*Journal of Mining institute.* 2021. Vol. 249. P. 427-440 DOI: 10.31897/PMI.2021.3.12
*Yaroslav.E. Shklyarskiy, Dias Daniel Guerra, Emiliia V. Iakovleva, Anton Rassõlkin*

UDC 621.311.25

# The influence of solar energy on the development of the mining industry in the Republic of Cuba

**Yaroslav E. SHKLYARSKIY**[1], **Dias Daniel GUERRA**[1], **Emiliia V. IAKOVLEVA**[1]✉, **Anton RASSÕLKIN**[2]

[1] *Saint Petersburg Mining University, Saint Petersburg, Russia*
[2] *Tallinn University of Technology, Tallinn, Estonia*

***How to cite this article*:** Shklyarskiy Ya.E., Guerra D.D., Iakovleva E.V., Rassõlkin A. The influence of solar energy on the development of the mining industry in the Republic of Cuba. Journal of Mining Institute. 2021. Vol. 249, p. 427-440. DOI: 10.31897/PMI.2021.3.12

***Abstract.*** Cuba is traditionally considered a country with an underdeveloped industry. The share of the mining and metallurgical industries in the gross industrial production of the republic is small – about 3 % of GDP. The development of deposits and the extraction of nickel ores is an important sector of the economy of the Republic of Cuba, since the largest reserves of nickel and cobalt on the North American continent are located on the territory of the country. The development of the country energy system can serve as a growth factor in this sector of the economy. Due to climatic features and impossibility of integrating new capacities into the energy system through the construction of hydroelectric power plants, solar energy is a promising direction. Determining the feasibility of using solar tracking systems to increase the generation of electricity from solar power plants is one of the main challenges faced by engineers and renewable energy specialists. Currently, there are no solar tracking systems in Cuba that can provide information to assess the effectiveness of this technology in the country. The lack of the necessary technologies, as well as the high cost of developing solar power plants with tracking systems, limit the widespread introduction of such complexes. Hence follows the task of creating an inexpensive experimental model that allows assessing the effectiveness of tracking systems in specific weather conditions of the Republic of Cuba. This model will allow in future to increase the efficiency of electrical complexes with solar power plants, which provide power supply to the objects of the mineral resource complex and other regions.

***Key words*:** experimental model; mining industry; Republic of Cuba; solar tracking system; efficiency; electrical complex; renewable energy sources; solar energy

**Introduction.** In recent decades, the field of renewable energy sources (RES) has acquired particular importance for the sustainable development of energy around the world. The share of electricity generated by renewable energy sources in the total electricity generation is increasing annually [30]. The leaders in the production of photovoltaic energy are Germany, Spain, Japan, and Italy. Photovoltaic power in Spain reached its maximum daily output to June 21, 2020 by integrating 68 GWh into the country grid, according to REE data. After this integration, in July of the same year, 1894 GWh were generated at photovoltaic stations, which is the maximum value of the energy generated by the source. [16]. The dynamics of the use of renewable resources in the energy supply systems of the Republic of Cuba is similar. This is due to many factors: the lack of traditional sources of energy (oil, gas), favorable climatic conditions, global trends. On the territory of Russia, renewable energy sources are also used today, which increase the energy efficiency of power supply systems. [1, 2, 4, 7]. In works [8, 9] the renewable energy sources problems of integration of renewable energy sources power supply systems in Russia [34, 36], problems of maintaining the quality of electricity generated by renewable energy sources, as well as environmental aspects of the use of this type of energy resource are widely covered [21, 29]. However, an absolute transition from traditional energy sources to renewable energy sources, according to leading world scientists, is impossible both because of their lower efficiency and the cost of this type of energy resource [3, 11].

The development of nickel mining and metallurgy in Cuba can be divided into 4 stages: 1942-1962, 1962-1986, 1986-1994 and 1994 – present. Each stage is characterized by an increase in the area affected by these activities. The extraction of minerals at all deposits is carried out in an open

way. According to the Ministry of Basic Industry, Cuba is one of the world's largest producers of nickel, the main export commodity, with a production capacity of about 75 thousand tons per year, and covers 10 % of the global demand for cobalt. Nickel is irreplaceable in the production of stainless steel and other alloys. Cobalt, in turn, is essential for the production of alloys used in such products as aircraft engines. Nickel became the country's largest source of export earnings in 2000, amounting to about 2 billion $. The main sales markets are Canada, Europe and China.

In early 2008, before nickel prices plummeted, Cuba announced that the mineral had supplanted tourism as its main source of foreign exchange. According to the National Mineral Resources Center, the province of Holguin contains 34 % of the world's nickel reserves with approximately 800 million tons of proven nickel and cobalt reserves and 2.200 million tons of probable reserves.

Currently, the mining industry has a negative impact on the environment in the regions. It should be noted that among the most significant consequences are deforestation of more than 5.000 hectares of forest land, pollution of inland and sea water bodies. The most common pollutants are sulfates and heavy metals (Ni, Cr, Mn, etc.). Since there are no large reserves of hydrocarbons (oil, coal, natural gas) and powerful rivers on the territory of the Republic of Cuba, renewable energy sources are a strategically important solution to the problem of increasing the volume of electricity generation and reducing the negative impact on the environment in the regions of production.

The expansion of mineral processing enterprises requires the widespread use of solar energy as an effective and economical alternative to traditional forms of electricity production in remote regions where there are no centralized power supply networks, in regions with underdeveloped power grids. However, the problem of maximizing the solar energy captured by photovoltaic modules has not been fully resolved [10].

The most well-known are two ways to maximize the electricity received from a photovoltaic installation: improving the structure of the photovoltaic panel, aimed at increasing its performance; an increase in the amount of solar radiation captured by the panel. For best results with the second method, the area of the photovoltaic panel should remain perpendicular to the radiation of the light source. For this, solar trackers are used in photovoltaic systems [17, 18, 23]. The scientific works of many scientists are dedicated to increasing productivity by improving the structure of photovoltaic panels [20, 27, 35], and this work does not consider them.

Currently, there are several types of tracking systems that optimize solar energy. Their main manufacturers are such companies as Nextracker, Array Techologies, PV Hardware, Arctech Solar, Soltec, Nclave, Convert Italia, STI Norland, GameChange Solar, SunPower. Nextracker is the leading manufacturer of photovoltaic trackers in the global market (up to 2019). The deliveries of this company today account for 29 % of the total volume. The second largest manufacturer in 2019-2021 is the Array Technologies company, followed by PV Hardware (PVH) and Arctech Solar, the Soltec concern occupies the fifth place in this rating. Until recently, America was the largest regional market and represented more than half of the global demand for photovoltaic devices. However, the Middle East and North Africa also experienced high growth rates.

The development of technologies in related fields in recent years has contributed to the development of technologies used in solar energy. Today, with the help of various software products that allow, through computer modeling, to study the processes occurring in electrical complexes, various motors and drives, including through the construction of digital twins, increasing the efficiency of specific installations and objects has reached a new level [19, 26, 34]. A special role in this was played by the development of electronic components that facilitate the study of processes. One of them is Arduino – a platform on which various research projects can be developed.

Arduino is an open source hardware and software platform based on a board with analog and digital inputs and outputs, in the Processing programming language, i.e. an open source platform for

electronic prototyping. It is suitable for the development of any type of project and does not require licensing. The first commercial Arduino board based on the 8-bit Atmel AVR processors entered the market in 2005 with low cost, sufficient functionality and a low threshold of entry. At the moment the models of boards with 32-bit ARM Cortex M3 microcontrollers are available.

Currently, there are other platforms similar to Arduino – Raspberry Pi, DSP and FPGA – with the advantages of software and hardware, reliable for conducting scientific research with high accuracy and quality. Arduino was chosen for this research because it is a free platform.

The object under study was a direct conversion solar power plant with a capacity of 2.5 MW, located on the territory of the Republic of Cuba in the province of Santiago de Cuba. The choice is due to the search for a solution to the problem of increasing the efficiency of converting solar energy into electrical energy in an optimal way, taking into account the climatic characteristics of the region. As you know, the climatic characteristics of this region are favorable for the use of solar energy, however, the existing systems are characterized by low efficiency, so the research task is urgent.

**Materials and research methods.** *Solar tracking systems*. There are several methods of obtaining electrical energy from solar radiation – direct conversion using photovoltaic modules, concentration of solar photovoltaic energy and solar thermal energy [15]. This paper deals with direct conversion solar power plants.

Currently, there are various technologies for the development of solar tracking systems, as well as various models that guarantee an increase in the efficiency of capturing the sun rays, which leads to an increase in the generation of electrical energy.

A solar tracker is a mechanical device capable of orienting solar panels so that they remain perpendicular to the sun rays, following the sun from east (dawn) to west (sunset). Solar trackers are used in all electrical installations that use a solar tracking system. For all the methods, the use of a tracking system for the sun increases the production of electrical energy by the complex.

There are various studies in the field of improving the efficiency of generating electricity from photovoltaic panels using uniaxial and biaxial tracking systems for the sun. In his work [22] Jose Gutierrez suggests a prototype of a low-cost system. The tracking algorithm is based on calculating the position of the sun by calculating solar time. At the heart of the work of Gabriel Willed et al. [37] the tracker is positioned in the direction of the highest solar activity, determined using equations that calculate the position of the sun. Other studies are based on feedback from light sensors that track the most illuminated point, and thus determine the control action of the solar tracking system [6, 12, 14]. Also in work [13, 31] aging and shading of photovoltaic panels which affect the conversion efficiency of solar energy are taken into account.

The following tracking systems currently exist:

• the surface of the panel rotates along the vertical axis and is oriented in the north-south direction; the rotation is adjusted so that the surface normal always coincides with the Earth's meridian;

• the surface of the panel rotates around the axis facing south and is tilted at an angle equal to latitude; the rotation is adjusted so that the surface normal always coincides with the Earth's meridian, the rotation speed is 15 degrees/h, similar to a clock;

• the surface of the panel rotates along the horizontal axis and is oriented in the north-south direction; the rotation is adjusted so that the normal of the surface always coincides with the meridian of the Earth (tilt-lifting mechanism “tip tilt”);

• the surface is always perpendicular to the sun.

Currently, there are models of solar trackers from various manufacturers on the international market, information on the cost of trackers is freely available. Table 1 lists some examples of current procurement costs for existing systems. The data presented in Table 1 correspond to the data as of June 2020.

*Table 1*

**The cost of solar trackers in the international market**

| Types | Cost, USD/W | Efficiency*, % |
|---|---|---|
| Vertical axis tracking and (1) | 0.08-0.14 | 10-25 |
| Horizontal axis tracking (2) | 0.08-0.14 | 10-25 |
| Tilt & lift tracking horizontal axis mechanism (3) | 0.19-0.25 | 10-20 |
| Biaxial tracking system (4) | 0.40-0.50** | 30-45 |

*Note.* * Efficiency of solar tracking systems versus stationary systems. ** Biaxial Solar Tracking Systems with GPS Satellite Navigation System.

A 1000 W biaxial solar tracking system can cost around 250 $. Minimum orders for these systems start from 5000 watts.

Obviously, the highest performance solar trackers have two axes. As for various biaxial devices, there are differences in productivity gains ranging from 30 to 45 % compared to stationary installations. In addition, it should be noted the differences in the cost of the equipment itself and the foundations for the complexes. Uniaxial solar trackers increase the performance of solar panels by 10-20 % compared to stationary designs. Biaxial systems can increase productivity by 25 % [11].

*The structure and characteristics of the experimental model developed for the study of solar tracking systems included in the electrical complex*. The project is developed on the basis of the Arduino Mega 2650 platform, which has 16 analog inputs with a resolution of 10 bits each, and 54 digital inputs.

Arduino is a microcontroller that executes a series of instructions (programmed by the author) compiled in an Integrated Development Environment (IDE). The Arduino IDE was used to implement the project.

As a part of solving the problem, an experimental model, in which an altitude-azimuth control system is used (Fig.1), was developed. The choice of this type of control is due to the fact that this type of tracking the sun provides the greatest efficiency in absorbing solar rays.

In addition to the components shown in Fig.1, *b*, the experimental stand includes a memory adapter, a Wi-Fi communication module, a microprocessor, a connection relay, an external power supply, and a built-in clock.

An increase in the efficiency of converting solar energy into electrical energy is achieved due to the implementation of two control systems in the installation simultaneously – astronomical and optical. With the help of sensors (photoresistors), the module is positioned to the brightest object, the position of which in altitude-azimuth is corrected according to the calculated equations of the position of the Sun, which were initially recorded in the program. The rotating mechanism is based on five volts servo drives. The motors and control circuits are powered by a solar battery. The installation makes it possible to evaluate, in specific climatic conditions of the region, the operation and efficiency of solar tracking systems in comparison with stationary systems. The structure of the experimental setup with all components is shown in Fig.2.

In order to find out which sensors of environmental parameters should be used in the experimental model, a correlation study was carried out, which allows to find the relationship between different

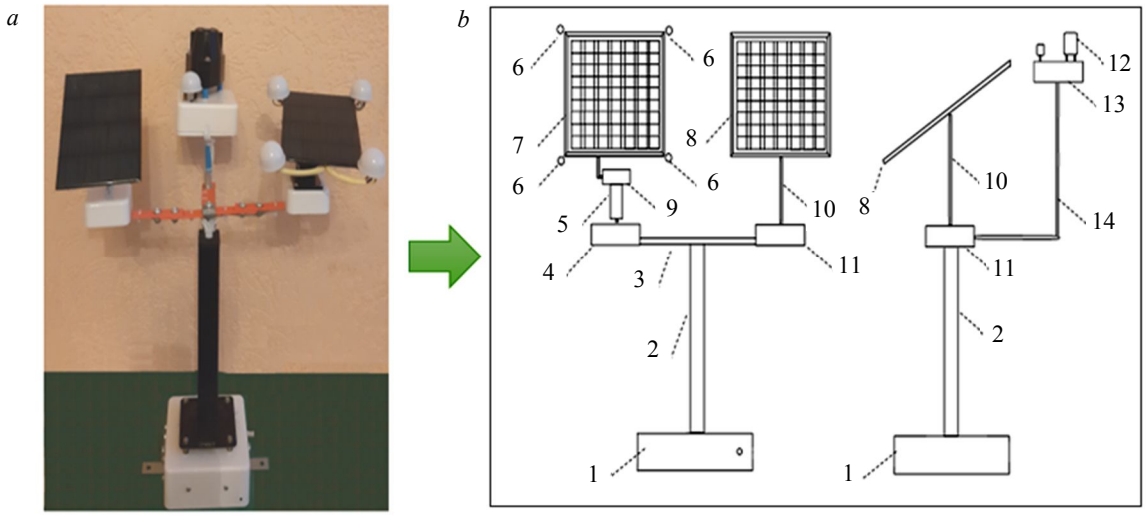



Fig.1. The external view of the installation (*a*) and the general view of the device (*b*) of the experimental stand

1 – connection box; 2 – T-shaped support; 3 – sensor of ambient temperature, atmospheric pressure and relative humidity; 4 – solar tracking system; 5 – servomotors for vertical rotation; 6 – sensors of sunlight and tilt; 7 – low power solar panel; 8 – meteorological station; 9 – servomotors for horizontal rotation; 10 – high-precision digital light sensors; 11 – stationary system;12 – solar radiation sensor; 13 – voltage and current sensor; 14 – operating temperature sensor

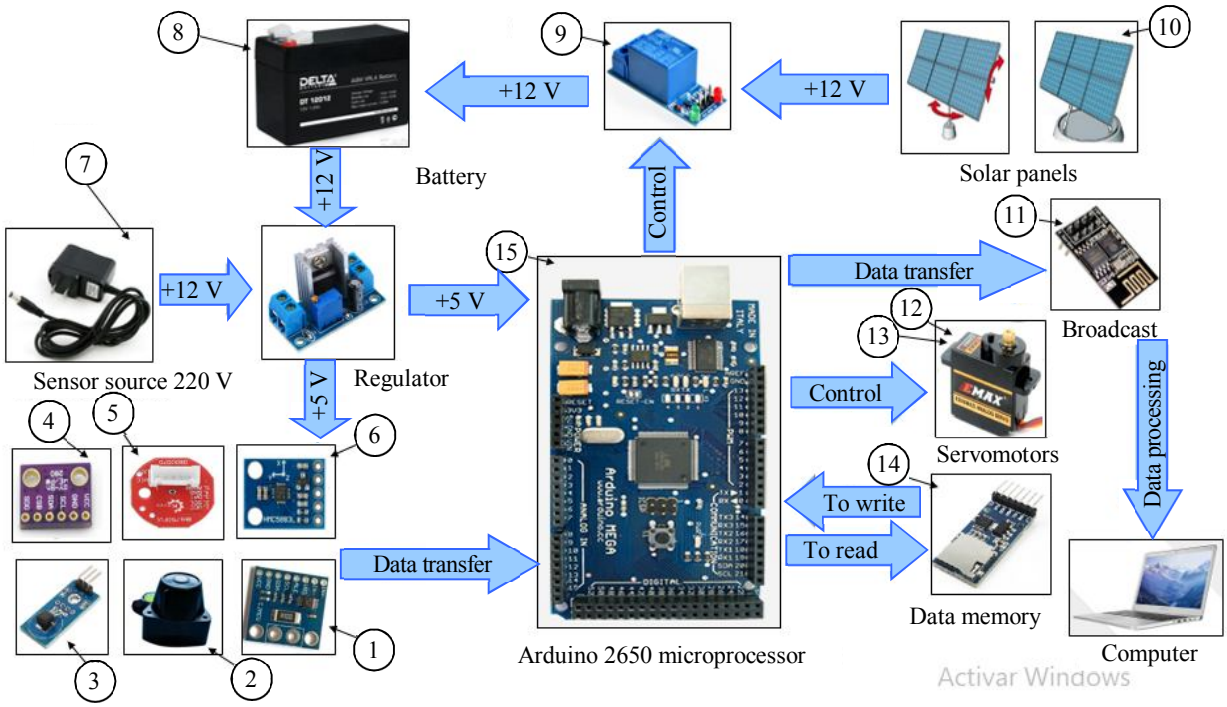



Fig.2. Experimental setup structure

1 – voltage and current sensor; 2 – solar radiation sensor; 3 – operating temperature sensor; 4 – sensor for ambient temperature, atmospheric pressure and relative humidity; 5 – sun light sensor; 6 – digital compass; 7 – external power supply; 8 – battery; 9 – connection relay; 10 – low power solar panel; 11 – Wi-Fi communication module; 12 – servomotors for vertical rotation; 13 – servomotors for horizontal rotation; 14 – memory card; 15 – microprocessor

variables – electricity $E_{df}$, solar radiation $I$, wind speed $V$, atmospheric pressure $P$, humidity $RH$ and ambient temperature $t$. Then, for each of the selected variables, the Pearson coefficient $R$ was calculated using the statistical program Mintab 18.0. Based on the calculation, it was determined whether the correlation between the studied variables is significant. The main criterion was the value of the Pearson coefficient $R < 0.05$. The analysis results are presented in Table 2.

*Table 2*

**Correlation analysis results**

| Parameter | | $E_{df}$ | $t$ | $V$ | $P$ | $RH$ |
|---|---|---|---|---|---|---|
| $t$ | $K$ | 0.756 (4) | – | – | – | – |
| | $R$ | 0 (1) | – | – | – | – |
| $V$ | $K$ | 0.548 (4) | 0.162 (3) | – | – | – |
| | $R$ | 0 (1) | 0 (1) | | – | – |
| $P$ | $K$ | –0.131 (3) | 0.004 (3) | –0.199 (3) | – | – |
| | $R$ | 0 (1) | 0.851 (2) | 0 (1) | – | – |
| $RH$ | $K$ | –0.703 (1) | –0.390 (4) | –0.405 (4) | –0.017 (3) | – |
| | $R$ | 0 (1) | 0 (1) | 0 (1) | 0.427 (2) | – |
| $I$ | $K$ | 0.711 (4) | 0.308 (4) | 0.411 (4) | 0.129 (3) | –0.718 (4) |
| | $R$ | 0 (1) | 0 (1) | 0 (1) | 0 (1) | 0 (1) |

*Note.* 1 – the correlation is significant $R < 0.05$; 2 – correlation is not significant $R > 0.05$; 3 – small correlation; 4 – high correlation.

The results show that atmospheric pressure has little correlation with other meteorological variables. The largest correlation of variables is observed between relative humidity and solar radiation (inverse correlation), ambient temperature and relative humidity (inverse correlation), ambient temperature and solar radiation (direct correlation) (Fig.3). The analysis presented in Table 2 helps to determine which main meteorological variables should be taken into account when assessing the energy characteristics of photovoltaic complexes with or without a solar tracking system in specific climatic conditions.

These coefficients were obtained for the climatic and geographical conditions of the Republic of Cuba, the use of this methodology is also planned to calculate the correlation at the facilities of the mineral industry in other regions.

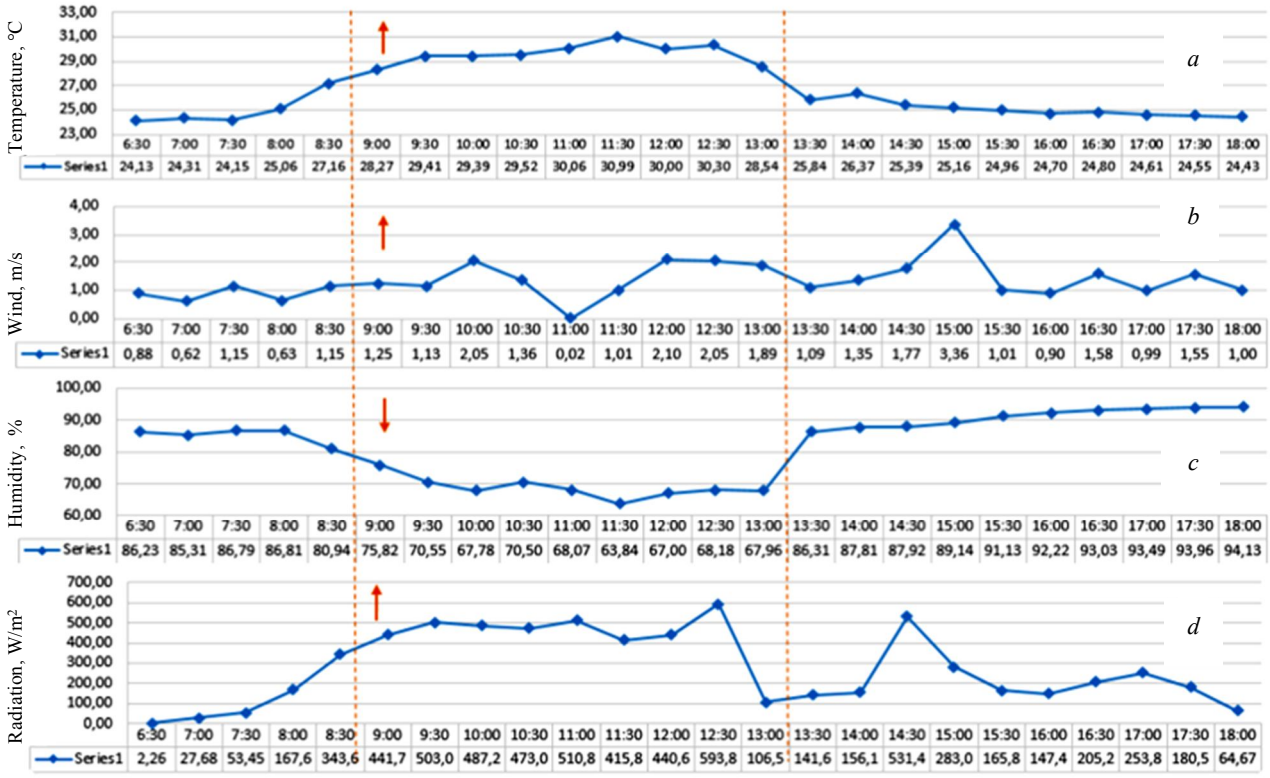



Fig.3. Meteorological variables: ambient temperature (*a*), wind speed (*b*), relative humidity (*c*), solar radiation (*d*) 23.10.2018 in the province of Santiago de Cuba, Republic of Cuba, corresponding to 20.02°N and 75.82°W

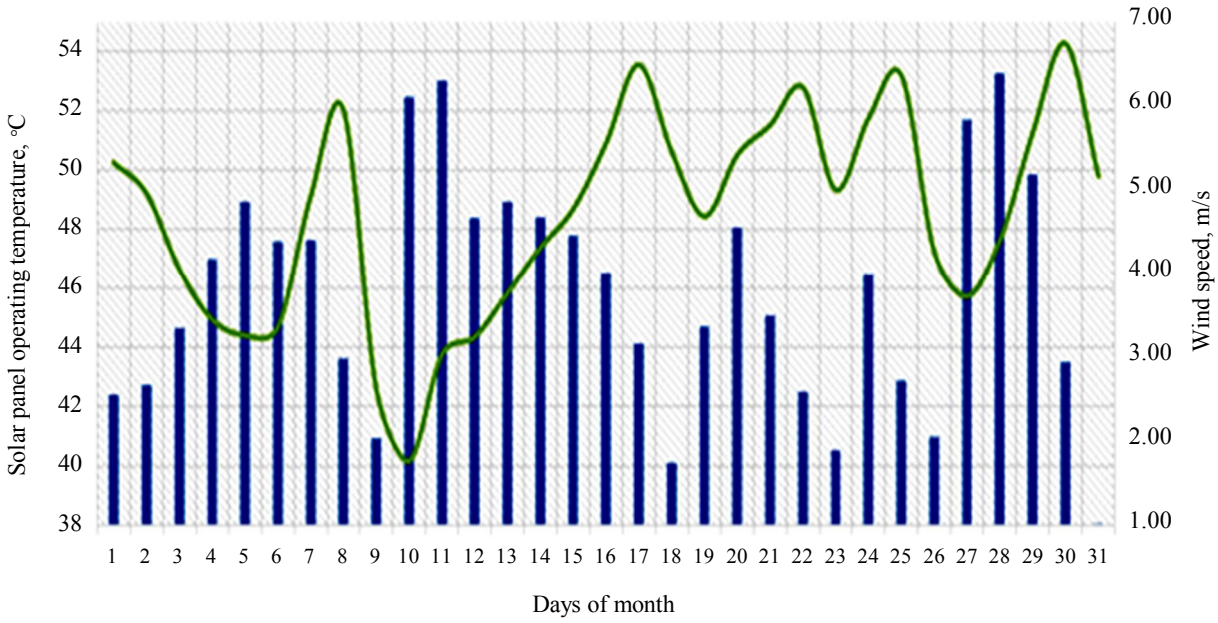



Fig.4. Solar panel operating temperature versus wind speed

The study also revealed that the energy produced by the photovoltaic system has a direct correlation with time (0.15), ambient temperature (0.76) (Fig.3, *a*), wind speed (0.55) (Fig.3, *b*), solar radiation (0.71) (Fig.3, *d*) and inverse correlation with relative humidity (–0.70) (Fig.3, *c*). This means that for given climatic conditions with higher radiation, the relative humidity is low, and vice versa. It should be borne in mind that previously measured climatic variables directly affect the thermal performance of the solar panel, i.e. operating temperature.

Figure 4 shows the dependence of the operating temperature of the solar panel (CNC85X115-18) on the wind speed in the region under study.

The results of experimental studies in real operational and weather conditions indicate that when a solar module operates with an average operating temperature of 50 °C, its power decreases by 10 %, therefore, the energy also decreases by 10 %, which is unacceptable. The following regularity was revealed – if the wind speed exceeds 3 m/s, the operating temperature of the module decreases significantly (at the wind speed of 3-7 m/s, the temperature decreases by 3-5 °C). This is a good thing, because the longer the panel is operating at standard operating temperature (25 °C), the higher its performance.

Based on the results obtained, it can be concluded that for high wind speeds in the region, the solar module will have more efficient electrical characteristics, since it will be cooled faster, which will reduce the operating temperature of the solar panel.

In addition, a correlation study was carried out, on the basis of which sensors of meteorological parameters were selected. The developed experimental model has 13 sensors that measure various parameters of the environment. The model uses five light sensors (BH1750FVI), two operating temperature sensors (DS18D20), one ambient temperature and relative humidity sensor (BME280), one solar radiation sensor (PYR20), one tilt sensor for solar cells, two constant current (INA226) and two voltage sensors (INA226), which measure the current-voltage characteristic of solar modules. Table 3 lists the technical specifications for each sensor in the installation.

Servomotors MG995 are installed in the model for vertical and horizontal positioning of the solar module. Both horizontal and vertical movements are determined by calculating the position of the Sun mathematically as a function of time. For this, an azimuth is determined, which describes the horizontal movement of the position of the Sun on its west-east trajectory

$$\gamma = \cos^{-1}\left(\frac{\sin\alpha \cdot \sin\varphi - \sin\delta}{\cos\alpha \cdot \cos\varphi}\right), \quad (1)$$

where $\delta$ – solar declination angle; $\varphi$ – angle of solar time; $\alpha$ – angle of solar elevation.

*Table 3*

**Sensor Specifications**

| Sensor type | Number | Specifications | Signal type |
|---|---|---|---|
| DHT11 Ambient Temperature, Barometric Pressure and Relative Humidity Sensor | 1 | +/– 1 °C; +/– 3 %; +/– 1 GPa | Digital |
| High precision digital light sensor BH1750FVI | 4 | From –1 to –65535 Lux (16 bit) | Digital |
| Light sensor BH1750 | 1 | 1-65535 Lux | Digital |
| DS18D20 operating temperature sensor | 2 | From –55 to 125 °C (12 bit) | Digital |
| Voltage and current sensor INA226 | 2 | 0-30 B; 0-3 A | Digital |
| Solar radiation sensor PYR20 | 1 | 0-2000 W/m$^2$ | Analog |

The solar altitude is also determined, which describes the vertical movement,

$$\alpha = \sin^{-1}(\cos\theta_z), \quad (2)$$

where $\theta_z$ – zenith angle.

In accordance with the calculation made, the solar module is placed perpendicular to the sun rays [24].

To calculate the efficiency of a system equipped with a solar tracker (energy gain) in comparison with stationary systems, it is necessary to use the following equation:

$$G_{an} = \frac{E_{dm} - E_{df}}{E_{df}} 100, \quad (3)$$

where $E_{dm}$ – electricity generated by a power plant with a tracking system; $E_{df}$ – electric power generated by a stationary power plant.

Equation (3) quantifies the increase in power (in percent) using the solar tracking system in relation to the energy of a stationary system, according to international literature, this value is 30-40 % [10, 32]. Value $G_{an}$ depends solely on the geographical characteristics of the research site, it also varies depending on the season.

The energy generated by the solar panels is stored in a 1.2 Ah battery that powers the experimental model.

The information collected by the experimental model is displayed on the control system display or can be downloaded in .txt format for further processing using software developed in GUIDE / MATLAB.

The IDE version 1.8.5 Arduino was used as a platform, it is used for programming instructions and codes that will later be loaded into the microprocessor.

The algorithm that controls the experimental model of the solar tracker consists of two main blocks: the first is responsible for measuring and collecting data provided by various sensors, the second is the algorithm for determining the position of the Sun (Fig.5).

First of all, the microcontroller takes readings from all sensors in the system. As soon as it is confirmed that there are no measurement errors and/or sensor malfunctions, the information obtained is stored in memory and displayed on the digital display. The microprocessor then executes commands to track the position of the Sun using equations (1) and (2). The calculated horizontal and vertical angular values are corrected using light sensors that search for the average value of the maximum intensity

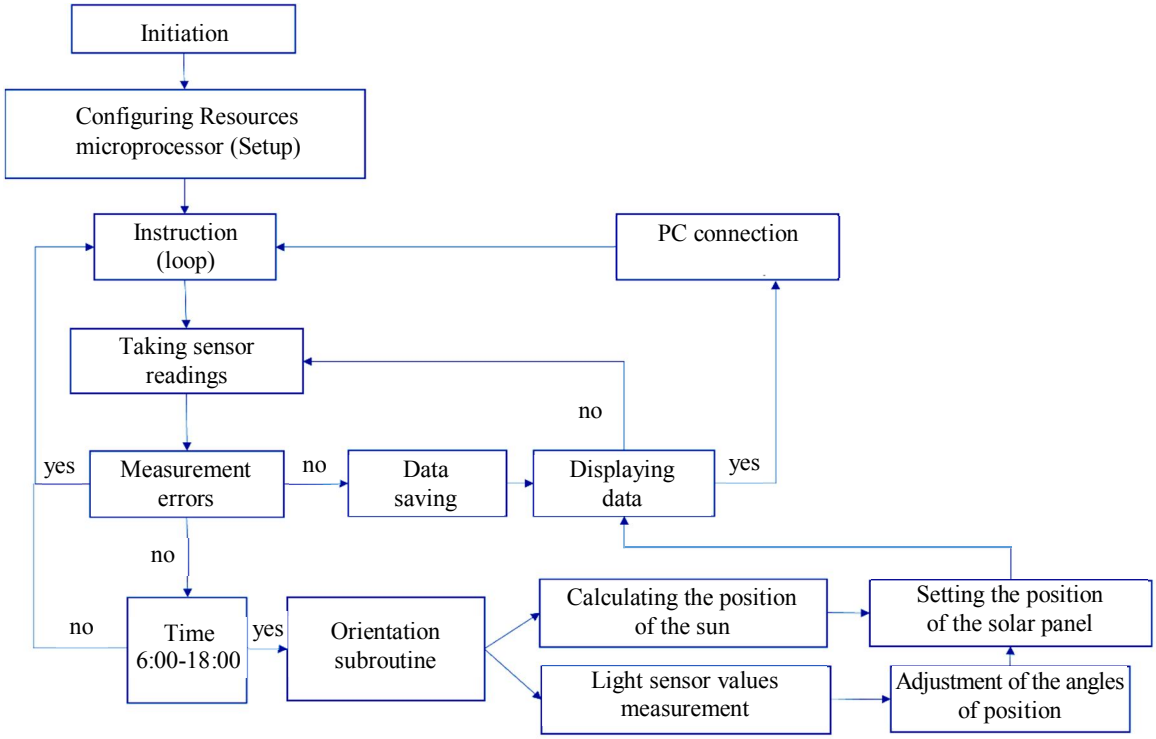



Fig.5. Control Algorithm for an Experimental Solar Tracker Model

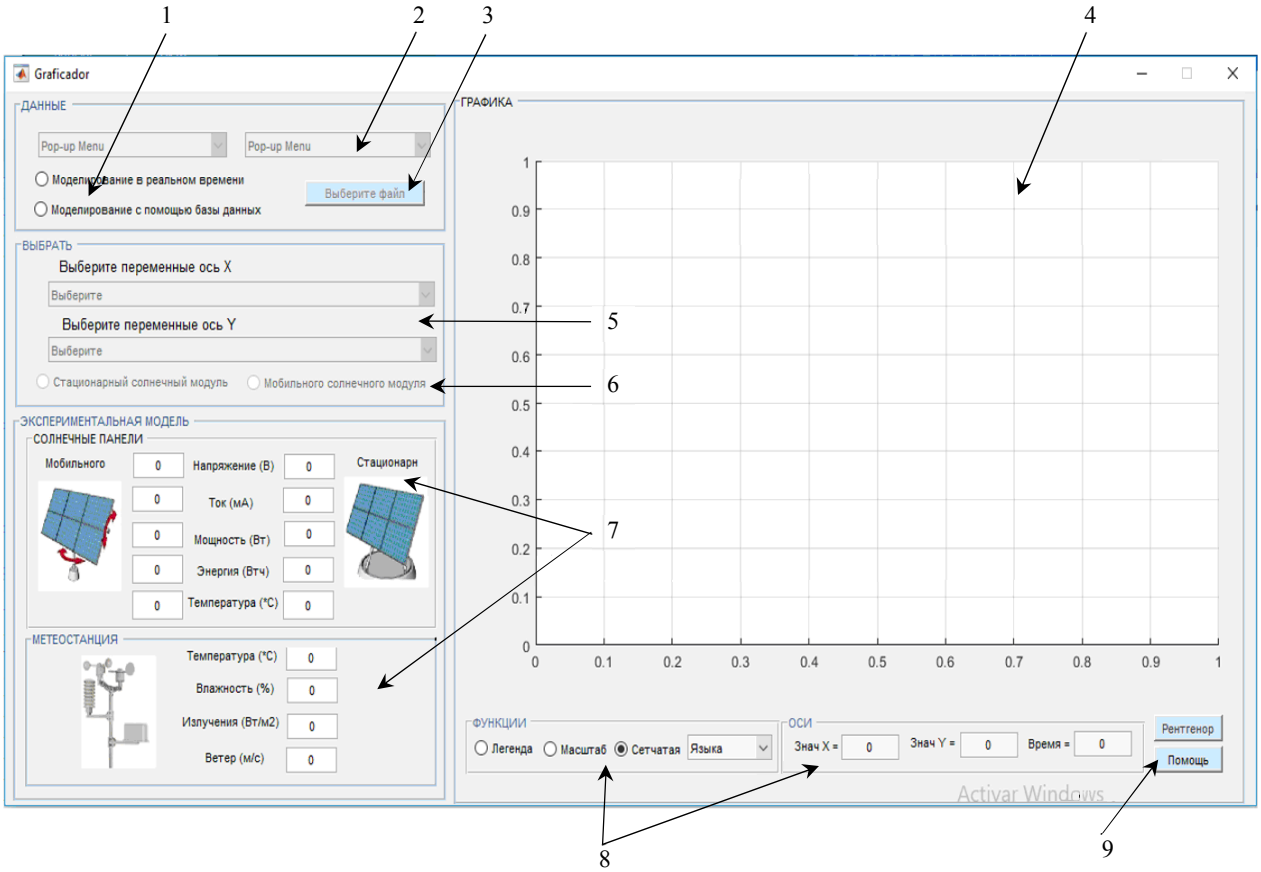



Fig.6. The interface of the data processing program in the GUIDE / MATLAB environment

1 – program operation mode; 2 – date and time; 3 – parameters of solar modules; 4 – graphs; 5 – system selection variable; 6 – type of tracking system; 7 – the results obtained; 8 – functional block of the system; 9 – schedule and help

of light in this space. The values of the horizontal and vertical angles are adjusted according to the tolerance determined in this case equal to 5 %. This percentage can be changed at the discretion of the person performing the measurements using the experimental system. The experimental system works with two combined sun tracking algorithms, such as an astronomical tracking system and an optical system. The optical tracking system adjusts to the solar tracking system more efficiently on cloudy or rainy days, on the other hand, the astronomical system positions the sun tracking system in accordance with the trajectory of the Sun during the day.

*Structure and operation of software designed for data processing.* With the development of an experimental model for studying solar tracking systems in accordance with the climatic conditions of the region, it became necessary to create software capable of processing data obtained from this model. A team of authors has developed software in the GUIDE / MATLAB environment, an interactive platform where it is possible to program in a visual environment and show the result. A patent was issued for this software product in 2020 [5]. The program processes all the information collected in the experimental model data file.

The developed program has two modes of operation (Fig.6): it can work in real time mode via a USB connection with an experimental model, where various variables of interest for both stationary systems and solar trackers can be entered; it can also work with a data file that the experimental model stores in memory.

After selecting the operating mode of the program, calculations are performed, and graphs of the dependences of meteorological variables on time are plotted.

The developed program performs the following functions: makes graphs of all variables measured by the experimental model; calculates the errors of different sensors of the experimental model; calculates and displays the results and graphs of the main variables of the solar tracking system and stationary systems; shows atmospheric values measured by the experimental model; calculates current-voltage characteristics and characteristics of electrical energy of each solar module of both systems and compares them.

With the development of this computational tool, processing the data obtained by the experimental model is faster and easier [25].

Fig.7 shows the results of processing the experimental model data using the developed program. The analysis was carried out using low power solar cells (CNC85X115-18).

The results obtained for the energy generated by the stationary photovoltaic system and the solar tracking system correspond to only one day (23.10.2008) out of 365 days a year. As can be seen from the graphs (equation (3), the energy supplied to the electrical system in 8 h using the solar tracking system is 30 % higher than that of the stationary system (the angle of inclination of the solar generator is 20°).

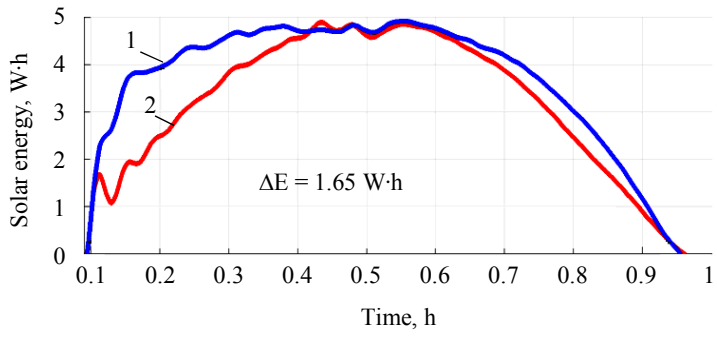



Fig.7. Comparison of the energy generated by the panel power 1.5 W supplied by fixed installation and installation of a solar tracking system.
Time measurement from 6:00 to 18:00
1 – energy (solar generator with sun tracking), $E$ = 7.15 W·h;
2 – energy (stationary solar generator), $E$ = 5.5 W·h

*Measurement errors of the experimental model.* Uncertainty can be defined as a parameter associated with a measurement result that characterizes the spread of values that can reasonably be related to the real value [22, 38].

The sequence of calculating the mathematical uncertainty of the experimental model is as follows:

• calculation of the arithmetic mean of the sample

$$\bar{x} = \sum_{i=1}^{n} \frac{x_i}{n}, \quad (4)$$

where $x_i$ – numerical value of the sample, $n$ – sample size;

• variance calculation

$$s^2 = \sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n-1}; \quad (5)$$

• the criterion for assessing the typical deviation was the positive square root of the variance

$$S = \sqrt{s^2}; \quad (6)$$

• average deviation calculation

$$G_m = \frac{s}{\sqrt{n}}; \quad (7)$$

• calculation of absolute error

$$E_a = G_m + E_i, \quad (8)$$

цруку $E_i$ – instrumental error or sensor measurement error;

• calculation of relative error

$$E_r = \frac{E_a}{\bar{x}} 100. \quad (9)$$

The values shown in Table 4 correspond to the equations above.

*Table 4*

**Measurement errors**

| Measured variable | $n$ | $\bar{x}$ | $S$ | $^*T$ | $E_a$ | $E_r$, % |
|---|---|---|---|---|---|---|
| Ambient temperature sensor, °C | 50 | 30.88 | ±0.479 | ±0.5 | 0.17 | 0.54 |
| Working temperature sensor 1, °C | 50 | 24.18 | ±6.77 | ±1 | 1.46 | 6 |
| Working temperature sensor 2, °C | 50 | 21.46 | ±4.17 | ±1 | 1.09 | 5 |
| Relative humidity, % | 50 | 63.88 | ±0.32 | ±2 | 0.14 | 0.22 |
| Wind speed, m/s | 50 | 1.22 | ±0.53 | – | 0.17 | 6 |
| Light sensor 1, Lux | 50 | 425.98 | ±29.74 | – | 4.2 | 0.98 |
| Light sensor 2, Lux | 50 | 463.16 | ±31.51 | – | 4.5 | 0.96 |
| Light sensor 3, Lux | 50 | 410.97 | ±37.05 | – | 5.2 | 0.94 |
| Light sensor 4, Lux | 50 | 355.92 | ±32.95 | – | 4.6 | 0.97 |
| Voltage sensor, V | 50 | 8.32 | ±0.74 | – | 0.2 | 2.5 |
| Voltage sensor, V | 50 | 8.48 | ±0.73 | – | 0.2 | 2.4 |

* Accuracy indicated by the manufacturer.

Having calculated the errors for each of the sensors of the experimental model, we can draw the following conclusions from the results obtained in Table 2:

• the values obtained by the analog operating temperature sensors LM35 show high relative errors of 6 and 5 %, respectively, and the wind speed sensor has a relative error of 6 %. These are large enough deviations, so it is necessary to determine the reasons for such a large error;

• the reasons that increase the measurement error can be different, the most probable are the following: the sensor can be damaged; the sensor is not calibrated; due to poor-quality implementation errors can be made when measuring with a sensor; electrical interference.

On the other hand, the uncertainty values for LM35 sensors (±6.77 and ±4.55 °C) significantly differ from the value provided by the manufacturer (±1 °C). Other sensors have adequate values of the relative error, some do not exceed 1 %.

One of the fundamental reasons the sensor is used to measure the wind speed in the experimental model is that the wind naturally cools the solar module, this entails a decrease in its operating temperature, which leads to an increase in the output voltage. This is due to the fact that there is an inverse proportional relationship between the temperature of the solar module and the output voltage. All this leads to an increase in the efficiency of the solar module.

As a result of the study, the analog sensors LM35 were replaced by the D18B20 digital temperature sensors, which have insignificant relative measurement errors.

**Conclusion.** Currently, there are several power supply systems that combine electrical subsystems for mining enterprises in the Republic of Cuba with power supply systems with solar installations. Cuba has reserves of nickel and cobalt, large deposits of copper ores, manganese ores of chromites, iron ore, asbestos, phosphorites. In 2006, the development of an oil and gas field began [32]. In 2014, a large Russian company Rosneft and the Cuban state oil company Union CubaPetroleo signed an agreement on cooperation in the field of enhanced oil recovery at mature fields and an agreement on joint development of the Cuban shelf. Therefore, the introduction of solar tracking systems into the power supply systems of the mineral resources complex will not only contribute to the development of the mining industry as a whole, but will also lead to an improvement in the environmental situation in the region. The introduction of two-axis tracking systems into the power supply systems of mining complexes will increase the supply of electricity by 30-40 %, depending on the geographical latitude in which the mining enterprise is located.

The use of a solar tracker is a significant technological solution in the field of optimizing the use of solar energy, since it will allow to more extensively use of energy for the development of industry in future. An experimental model of a biaxial solar tracking system will increase the radiation absorbed by the panels, and therefore the generated energy [39]. At the same time, using the developed model, all electrical parameters of these systems and their dependence on the climatic conditions of the region can be studied.

The proposed experimental model corresponds to the required parameters, and its measurement errors correspond to the range of accepted values. The experimental model is a cost-effective alternative for researching solar trackers in various climatic conditions, as well as in other countries, since the cost of this experimental model does not exceed $100.

The experience gained in the course of the research presented in this paper can be applied in conducting similar studies in Russia [33]. When developing a strategy for the development of energy systems in the eastern regions of Russia, one should take into account the possibility of organizing solar generation centers. [28]. Research of this type will help to objectively assess the technical and economic effect of the application of solar tracking technology in specific climatic conditions.

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***Authors:*** **Yaroslav E. Shklyarskiy,** *Doctor of Engineering Sciences*, *Professor*, *Shklyarskiy_YaE@pers.spmi.ru, https://orcid.org/0000-0001-8803-9898* (*Saint Petersburg Mining University*, *Saint Petersburg*, *Russia*), **Dias Daniel Guerra,** *Postgraduate student*, *dgd210386@gmail.com, https://orcid.org/0000-0001-5752-1251* (*Saint Petersburg Mining University*, *Saint Petersburg*, *Russia*), **Emiliia V. Iakovleva,** *Candidate of Engineering Sciences*, *Associate Professor*, *yakovleva_ev@pers.spmi.ru, https://orcid.org/0000-0002-7354-0185* (*Saint Petersburg Mining University*, *Saint Petersburg*, *Russia*), **Anton Rassõlkin,** *Doctor of Engineering Sciences*, *Professor*, *anton.rassolkin@taltech.ee, https://orcid.org/0000-0001-8035-3970* (*Tallinn University of Technology, Tallinn, Estonia*).

*The authors declare no conflict of interests.*

*The paper was received on 11 March, 2021.*
*The paper was accepted for publication on 21 May, 2021.*