPs using fossil fuels, 2.1% - the share of nuclear power plants, and 27.2% - RES [9]. As of 2020, the share of the electricity generated from green sources accounted for 27.8% of the total electricity produced in Mexico. Under the Paris climate agreement, Mexico has committed to increase its electricity generation from clean sources to 35% by 2024, and to achieve a zero share or low-emission electricity generation up to 40% by 2035. In the long term, the capacity of the energy sector is estimated to be increased up to 50% by 2050, including both renewable energy sources and low-carbon nuclear and fossil fuels [5, 10].

2. The territories of the countries are characterized by a relief diversity.

The relief of Azerbaijan covers mountains, foothills, lowlands, plains, and gorges. Moreover, about 60% of the country's area includes mountainous territories [11]. The geographical position and complexity of the relief determine the country's inherent land shortage [12]. The situation was aggravated by the fact that 20% of the territories of Azerbaijan were under occupation for almost 30 years. Ecocide due to land and forest burnings, flora and fauna destruction, widespread contamination of the liberated territories with mines, changes in river beds, poisoning of water resources and other illegal actions led to the degradation of fertile lands in Karabakh and Eastern Zangezur [13].

The relief of Mexico is made up of high mountain ranges, low coastal plains, high plateaus and deserts. Most area lies at a height of 1000 m above sea level. Mountainous regions and highlands occupy almost 2/3 of the country's area, while lowlands and plains are rare [14, 15]. Thus, Mexico is also characterized by a land shortage and the predominance of remote mountainous regions with hard-to-reach settlements.

3. The climate of Azerbaijan is shaped by the geographical position, relief and the Caspian Sea. Several climate types, namely dry steppe, humid subtropical, cold mountainous, etc. are observed in the country [16]. The climate of Azerbaijan provides ample opportunities for increasing the production of electricity and thermal energy through the use of solar radiation. The number of sunny hours in Azerbaijan is 2400-3200 hours per year [8, 17].

The climate of Mexico is also shaped by the geographical position, relief, the Mexican segment of the Pacific Ocean and the Caribbean Sea. The climate of Mexico in the north is subtropical, and tropical in the rest of the country, with humid and hot coastal plains. There are about 3126.3 hours of sunshine in Mexico during the year. On average, the duration of solar radiation reaches 102.84 hours per month [16].

4. The main priorities of Azerbaijan's policy in the socio-economic sphere are aimed at diversifying the economy through the development of the non-oil sector, including agriculture, renewable energy, etc. International Renewable Energy Agency (IRENA) experts estimate the solar and wind potentials of Azerbaijan to be very high, along with its biomass, geothermal and hydropower resources [18]. Political documents adopted in recent years actively support the development of green energy [19-21]. These documents considerably focus on the development trend of the green economy in the agriculture of Azerbaijan. Thus, one of the five main national priorities is "a clean environment and green growth". Particular attention is paid to the high potential for the use of solar energy in the territories of Azerbaijan liberated from occupation, which are predominantly agricultural lands. Currently, with the involvement of leading companies, to ensure the effective use of the potential of renewable energy sources, the creation of energy efficient technologies, concepts and master plan are being developed to create a green energy zone in the liberated territories. The work has already begun on the creation of the first Industry 4.0-based "smart village". This implies the widespread use of modern telecommunications, smart sensors, the Internet of things, distributed transmission, storage and processing of big data, cloud computing, etc. Obviously, the demand for energy production, modernization of energy infrastructure, and the creation of reliable autonomous power supply systems are growing with the development of technology.

Renewable energy sources are vital and have great potential in stimulating the socio-economic development of Mexico. Thus, the government adopted and is implementing a framework to provide modern environmentally friendly energy to almost 3 million people in remote rural areas of Mexico without access to electricity, as well as to reduce the use of traditional biomass for domestic purposes [5, 10]. ENEL Green Power company in Mexico has recently offered the world's lowest prices for solar energy [22].

5. At present, the technical potential of solar energy is estimated to be the highest among RES, particularly in countries with significant annual solar radiation resources. The use of solar energy could help address the problems associated with energy supply in remote and hard-to-reach areas of Azerbaijan and Mexico, which have a difficult landscape and suffer from land shortages. Along with power generation, solar installations can contribute to agricultural systems by reducing wind erosion, as well as saving water.

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 and melon-growing, fodder plants (barley, corn, sunflower, unpolished rice), cotton-growing, tobacco-growing, tea-growing, potato-growing, viticulture, seed, kernel and other species of fruits [23].

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 [15].

Today, 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 Surakhany and Sahil, on the island of Pirallahi, in the regions Samukh and Garadagh, Sumgayit and Nakhchivan. For example, the new Surakhani solar power plant, covering 7 hectares, has a planned total capacity of 2.8 MW. The station includes 8,000 Photovoltaic Panels (PV) with the capacity of generating almost 12,000 kilowatt-hours of electricity per day. Another 4,000 panels are planned to be installed in the future.

A wide network of solar power plants installed in various regions of Mexico is available [5]. Many of proposed solar installations consist of large photovoltaic systems [3]. Construction and operation of such systems, an introduction of new technological solutions can make significant changes in the structure of agriculture and the economy of both countries as a whole.

3. The state of the problem of using solar energy in 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 [24]. Although photovoltaic systems require less land than other renewable energy options [25], 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 [26]. 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. The growth rate under the photovoltaic panels did not decrease at all.

To date, three types of agro-electric systems have been proposed for simultaneous growth of crops and electricity production on agricultural lands. The first type was proposed in early 1980s using photovoltaic panels in the spaces between crop rows [27]. The second type is the photovoltaic greenhouse, in which a part of transparent roof is replaced by photovoltaic panels. The use of photovoltaic energy for greenhouses is a promising solution in the struggle for land resources between food and energy production, as it offers continuous food production and electricity generation throughout the year [28]. The third type consists of photovoltaic panels mounted on poles above crops. Pole-mounted photovoltaic systems 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. The system is designed to provide enough sunlight for crops and enough space for agricultural machinery. In addition, the structure does not have a concrete base, being easy to disassemble.

Fig. 2 illustrates an example of the placement of solar concentrators.

a) b)

Fig. 1. The structure of solar concentrators located on agricultural fields:
a) The supports structure, b) The structure with mounted solar concentrators [29]

In 2016 in India, solar installations and aloe plantations were placed together to maximize water efficiency in drylands by combining water use for panel cleaning and irrigation, diminishing dust generation by increasing soil moisture, and minimizing the effect on natural areas through planting agricultural crops that stimulate economic earnings to improve life in rural areas [3].

In 2018, Amaducci and Colauzzi [30] proposed an agro-electric system, solar tracking, mounted on suspended structures (piles) (Fig. 2). 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 Agrovoltaic system, Scilab [31] develops a software platform combining the radiation and shading model with the universal plant growth simulator GECROS [32]. The platform is designed to serve and manage large sets of climate data and various environmental situations using an open access software relational database.

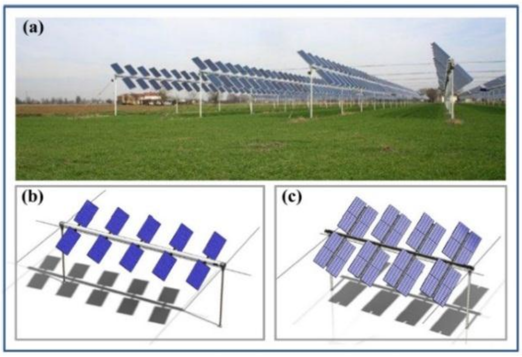

Fig.2. Agro-electric system [30]

a) General view of the system, b) Unit equipped with 5 secondary axles and 10 solar panels, c) Unit equipped with 4 secondary axles and 32 solar panels

The GECROS agricultural crop model predicts the biomass and yield depending on climatic factors (radiation, temperature, wind speed and humidity) and available water and nitrogen amount in the soil. The model represents the response of agricultural crops to individual physiological processes and environmental variables, consequently including the mechanisms governing the agricultural crops dynamics.

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, 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.

4. Challenges of combining solar energy and agriculture

Global demand for energy is growing rapidly, which, in turn, leads to an increase in the need for the use of green energy for irrigation, domestic purposes, etc.

The studies [2-4], [24-26] highlight the possibilities of installing solar concentrators in combination with an agricultural field infrastructure. They show 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 (Fig. 3).

Solar energy requirements differ for crops depending on their metabolism and the time 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 shaped solar concentrators covered with flat triangular or square mirrors. For example, the studies [33 – 37] present the development of such concentrators. The cost of such solar concentrator is low due to 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 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.

Solar concentrators can also be used to preserve rainwater for irrigation, building rainwater collecting systems nearby or around them. These devices can be designed as inverted umbrellas opening when it rains and closing when it doesn’t, enabling the preserved water to be used for solar-powered irrigation.

The main goal 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.

Detailed implementation of the first task is described below.

5. Evaluation of the effectiveness of possible models for combining agricultural plants with solar concentrators

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 most important in a particular situation.

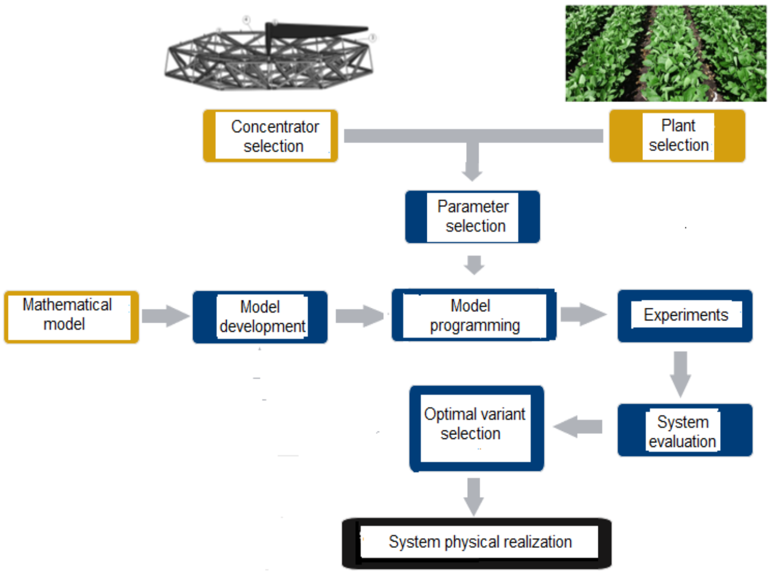

Fig.3. The scheme of combining solar energy with agricultural plant

The simplest model is the linear model. In this case, the objective function has the following form:

$$f_1(x) = a_1x_1 + a_2x_2 + a_3x_3 + ... + a_nx_n \quad (1)$$

where $x_1, x_2, ..., x_n$ are the selected parameters for the field and plants, whereas $a_1, a_2, ..., a_n$ are the coefficients obtained by calculation or experiment for a specific task.

The characteristics taken into account in solar concentrators include their dimensions, weight, plate width or dish diameter, shade produced, mounting structure, material of construction, distribution and number 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:

$$f_2(y) = b_1y_1 + b_2y_2 + b_3y_3 + ... + b_my_m \quad ,(2)$$

where $y_1, y_2, ..., y_n$ are the selected parameters of the characteristics of solar concentrators, whereas $b_1, b_2, ..., b_n$ are the coefficients obtained by calculation or experiment.

Some of these parameters can be obtained from various statistical tables, for example, the yield rate of certain crops. Some of these 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 combined system.

Two main criteria are available for assessing the system performance. 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.

In this study, we identified the following parameters for agricultural crops:

- dimensions of processed field;
- soil type;
- solar radiation in the cultivation area;
- definition of cultivated plant;
- plant dimensions;
- distance between plants;
- stages of plant growth;
- humidity.

The following parameters are important for solar concentrators:

- dimensions of solar concentrator;
- concentrator weight;
- dimensions of supporting structure of the solar battery in cultivation area;
- position and orientation.

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.

Based on the results of the first stage, a computer system identifying the best placement of solar concentrators in the crop field is developed. This computer system determines the best strategy for distributing solar concentrators before it is implemented in real conditions. The computer system can be developed by model developers, or available software systems can be used, for example, software modules described in [31].

6. Possible options for the model implementation

A holistic system combining renewable energy sources and agricultural fields may use new designs of solar concentrators. Fig. 4 shows several prototypes of solar concentrators developed and patented in Mexico, Spain and the United States of America [2], [33 - 37]. 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 that is assembling. This stage is estimated to require automation in the future, which will significantly reduce the cost of the assembling process.

Fig. 4. Prototypes of flat mirror solar concentrators

Micro Equipment technology (MET) has been developed over the past few years [38]. 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.

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 tuber 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 [30]. 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.

7. Conclusion

We proposed creating integrated systems for generating electricity through solar energy and agricultural products on one field. Without any modification or experiment implemented directly in the field, the model enables evaluating the distribution of concentrators in the fields, avoiding the process of assembling solar concentrators in the field, and obtaining results without experimenting with real planting 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 geospatial positions of Azerbaijan and Mexico located in privileged regions of solar radiation, they have many opportunities for the practical use of solar energy.

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