UDC 620.93
DOI: 10.15587/1729-4061.2024.301538

IMPROVEMENT OF SOLAR CONCENTRATOR STRUCTURE

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Green energy includes solar, wind, geothermal and other types of energy sources generation. The object of this research is solar concentrators. The problem to be solved is related to the development of the structure frame, especially for solar concentrators with flat triangular or square mirrors that approximate a parabolic shape surface. The essence of the investigation is developing and producing several prototypes of solar concentrators that have a low cost of materials but the devices were assembled by hand and therefore the manufacturing cost is sufficiently high. Therefore, it is important to reduce the cost through automation of the solar concentrator production process. To obtain better conditions for future automation, we need to reduce the number of metal structural elements of the solar concentrator. In this case, the automation problem is simpler for its realization. The results obtained are related to the improved solar concentrator structure that can be technologically simpler than the previous one and lighter in weight. The development of improved solar concentrator design and structure can help reduce the cost of assembly and accelerate the solar concentrator assembly process. In the case of mass production, they can be used in practice. The proposed solar concentrators can be used for different applications, for example, green buildings in rural areas, or chemical reactors to accelerate the chemical process of organic waste processing. Another application is to use solar concentrators in combination with agricultural fields. These solar concentrators can be used with small-scale thermal energy storage (TES). Using TES, it is possible to make power plants for green buildings. Small solar power plants can support all the energy demands of residential houses

Keywords: flat facet parabolic solar concentrator, solar energy, thermal energy storage (TES)

Received date 31.01.2024
Accepted date 02.04.2024
Published date 30.04.2024

How to Cite: *Baydyk, T., Mammadova, M., Velasco Herrera, G., Kussul, E. (2024). Improvement of solar concentrator structure. Eastern-European Journal of Enterprise Technologies, 2 (8 (128)), 38–45. https://doi.org/10.15587/1729-4061.2024.301538*

1. Introduction

Energy consumption is growing all over the world due to new lifestyle trends related to the increasing use of electronic devices. Global energy consumption will grow by nearly 50 % from 2018 through 2050, according to the U.S. Energy Information Administration (EIA) [1]. With the threat of global warming and the rising cost of energy, the trend towards the use of renewable and sustainable energy sources is becoming more and more popular.

The use of solar energy, for example, in Mexico or Azerbaijan, has great potential, since these countries have good conditions for the development of this industry, which is expressed in the duration of sunny days, their number, as well as direct solar radiation on the surface [2]. Solar energy is the most powerful and affordable, and the use of solar energy is leading in renewable energy.

Solar power plants are designed to convert the energy of solar radiation into heat and electricity. There are the following types:

1) photovoltaic (PV) converters that are used to directly convert electricity through the photovoltaic effect [3, 4];

2) thermal Concentrated Solar Power (CSP) that are designed to produce thermal energy for its further use or conversion into other types of energy. To generate thermal energy, mirrors and lenses are used in CSP.

Photovoltaic converters use semiconductors. The operation of the device is based on the emission of photoelectrons or the internal photoelectric effect. Currently, silicon-based photovoltaic modules (single-crystal and polycrystalline) are the most common type.

Solar concentrators are devices that capture incoming solar radiation and convert it into usable heat. This heat is transferred to the working liquid for transfer directly to the consumer, to a heat exchanger, or a heat engine (for example, Stirling or Ericsson engines) to generate electricity. The temperature level of the working liquid determines its energy performance, and the main factor is the mass flow rate of the working liquid. There are installations for the simultaneous production of electricity and hot water at the outlet.

Renewable energy has many aspects to develop. Solar, wind, geothermal energy and so on demand special instruments and apparatus to generate electricity from different energy sources. So, industrial engineering and engineering design are very important to be developed. But not only the engineering side of this problem is important. For example, the storage and transportation of renewable energy are very important too [5]. For this reason, mathematical models are constructed to evaluate or optimize renewable energy systems [6, 7]. In [7], the authors not only created the mathematical model but also applied the model to analyze energy storage and hydrogen production at renewable energy power plants in Japan in 2050.

It is important to integrate renewable energy sources for new housing developments to reduce the demand for grid energy and carbon emissions [8]. Different technologies are oriented to include or combine with green energy [9, 10]. An effective response to climate change is a rapid replacement of fossil carbon energy sources with green energy [10]. So, the target of decarbonization in the energy sector can be achieved. The intensification of the use of different renewable energy sources is essential for the fulfillment of the Paris Agreement or for achieving the goals of sustainable development [11].

So, green energy, and especially solar energy generation, is a very actual and important area of science and engineering. Creating cheap and effective devices is a challenge for scientists.

2. Literature review and problem statement

Solar energy is one of the most accessible energy sources. Different countries actively develop photovoltaic systems. For example, the paper [12] presents the results of research on solar energy using photovoltaic systems. The development and application of solar energy have been regarded by the government of India and common people, and they have shown that solar photovoltaic energy can provide more energy in the future compared to other renewable energies.

There were unresolved issues related to generating energy in remote areas where it is not possible to place fields of photovoltaic panels. So, not only photovoltaic systems were developed but parabolic solar concentrators too [13]. The authors developed a system comprising external parabolic solar concentrators integrated with cylindrical vertical type sensible-based TES tanks. Solar concentrators can generate thermal energy in the highest operating temperature range (≥300 °C) and can be used in solar thermal-energy applications in the industrial sector [14] and in remote areas of the country. A parabolic dish concentrator converts, as described in [15], 72 % of solar energy into usable heat. With 50 % of global energy consumption in the form of heat, the market for thermal energy is vast.

Parabolic concentrators are expensive because of using large-area curved mirrors. A way to overcome these difficulties can be using plane mirrors. To reduce the cost, we propose to use plane mirrors that cost 2–3 dollars for one square meter. For our task, it is necessary only to cut them. Low-cost parabolic solar concentrators based on a multitude of small triangular flat mirrors that can approximate parabolic surfaces were developed [2]. These solar concentrators can be used for energy supply to residential houses [16]. A small-scale residential power plant that can be used in remote areas contains flat facet parabolic solar concentrators, TES, and a powerhouse hall. The main goal of these works is to decrease the cost of materials and labor needed for parabolic solar concentrator manufacture.

Flat facet solar concentrators were proposed in the 80^{th} years, and the prototype of a solar energy plant based on these concentrators was made in Australia, White Cliffs (1998) [17, 18]. After that, many versions of flat facet solar concentrators were proposed, developed and patented. In the publications [19–21], we describe several prototypes of flat facet concentrators and methods of adjustment of the parabolic surface. We estimate the cost of concentrators near 20 or 30 USA dollars per square meter. This cost allows supplying all needed energy for houses in countries with a hot arid climate, for example, Azerbaijan and Mexico. In countries with cold climates, such as Ukraine and Canada, solar energy can provide a significant part (sometimes more than half) of the energy consumed by a residential house. So, we consider the possibility of using solar concentrators in different countries.

A solar parabolic concentrator can be used with different receivers in the focal point, for example, with the Stirling or Ericsson engines that can transform thermal energy to electricity. The parabolic concentrator with a spiral receiver for converting thermal energy and obtaining water at a temperature of 85 °C for domestic needs is described in different applications [22]. At present, among countries with low incomes, parabolic concentrators with a temperature suitable for heating water or cooking are popular. Solar parabolic cooking units are very popular in India [23]. In the Kalahari desert in South Africa, two solar concentrators with a diameter of 12 meters each were installed with Stirling engines. Studies have shown that conventional solar panels can provide 15 percent of the energy they receive in electricity, but the Ripasso company has developed a solar concentrator and has managed to double this amount to 34 percent [24], which demonstrates the advantages of solar concentrators compared to panels. The main problem is that only several prototypes were made. We can suppose that they were done manually without automatization. Every prototype is a one-piece item.

The company specializing in the production of parabolic solar concentrators Solarflux (USA) [25] has developed a model from environmentally resilient low-cost metal components. So, industrial companies that produced solar concentrators tried to reduce the production cost.

The ZED Solar (developed by AEDesign) developed a parabolic concentrator dish (Solar Invictus) with a diameter of 9 m [26, 27]. The size of this concentrator is quite large. It is difficult to install it, for example, on the roof of a building. Such constructions require a lot of space.

In addition to the solar concentrator models described above, there are a dozen interesting ones, such as the Spanish-German project EuroDish [28, 29], which have very good energy conversion rates. Industrial designs can use various energy converters, however, it should be noted that most projects use a Stirling engine to convert to electrical energy.

Low-cost flat facet solar concentrators are proposed for different applications, for example, for the combination of solar concentrators and agricultural fields [30, 31].

Tropical countries with high air humidity can be another application area for solar concentrators. In this case, it is possible to use solar-powered dehumidifiers [32, 33] with hot air generated by solar concentrators.

These solar concentrators can be used with small-scale TES [6]. Using TES, it is possible to make power plants for green buildings. Small solar power plants can support all the energy demands of residential houses.

Most of the described and developed models are efficient and good for green energy. The main problem that we can see is connected with their production. The manual labor and manual assembly are the points that can elevate the cost of the product. So, it is very important to simplify the solar concentrator structure for future automation of these processes.

The models of solar concentrators developed in different countries are used for different applications. The critical point is the size of solar concentrators. Nine meters in diameter (for example, as Solar Invictus has) is large for some applications. If we want to install solar concentrators on the roofs of buildings, it is necessary to reduce the diameter of solar concentrators and their weight. The weight can be reduced by decreasing the number of structural elements. Another critical point for all the developed and discussed above models is that every prototype is a one-piece item. The manual labor elevates the cost of solar concentrators. Before automating the solar concentrator production process, we need to simplify the structure of the solar concentrator.

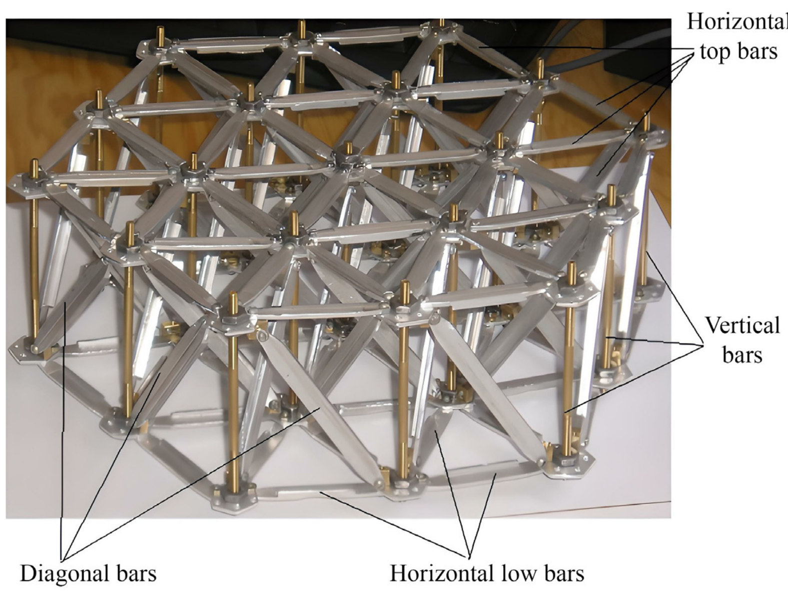


Fig. 1. First structure project [19]

3. The aim and objectives of the study

The aim of the study is to develop a new structure frame prototype of a solar concentrator. This will make it possible to propose a new structure (support frame) of solar parabolic concentrator with reduced cost, lower weight, and better conditions for automatic production.

To achieve this aim, the following objectives are accomplished:

– to give the essence and critical review of the possibilities for improving the first model;

– to consider the possibility to decrease the number of metal structural elements and respectively the weight of the whole structure of the solar concentrator and propose the improved design with connections of metal elements with mirror triangular elements.

4. Materials and methods

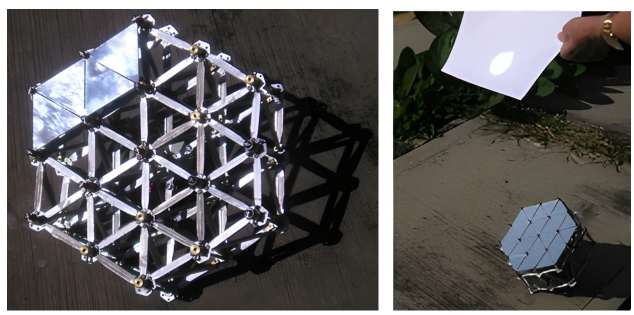
4. 1. Object and hypothesis of the study

The object of the study is a solar concentrator. The main hypothesis of the study is connected with the simplification of the frame structure of the solar concentrator with flat triangular mirrors. The methods that were used are computer simulation and physical prototyping.

4. 1. 1. The first prototype of a solar concentrator

The first models of solar concentrator prototypes were developed, manufactured and described in our publications [19, 20]. Fig. 1 shows the support structure of the solar concentrator. The structure contains horizontal top aluminum bars, vertical bronze bars, diagonal aluminum bars and horizontal low aluminum bars. Horizontal top bars are connected as triangular cells that are the base for triangular mirrors.

The solar concentrator structure has a hexagonal shape, i.e. it has six external sides. The structure has aluminum triangles to have the possibility to collocate the plane triangular flat mirrors: one mirror for one triangle. In total, this prototype has 24 cells for 24 mirrors. In Fig. 2, *a*, we demonstrate four mirrors collocated and fixed on the support structure.



a *b*

Fig. 2. Support structure of the first prototype: *a* – four mirrors collocated on the structure; *b* – concentration of solar energy in the focal point

Fig. 2, *b* shows the first prototype in complete form with all triangular mirrors and with concentrated solar light in the focal point.

4. 1. 2. Number of mirrors

In common case, we can calculate the number of mirrors N using the following equation:

$$N=(6*n^2)-6, \quad (1)$$

where n is the number of layers. In the next paragraph, we will explain this formula in more detail. Several prototypes of one meter in diameter were made. In these prototypes, we did not place mirrors in the center (minus 6 mirrors). This hole is used to collocate the gauge with a parabolic edge to adjust all screws to obtain the parabolic surface curve [19, 20].

Fig. 3 shows the solar concentrator prototype that contains six layers and, in accordance with equation (1), contains 210 flat mirrors. This structure was patented in the USA, Spain and Mexico. In this case, we used the same principle: one cell for one flat mirror. The diameter of this prototype is one meter.

The main disadvantage is the large number of elements in the structure. We use aluminum, which is lightweight, but the number of elements complicates the assembly of the device.

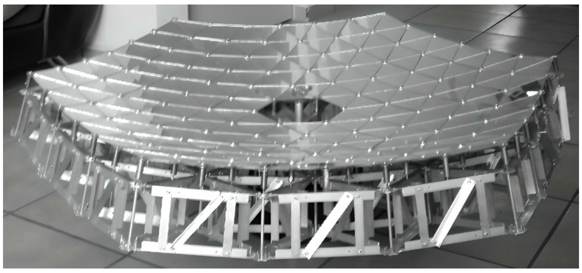


Fig. 3. Prototype with the first structure model [20]

The assumptions made in the work are as follows: we can reduce the number of structural metal elements without losing structural strength; with reducing the number of elements we can make the structure lighter than the previous one. Simplifications adopted in the work are connected with the idea that we can use structural elements of the previous prototype as basic elements of the solar concentrator structure.

4. 2. Materials

The materials that were used in the study are metallic components for the support frame. Aluminum bars were used (Fig. 1–3). The structure in this case is sufficiently light and firm. Before constructing the prototypes, the elements and structure of the solar concentrator were simulated using SolidWorks.

4. 3. Methods

The method that was used in the study is a geometrical model of the solar concentrator. The diameter of the solar concentrator was selected as 1.6 meters. Calculations using this model demonstrated the possibility to obtain sufficient thermal energy with the proposed solar concentrators.

4. 3. 1. Geometric model of the solar concentrator

This part presents the mathematical description of the model. The sketch of the solar concentrator is drawn in the SolidWorks software environment (Fig. 4).

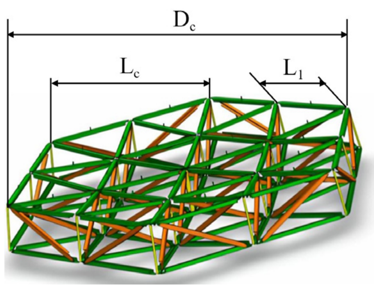


Fig. 4. Model of a solar concentrator with parameters [6]

The surface area of the parabolic concentrator can be calculated using equation:

$$A_c = \frac{\pi D_c^2}{4}. \quad (2)$$

Here A_c is the surface area; D_c is the diameter of the solar concentrator (Fig. 4). For this calculation, it was accepted that D_c=1.6 meters. When numerical values are substituted, A_c=2.01 m^2. We round this value to 2 m^2.

The power of the solar concentrator with this surface area can be represented as:

$$W_C = N \cdot L_1^2 \cdot C_S \cdot \frac{t_M}{24} \cdot \eta_C \cdot \frac{\sqrt{3}}{4}, \quad (3)$$

where W_c is the power of the solar concentrator, N is the number of mirrors, L_1 is the size of the mirror side (L_1=0.13 m), the solar constant C_s is the amount of energy that reaches 1 square meter of the earth [34] (C_s=1.361 kW/m^2), the number of hours (average) t with the direct sun (not diffuse), for example, in Mexico, is 7 hours of sunlight per day, the concentrator efficiency η_C is 0.7.

Satellites have directly measured the amount of energy arriving at Earth from the Sun as sunlight. Although this value varies slightly over time, it is usually very close to 1.361 watts of power per square meter (1.4 kW).

The concentrator contains N=210 flat mirrors, which have a triangular shape with the size of one side L_1 (Fig. 4) [6].

So, a concentrator power of more than 2 kW was obtained (from equation (3) W_c=2091.53 W), which is sufficient to build a system with thermal energy storage and use it for chemical reactor heating [6].

4. 3. 2. Calculation of the number of structural elements

To calculate the number of structural elements, we present schematically part of the solar concentrator structure. On the basis of each external side (side L_C in Fig. 4), we can demonstrate the triangular zone that begins from the outside line to the central point of the solar concentrator structure. One triangle is schematically presented in Fig. 5. The triangle corresponds to the triangle ABC (in this case, AB=L_c).

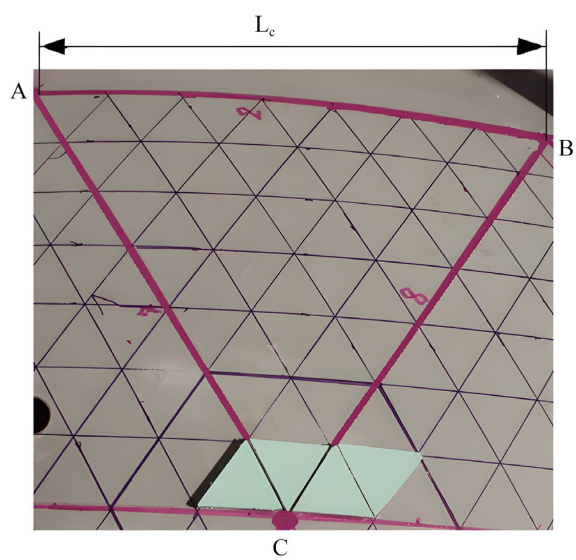


Fig. 5. Triangle ABC of the solar concentrator

You can see the triangle ABC (magenta color), where point C is the central point of the solar concentrator structure, and near this point, we begin to place four triangular mirrors. Triangle ABC is 1/6 part of the solar concentrator structure (for this reason, in equation (1) we multiply by 6). We have seven lines, which are parallel to the AB line (blue color). So, every zone has 49 triangular mirrors. In total, we have the solar concentrator with 288 mirrors (49*6–6= =294–6=288 mirrors) if we do not include six mirrors in the center of the solar concentrator structure.

Every mirror is collocated on a cell from three upper aluminum bars that are connected with three vertical bars with other three lower aluminum bars. To make the system from bars tough, three diagonal bars were added. So, every cell includes 12 bars. If the structure contains 288 mirrors, then we need to construct it 3,456 metal bars.

In the first type of structure, every triangular mirror has a support cell for every mirror (Fig. 1, 2). Every vertex of the triangle has a fixing screw.

The problem of this prototype is the complexity of the solar concentrator structure (Fig. 4) and the large number of structural metal elements for automatic assembly.

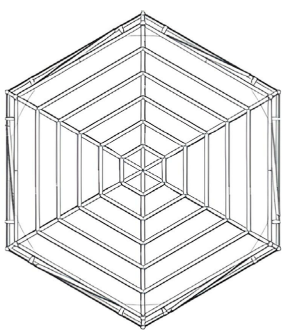
4. 4. Software

The methods that were used in the study are simulation of the support structure using SolidWorks. After that, the hardware as prototypes of solar concentrators was made to validate the proposed solutions. At the first stage, we used the SolidWorks software to simulate 3D models of the solar concentrator structure.

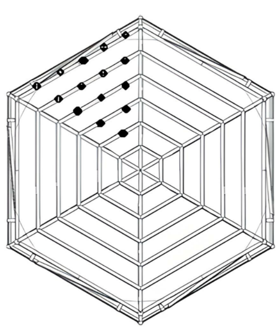
5. New structure of the solar concentrator with flat triangular mirrors

5. 1. Reducing the number of structural elements

The second structure of the support frame was developed after the model described in section 4. 1. 1. The new structure is presented in Fig. 6. Instead of triangular cells for every mirror, it was proposed to have parallel bars in every zone of the structure to collocate several mirrors. As for the first and second prototypes, the structure has six zones (hexagon shape); so the structure in both cases has six external sides. Fig. 6, *a* shows the structure from parallel bars. Fig. 6, *b* shows one zone with screws (black points) that are used to fix the triangular mirrors. The same scheme is used for all six triangular zones of concentrators.



a



b

Fig. 6. Second structure model: *a* – structure from parallel bars; *b* – one zone with screws (black points)

In Fig. 7, we present the scheme of screw connection for mirrors with metallic elements that we use. This connecting node contains a distance ring, a washer (to protect the mirror) and a screw.

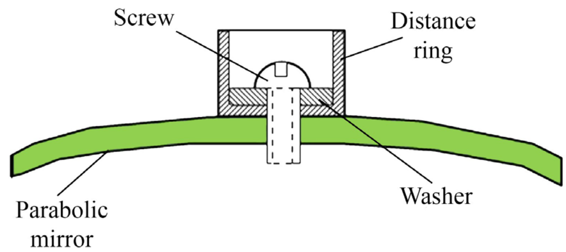


Fig. 7. Scheme of screw connection for mirrors

For the first model, the number of metal structural elements in the case of seven parallel lines in every zone was calculated (Fig. 5). It was 3456 aluminum bars.

5. 2. Calculation of structural elements

If we analyze the second model with seven lines, we decrease the number of metal elements by 56 (in Fig. 6 we demonstrate only six lines in every zone). In Fig. 8, we present the structure with mirrors in one zone.

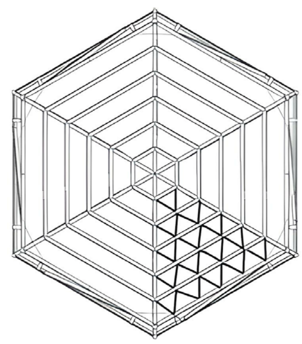


Fig. 8. Structure with mirrors

The total number of triangular mirrors N can be calculated as in equation (1). But the number of horizontal top bars, vertical bars, diagonal bars and horizontal low bars (Fig. 1) will decrease significantly.

In Fig. 9, we presented the simulation of the solar concentrator structure with flat triangular mirrors with the new support frame.

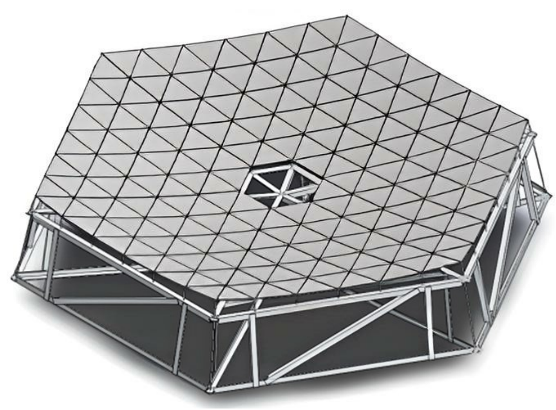


Fig. 9. Concentrator with the second structure model

For example, we can analyze the situation with horizontal top bars. The number of bars in the center of the prototype is not changed: six radial bars and six perimertric bars. In total, we have 12 bars in the center with a length of triangular size *a*. With every new line, the gain will be more significant. The primer line after the center in the first prototype (Fig. 1) had:

K_1=(7–1)*6=36 bars

with a length of triangular size *a*.

In the new version (Fig. 8), line 1 has:

K_2=(2*6)*l*=12*l*+2*a* bars,

where *l*=2*a*. If the first line has a bar with length (*a*), the second line has the size of (2*a*). And every new line will have the size (*n**a*), where *n* is the number of lines.

We can imagine the prototype with two lines. In this case, for the first prototype:

K_1=(11–2)*6=54 bars.

For the second prototype:

K_2=(3*6)*l*+2*a*=18*l*+2*a* bars

with a length (*l*=3*a*).

If the frame has three lines for the first prototype:

K_1=(15–3)*6=72 bars.

For the second prototype:

K_2=(4*6)*l*+2*a*=24*l*+2*a* bars

with a length (*l*=4*a*) and so on.

This reduction in the number of bars is described only for horizontal top bars. But if we also analyze the vertical, diagonal and horizontal low bars, the savings will be greater. In total, if for the first prototype, it was said about thousands of structural elements, then in this new case it is only about tens of elements.

If the structure contains six or seven lines in one zone, we can have a solar concentrator from one to two meters in diameter. It is not heavy and can be carried, transported and installed in different places. The advantage of the new model is the lower consumption of metal bars. So in this case, the solar concentrator will be light in comparison with the weight of the previous one.

6. Discussion

The geometrical model of a solar concentrator is proposed, and the results of calculations with this model (2), (3) demonstrated that it is possible to build a solar concentrator of 1.6 meters in diameter to obtain sufficient energy for heating. Due to its small size and weight, the concentrator can be easily transported and installed. This solar concentrator is possible to install on the roofs of buildings as TV antennas.

The main result that was obtained is the development of a new support structure for a prototype of a solar concentrator. The new support structure (support frame) of the solar parabolic concentrator was developed to reduce the number of structural elements and, as a consequence, reduce the cost and make the structure lighter and easier for automatic assembly (Fig. 6, 8).

This prototype, compared to the first model developed earlier (Fig. 1, 2), contains fewer metal elements in the structure. It is not necessary to construct a cell for every triangular mirror from metal elements as it was made in the first prototype. For mirror supporting, it is sufficient to have horizontal bars as presented in Fig. 6, 8.

Green energy is the future of energy development. So, any contribution to the technological aspects of this solar energy capture process is very important.

A new frame of a solar concentrator prototype was developed and described, in which the parabolic surface was approximated by triangular plane mirrors. After analysis of the first model of solar concentrator, the possibilities for its improvement were found. The first prototypes are presented in Fig. 1, 2. For comparison, the new structure is presented in Fig. 6, 8. The new structure has advantages compared to the previous version. For example, fewer structural elements, which allows for an easier assembly process. Fewer automation steps result in shorter building times. Also, in this case, the prototype structure becomes lighter. It is easier to transport and install this compact solar concentrator prototype with a diameter of 1.6 meters.

This new structure is more convenient for automating the assembly process of solar concentrators in the future.

Parabolic solar concentrators provide a clean, inexpensive source of thermal energy for a wide range of applications, including industrial process heat, space heating and cooling, hot water, water desalination and purification, as well as remote and distributed power applications.

The proposed solar concentrators can be used directly to produce heat energy. To produce electrical energy, it is necessary to use a Stirling thermal motor or Ericsson motor in the focal point to convert heat energy to electricity.

The proposed solar concentrators can be used for different applications, for example, green buildings in rural areas, or chemical reactors to accelerate the chemical process of organic waste processing. Another application is to use solar concentrators in combination with agricultural fields. These solar concentrators can be used with small-scale TES. Using TES, it is possible to make power plants for green buildings. Small solar power plants can support all the energy demands of residential houses.

The limitations of the study that must be taken into account when trying to apply in practice are connected with the necessity to develop or adapt an existing sun tracking system, which can increase the efficiency of a solar concentrator system. It is important to investigate as well as in further theoretical studies of solar concentrator systems to improve their structure and work.

7. Conclusions

1. In comparison with existing models of solar concentrators, a concentrator from one meter to two meters in diameter was proposed, which is less than is known from the literature (for example, 9 meters). It was demonstrated with the geometrical model that a diameter of 1.6 meters is suffi-

cient to produce thermal energy. The number of structural elements was more than three thousand elements.

2. A new model of the support frame of the solar concentrator was proposed. The result is a decreased number of structural metal elements. A new design of the frame structure is presented, which contains fewer metal elements, is lighter than the previous one and more convenient for the automatic assembly process. Instead of thousands of structural elements, as for the first prototype, in this case, we are talking about several tens. The disadvantage is related to the size of elements. For the first concentrator, all elements are unified; there are only three types. For the second solar concentrator, there are different elements with different sizes but there are much fewer of them. The cost of both types of concentrators is low because of using flat triangular mirrors. With this investigation, the cost of a solar concentrator can decrease even more. The scheme of screw connection for mirrors with metallic elements was proposed. This connection method is safe and reliable.

Conflict of interests

The authors declare that they have 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.

Financing

This research was partly supported by the UNAM-DGAPA-PAPIIT IT 102320 project.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Acknowledgments

We thank Dra. Airam Curtidor for her comments on the text of this paper and the master's and PhD students who helped us in different aspects of investigation.

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