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Development of Modular Design Energy Generation and Storage System for Autonomous Power Supply

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The article presents the design conception of a high mobility energy generation and storage system with intelligent energy conversion and storage systems for use in military and civilian purposes in regions with damaged infrastructure, where access to electricity and hot water is limited or threatened due to man-made actions or natural damage. The proposed system main feature is modular design which combines a heat collector, electrical energy converter, and related energy storage systems. The modular, reliable design and ease of deployment of the proposed system, the size of which allows to carry out in standard shipping containers, enables rapid and flexible scaling of a deployed solar power plant, production and storage of electricity and hot water. The design of the module of the proposed system is based on the use of highly efficient multi-junction III-V solar cells in combination with economically and reliable plastic made system for concentrating solar radiation. At the same time, the cooling of solar cells to maintain their operating temperature provides heating of water to the minimum values required in domestic conditions. Also, the modular principle is the basis of the system for storing and distributing electrical energy, which is supposed to be made of highly efficient Li-Fe based rechargeable batteries, which today have one of the best indicators in terms of the ratio of volume and accumulated energy. An intelligent control system based on microcontrollers provides accurate positioning of solar cells, the implementation of the MPPT algorithm to maximize power generation and maintain a balance between supplying consumers and charging batteries. Modularity makes it possible to form emergency power supply complexes of different power (45 W of electric power and 50 W of thermal energy per one module) for provide emergency and permanent power supply of most electronic devices according to the standard protocols PD 3.0, QC 3.0, 12 V, 220 V as well as supply consumers with warm water for basic needs.

Keywords: Mobility, Solar Cells, Storage, Batteries, Efficiency.

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1. INTRODUCTION

For Ukrainian civilian and military users, damage of the country's energy infrastructure caused by the war has limited the reliable supply of electricity and hot water. Similar needs also arise as a result of natural phenomena, such as hurricanes and the effects of global warming, and are relevant for some US states and countries in Africa and Asia. Currently available solar heat generating and combined cogeneration systems are designed to work in conditions of unconcentrated sunlight, as a result of which a typical energy supply system of an average household or a small civilian or military point has a photoreceiving surface area of 10-15 m^2 or more and consists of expensive, heavy and fragile solar panels based on silicon. In the conditions of war on the territory of Ukraine, as well as during the liquidation of the consequences of natural disasters, the mass deployment of such systems for the energy supply of the civilian population and military consumers is not optimal, since the dimensions of such systems do not ensure their rapid transportation and deployment.

Using concentrated sunlight, it is possible to significantly reduce the number of solar cells needed to achieve the same level of electricity production [1, 2], by developing a system that combines a heat collector, an electrical energy converter, and the corresponding energy storage systems.

The purpose of the article is to develop and analyze the design of a high mobility energy generation and storage system with intelligent energy conversion and storage systems for military and civilian use in regions with damaged infrastructure, where access to electricity and hot water is limited or threatened due to man-made actions or natural damage.

2. DESIGN CONCEPTION OF A HIGH MOBILITY ENERGY GENERATION AND STORAGE SYSTEM

In recent years, there has been a steady trend among photovoltaic system researchers to introduce mass production of photovoltaic systems that use concentrated solar radiation, and one of the most obvious advantages of such systems is usually a radical improvement due to a reduction in the weight and size of the system. The implementation of such developments became possible thanks to the introduction into mass production the highly efficient solar cells (SC) based on GaAs, capable of working in conditions of concentrated solar radiation, the efficiency of the best samples

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among which exceeds 40 % [3-5]. The reduced size of the solar battery from such SC significantly simplifies the solution to the problem of efficient heat transfer from the SC to the heat exchanger, in particular, the contact of such elements can be made by soldering. It is assumed that with such design, the long-wave component of solar radiation passes through the SC practically without loss and is absorbed directly in the heat-receiving unit, thereby reducing the operating temperature of the SC without losing the efficiency of thermal energy collection [6, 7].

Based on the results of the exploratory research, the concept of a high mobility energy generation and storage system using concentrated solar radiation, highly efficient solar cells based on SC from gallium arsenide, and intelligent systems for converting and storing electrical and thermal energy was developed.

The key features of the proposed system are portability and potential for rapid response due to the possibility of transportation in a standard container.

Structurally, the solar concentration system is a size-critical component of the complex, and therefore must be able to be packaged to a minimum size and weight and then deployed with minimal effort and time.

To solve this problem, a modular design of a high mobility solar system is proposed (Fig. 1), the main elements of which include a generating module (GM) - where solar cells based on GaAs and a solar concentrator based on Fresnel lenses [8, 9] will be installed on a light aluminum or composite structural frame and storage and conversion module (SCM) - in which the schematic solution of an intelligent energy conversion and storage system provides the ability to work with the required number of batteries based on high-efficiency lithium-iron-phosphate batteries and hot water tanks.

Each of these modules is a structural unit by varying the number of which we can scale the power of the system.

As can be seen from Fig. 1, by using repeated solar energy conversion units of about 0.16 square meters each, we have the ability to vary the size of the deployed array of these units to provide the required volume of electrical and thermal energy production. The proposed surface area of this solar energy system will be comparable to typical silicon-based solar panels. Such a result can be achieved by using Fresnel lenses, which are characterized by a small focal length, at the level of the diameter of the lens itself, to concentrate solar radiation.

In turn, the energy storage module due to the existing power reserve of the conversion and charging board has the ability to work with different numbers of battery cells, which is directly dependent on the number of generating modules and depends on the needs of the system customer.

This solar concentrating design requires a tracking system to keep the device pointed at the sun during the day. For this, can be used compact, high-performance mounts for satellite communication or radar system which manufactured in accordance with MIL-STD requirements for resistance to adverse weather conditions and other external factors.

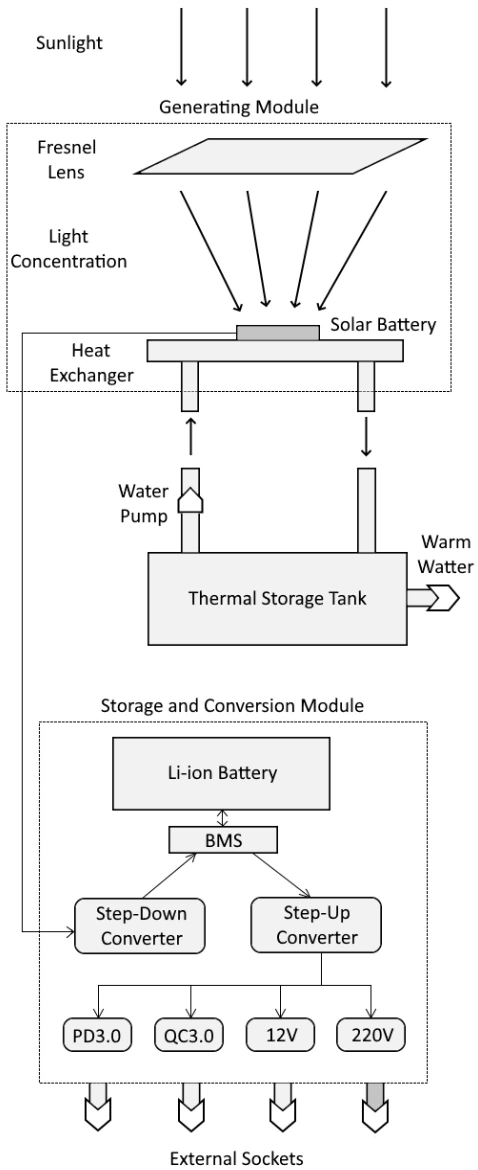


Fig. 1 – Scheme of a high mobility energy generation and storage system

3. POWER GENERATION MODULE

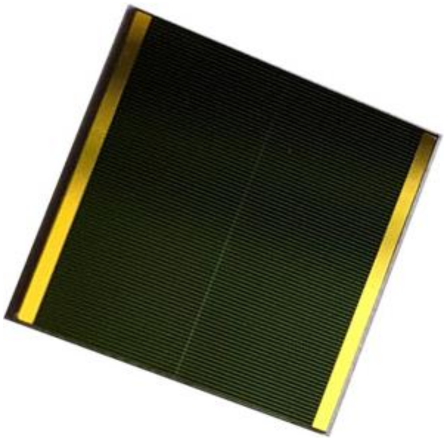
The main element of the proposed system should be a heat-electricity generating unit whose design is based on the principle of modular design, which allows the flexible adjustment of the installation's power to meet energy needs in a specific place of its use.

For this, the heat-electricity generating unit will consist from separate generating modules (GMs) that have a conceptually complete design and can generate up to 150 W of energy under lighting conditions of 800 W/m^2, of which 45 W are electric and 50 W are thermal energy, having in total near 70 % generation efficiency. Fig. 1 shows the schematic design of GM, the main design features of which are the use of a battery from highly efficient (up to 40 %) solar cells based on gallium arsenide, which work in conditions of concentrated solar radiation, created using Fresnel lenses, the construction of which is made from plastic and implemented in a large-scale production.

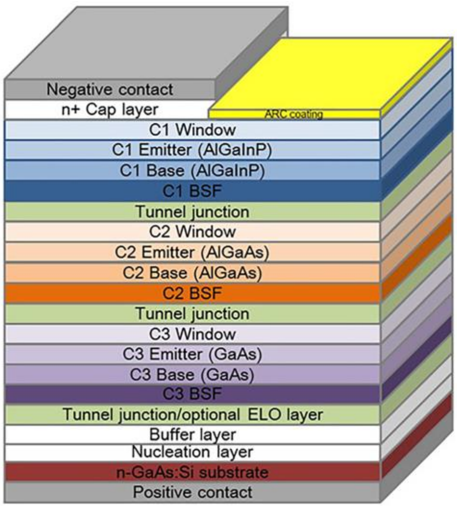
As can be seen from Figure 1, this design of GM provides its closed design, which is a significant advantage compare to systems that use parabolic mirrors to concentrate solar radiation. Removal of excess heat from the SC and generation of thermal energy is provided by installing the SC on a heat exchange element which is connected to a typical double-circuit heat exchanger tank.

During the development of the proposed system, we performed preliminary studies aimed at confirming the effectiveness of the GM concept shown in Fig. 1.

Solar cells based on gallium arsenide, produced in the USA and studied in [10], was chosen for the generation of electrical energy, which, according to the specification, have an efficiency of up to 29.5 % under illumination conditions of 50 W/cm^2 and can work effectively at an operating temperature of up to 75 ^{o}C. The appearance of such a SC is shown in Fig. 2a, and its cross-section is shown in Fig. 2b. A feature of the design of such SCs is that due to the presence of a grid like electrode on the back surface, they are able to directly transmit the long-wave component of solar radiation to the heat exchange unit, which reduces the heat load on the SC itself.



a)



b)

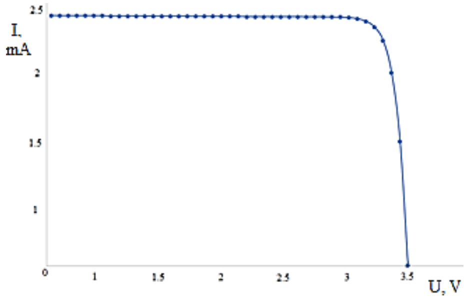
Fig. 2 – Appearance of SC based on gallium arsenide (a) and its cross section (b)

In the process of preliminary testing and development of the technology of connecting SCs with contact electrodes, a series of illuminated voltage-current characteristics measurements of such SCs was carried out using the measuring stand shown in Fig. 3.

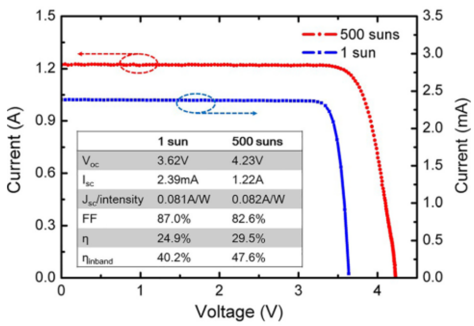
Fig. 3 – Measuring stand of illuminated current-voltage characteristics of SC

The stand includes a solar radiation simulator USO–3, developed at the Micro- and Nanoelectronics Department of NTU "KhPI" and capable to provide SC irradiation with a frontal surface area of up to 25 cm^2 in conditions that correspond to the AM1.5 mode in terms of spectral and energy characteristics (1000 W/m^2). The current-voltage characteristics were measured by a Keithley–2400 source meter connected to a PC with the LabView software, due to which the measurement was carried out in a fully automatic mode during a time that excludes the influence of SC heating on its characteristics.

A typical current-current characteristic for the tested SC samples is shown on Fig. 4a.



a)



b)

Fig. 4 – Typical current-voltage characteristic of SC based on gallium arsenide, measured for illumination conditions $K_i = 1$ (a) and current-voltage characteristics of similar SCs given in [10] for illumination conditions $K_i = 1$ and $K_i = 500$

As can be seen from the analysis of the obtained results, the tested SE has a very high value of the current-voltage characteristic fill factor, so even in suboptimal lighting conditions (such SC are designed to work at K_i up to 500), their efficiency is at the level of 25 %. Comparing our results with presented in [10] reference current-voltage characteristic (Fig. 4b), it can be concluded that the processes of connecting the SC to the measuring circuit did not have a negative effect on the SC characteristics, and as can be seen, the current-voltage characteristic measured by us at a single concentration coincides with the one provided by the manufacturer.

It is obvious that the research of such SCs is of the greatest interest precisely in the range of their working concentrations, for the implementation of which a full-scale experiment using a concentrating system can be best suited. In the developed system as a concentrator of solar radiation in one GM, it is planned to use a Fresnel lens, the appearance of which is shown in Fig. 5. Also, Figure 5 shows the appearance of the focal spot of the lens during field tests.

Fig. 5 – Concentrating system based on a Fresnel lens

Such a Fresnel lens has geometric parameters – 40 by 40 cm, and the size of the focal spot in which $K_i = 200$ is provided is about 2 × 2 cm. It is made on the basis of transparent acrylic plastics, which are characterized by low cost of production (the cost of one lens is $ 10) and durability to the influence of external factors, both mechanical and chemical. Optical features of the Fresnel lens – the focal distance is equal to the size of the sides of the lens, allows to minimize the geometric dimensions of the GM and make it in the form of a closed box to prevent external influence on the SC. Since a plastic lens has a small weight compared to a glass one, the structural elements of such a box can be made by an economical method of 3D printing from ABS plastic, which is strong enough for this purpose and is also resistant to atmospheric effects. The use of 3D printing when working out the structural solution of GM allows to quickly test different design approaches and, if necessary, change the design of elements without using machine tools or toxic glues.

Another important element in the GM design is the heat exchange unit, which ensures the removal of heat from the SC during their operation and the transfer of thermal energy to the coolant with its further utilization. The use of SC based on gallium arsenide allows maintaining a higher coolant temperature compared to SC based on silicon, but at the same time narrows the temperature range in which the SC should be maintained and makes the speed of heat removal from the SC more important. In order to meet such requirements in the developed system, it is planned to use the previously created design of the heat exchange unit with so-called microchannels in the area of the coolant flow. The mathematical model of heat exchange unit solution is created in the Solid Works Flow Simulation software environment and used for optimization studies is shown on Fig. 6.

As you can see from the figure, the microchannels are made on the back side of the heat receiver and are located parallel to the flow direction of the coolant. Experimentally [10, 11] it has been confirmed that such a design provides a turbulent flow of the coolant, which is characterized by a very high intensity of heat transfer and allows the efficient heat removal even in the case of SC operation in conditions of highly concentrated solar radiation. This design was tested in a previously developed system which was designed for the use of silicon multi-junction "photovolt" type SCs. Unlike silicon SC devices based on gallium arsenide have a higher efficiency, which allows to significantly reduce the area of the heat-receiving surface and make it from the optimal material, which for such units is copper. Reducing the use of copper makes it possible to reduce the cost of the developed photoelectric system as a whole.

In the proposed design of the heat exchange unit, it is important to ensure heat transfer from the SC itself to the heat exchange unit. Previously, for this purpose, SCs were usually attached to the heat exchanger by soldering, which is not technological enough and can negatively affect on to SC characteristics. Thermal interfaces on an adhesive basis have a number of disadvantages, the main ones of which are insufficient coefficient of thermal conductivity and low durability in conditions of constant heating. At present, thermal interfaces based on metal compounds, known under the general name "liquid metals", are introduced into wide production. Typical samples of such compositions have a high coefficient of thermal conductivity up to 100 W/(m*K), are stable when working outdoors and allow minimizing the thickness of the thermal interface layer, which is optimal for both technological and economic reasons.

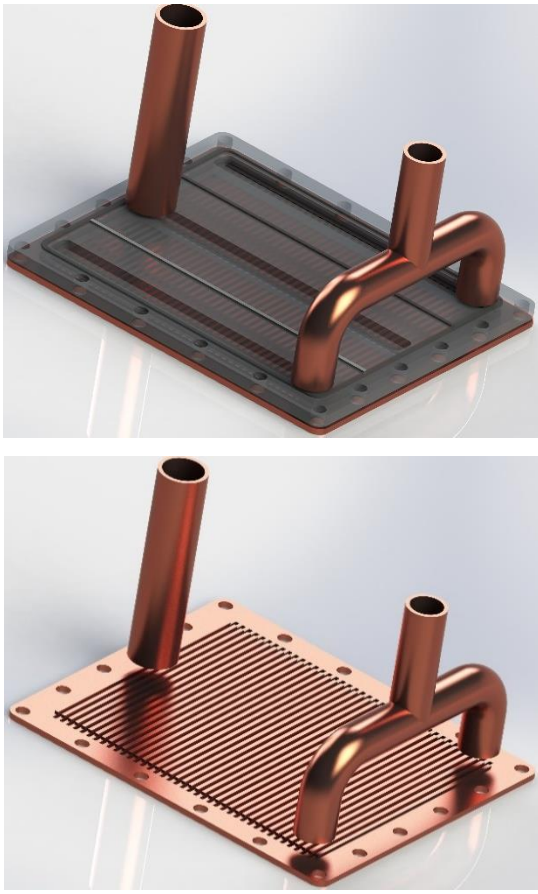


Fig. 6 – Heat exchange unit with microchannels

The proposed GM design allows to create a technologically complete product, using which scaling of the system power will be carried out by varying the amount of GM in its composition, and not by increasing the area of the mirror concentrator as in known cogeneration systems. Thus, according to preliminary calculations, to meet the needs of an average military outpost or a place of temporary residence, it is sufficient to use a system consisting of 8 – 10 GM in combination with the flexible capacity developed energy storage.

4. ENERGY STORAGE AND CONVERSION MODULE

For rapid accumulation of electrical energy, the most optimal solution is using of lithium or lithium-iron-phosphate accumulator batteries. However, their use in power supply system's requires the implementation of specialized energy-efficient converters of electrical energy: matching – which provide communication between the battery and the conversion system [12] and service – which ensure a safe operation mode of the accumulators (equalization of voltage levels on serially connected accumulators, control over compliance with the limit values of the voltage levels on each battery cell) [13, 14]. It is known that lithium-based batteries have a number of advantages over lead-acid batteries, but require stricter compliance with the voltage on a single battery cell. Thus, the voltage ranges of the Li-Ion battery regulated by the developer is 2.5-4.2 V [15]. Exceeding the lower limit causes premature "aging" of the battery, and exceeding the upper limit can cause the final failure of the storage device.

Powerful storage batteries for electric power supply systems are used in the form of assemblies consisting of a series-parallel connection of single storage units. During their operation, the problem of uneven discharge or charge arises, to compensate for which it is necessary to balance the voltage levels in the stack batteries. There are a large number of circuit solutions that perform voltage equalization. Conventionally, they can be divided into two large groups: passive (resistive) and active balancing systems.

The first group is sometimes called "resistor balancing". This method is mainly used in a cheap device. Virtually all excess energy from overcharged batteries is dissipated as heat, which is certainly the main disadvantage of the passive method. In the active balancing method [16, 17], capacitors or inductances with negligible energy losses are used to transfer energy from overcharged batteries to less charged batteries.

The analysis [18] of the mathematical model of the operation of two types of buffer elements (capacitive and inductive) made it possible to give a qualitative assessment of their effectiveness (Fig. 7). The first, in comparison with inductive ones, not only have worse energy characteristics, but also do not allow to perform "scaling" of the device without significantly complicating the control system. With a large number of storage devices (more than three), preference should be given to transformer balancing systems, as a special case of inductive topology.

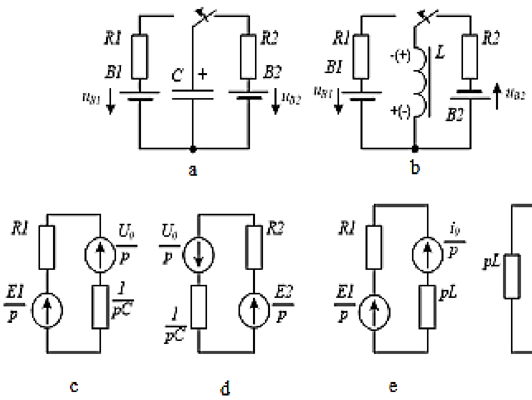


Fig. 7 – Simplified diagrams of balancing circuits (a, b) and their substitution operator diagrams at the stages of energy storage (c, d) and transmission (e, f), respectively. In all schemes, the condition $UB_2 > UB_1$ is fulfilled

However, in the case of developing economic solutions with a small capacity, passive balancing systems are usually chosen.

For emergency power supply of critically needed electronics and communication systems, about 50-100 W of electrical energy is usually required per hour (charging a cell phone – up to 25 W, a laptop - up to 60 W, a router or PON terminal – 10 W, a Starlink system - up to 60 W). For the basic needs of emergency power, taking into account the need for uninterrupted operation of the specified systems for at least 5 hours, it is necessary to equip each module of the system with an electric energy storage device with a capacity at least 500 Wh.

In order to reduce the cost, the specified battery can be implemented according to a standard solution with the possibility of scaling:

– li-ion battery assembly, 32 Ah 4 s (16.8 V, 537 Wh), with the appropriate balancing and protection board (BMS);

– step-up module (to compensate the loss of voltage in the battery during discharge, the module increases the voltage to the desired level);

– step-down module CC/CV at 16.8 V 150 W (for charging the battery);

– battery charge indicator.

On the basis of the proposed solution, a laboratory sample of an electric energy storage device was developed on the base of common Li-Ion batteries in the 18650 form factor (Fig. 8).

Fig. 8 – Laboratory sample of electric energy storage

The electrical energy conversion system must be performed based on standard electronics power protocols:

– increasing module Power Delivery 3.0;

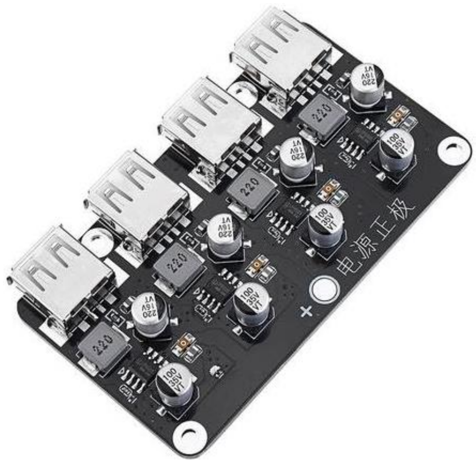
– USB Quick Charge 3.0 modules;

– 12 V power supply;

– 220 V inverter.

The specified modules are available in a miniature version for installation in a common energy storage and conversion unit (Fig. 9).

a)



b)

Fig. 9 – Power Delivery module XY – PDS 100 with power up to 100 W (a) and USB Quick Charge module MH-KC24 for four outputs with a power up to 24 W on each (b)

5. CONCLUSION

As a result of the research work, the design conception of a high mobility energy generation and storage system with intelligent energy conversion and storage systems is proposed for use in military and civilian purposes in regions with damaged infrastructure, where access to electricity and hot water is limited or threatened due to man-made actions or natural damage. For Ukrainian civilian and military users in our country, the damage to the energy infrastructure caused by the war has limited the reliable supply of electricity and hot water. The proposed modular system combining a heat collector, electrical energy converter, and related energy storage systems is a promising candidate to solve this problem in a rapidly deployable modular form factor.

The modular, reliable design and ease of deployment in the proposed system, the size of which corresponds to numerous units in standard shipping containers, enables rapid and flexible scaling of a deployed solar power plant, production and storage of hot water. Modularity makes it possible to form emergency power supply complexes of different power (45 W of electric power and 50 W of thermal energy per one module) and to provide emergency and permanent power supply of most electronic devices according to the standard protocols PD 3.0, QC 3.0, 12 V, 220 V. In addition, the system able to provide consumers with warm water for basic needs.

High mobility energy generation and storage system to the specific needs of Ukrainian and foreign civilian and military consumers will be carried out, including damage to the energy infrastructure, when the urgent problem is the backup autonomous supply of electric and thermal energy (hot water).

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Розробка модульної конструкції системи генерації та накопичення енергії для автономного електропостачання

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У статті представлено концепцію розробки високомобільної системи генерації і накопичення енергії з інтелектуальними системами перетворення та накопичення енергії для використання у військових і цивільних цілях у регіонах з пошкодженою інфраструктурою, де доступ до електроенергії та гарячої води обмежений або знаходиться під загрозою через людину або природні пошкодження. Основною особливістю пропонованої системи є модульна конструкція, яка поєднує в собі тепловий колектор, перетворювач електричної енергії та відповідні системи накопичення енергії. Модульна, надійна конструкція та простота розгортання запропонованої системи, розмір якої дозволяє здійснювати транспортування в стандартних транспортних контейнерах, забезпечує швидке та гнучке масштабування розгорнутої сонячної електростанції, виробництво та зберігання електроенергії та гарячої води. Конструкція модуля пропонованої системи базується на використанні високоефективних багатоперехідних сонячних елементів III-V у поєднанні з економічною та надійною пластиковою системою концентрації сонячного випромінювання. При цьому охолодження сонячних батарей для підтримки їх робочої температури забезпечує нагрівання води до мінімальних значень, необхідних у побутових умовах. Також модульний принцип лежить в основі системи накопичення та розподілу електроенергії, яку передбачається складати з високоефективних акумуляторних батарей на основі Li-Fe, які на сьогодні мають одні з найкращих показників за співвідношенням об’єму та накопичена енергія. Інтелектуальна система управління на основі мікроконтролерів забезпечує точне позиціонування сонячних елементів, реалізацію алгоритму MPPT для максимального збільшення вироблення електроенергії та підтримки балансу між живленням споживачів і зарядкою акумуляторів. Модульність дозволяє формувати комплекси аварійного живлення різної потужності (45 Вт електричної потужності та 50 Вт теплової енергії на один модуль) для забезпечення аварійного та постійного живлення більшості електронних пристроїв за стандартними протоколами PD 3.0, QC 3.0, 12В, 220В, а також забезпечити споживачів теплою водою для основних потреб.

Ключові слова: Мобільність, Сонячні батареї, Зберігання, Батареї, Ефективність.