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APPLICATION OF HIGHLY EFFICIENT HYDROGEN GENERATION AND STORAGE SYSTEMS FOR AUTONOMOUS ENERGY SUPPLY

Purpose. Development of scientific and engineering solutions to improve the reliability of power supply of stand-alone systems and mitigate the environmental burden by using hydrogen technologies for energy storage.

Methodology. The calculation method provides a set of optimal technical solutions for determining the effective operating modes of a stand-alone power supply system for supplying hydrogen to a fuel cell based on the electric load schedules of a particular consumer by using a computational experiment.

Findings. Based on the study, a technological scheme of a stand-alone power supply system based on fuel cells was developed, and an approach to the creation of a metal hydride system for accumulating and supplying hydrogen to fuel cells was substantiated. A calculation algorithm was developed that allows calculating the annual energy balance of a specific consumer and selecting the necessary equipment to implement the scheme based on the annual heat and electric load schedule.

Originality. An alternative scheme of guaranteed electric power and heat supply for a stand-alone house without using imported fuel is proposed. The advantage of such a scheme is that it is closed because hydrogen is produced on site to power the fuel cell, while the metal hydride hydrogen storage system is capable of performing hydrogen absorption and its release due to the hot and cold water resources available in the system.

Practical value. The technology for converting the energy of primary sources by creating a wind-driven energy technological complex using an electrolysis plant and a metal hydride hydrogen storage system will solve the problem of smoothing the irregular electric power supply from renewable sources.

Keywords: *power supply, power plant, hydrogen, fuel cells, metal hydride accumulator*

Introduction. By introducing scientific-and-technological advancements, the cost of electric power generated by wind-driven power plants (WPP) has become practically equal to TPP-generated power, and with account of additional costs related to environmental factors, it is lower. Further cost reduction and an increase in the effectiveness of these plants are achieved by increasing the capacity and improving the technical-and-economic indicators of WPP with introduction of advanced scientific-and-technological solutions.

Wind energy accessibility is widely adopted in stand-alone power supply systems for consumers. Worldwide, the hydrogen economy and the industry of fuel cells is consolidating its positions, forging ahead from technological projects to their commercialisation. Recently, not only industrially developed countries (the USA, Germany, Japan, Canada, and others), but also the countries of the Asia-Pacific Ocean region are being involved in implementing these projects [1, 2].

Since the operation of wind-driven power plants depends on an irregular wind force as an energy source, the choice of key complex parameters (the productivity of the electrochemical high-pressure hydrogen and oxygen generator, the parameters of hydrogen storage in the gaseous state under high pressure and in metal hydrides, as well as the parameters of fuel cells (FC)) depends on the region and the complex location. Hence, the development of off-grid (stand-alone) power plants that use this kind of energy should provide for additional systems to smoothen the energy supply.

The basic feature that distinguishes the electrochemical technological complex for producing high-pressure hydrogen and oxygen, which was developed at A. Pidhornyi Institute for Mechanical Engineering Problems NAS of Ukraine, from existing widely used technologies, is the separation in time of the processes of release of gases (hydrogen and oxygen). This means that the operation of the electrochemical system is cyclic and comprises hydrogen and oxygen liberation half-cycles [3, 4].

Recently, advancements in designing and developing FC that convert hydrogen and oxygen to electric power with high efficiency have aroused a growing interest in hydrogen energy technologies. Combined with renewable energy sources, such as wind power engineering, these technologies help develop high-efficiency systems for stand-alone power supply, which improve the reliability and quality of power supply to consumers. The most promising power plants for off-grid consumers are 1 to 20 kW power plants built around low-temperature al-

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kaline FC. They are distinguished by high efficiency, and are environmentally friendly and noiseless in operation. The development of technologies and the transition from an electrical energy system based on fossil fuels to one based on hydrogen power engineering is restrained by several engineering challenges, the key one being hydrogen storage and its usage in stationary power plants [5, 6].

Among the variety of promising hydrogen storage methods, the distinctive one is its storage in a bound state in metal hydrides or intermetallic compounds. This storage method meets the requirements of installing stand-alone power plants, the key ones being a high safety level, reliability and environmental compatibility. In addition, metal hydrides (MH) are capable of liberating and absorbing hydrogen due to the presence of hot and cold heat carrier resources in the power supply system, and effecting machine-free compression of gaseous hydrogen by using low-potential heat [7, 8]. The most compact and safe method of providing power to low-temperature fuel cells is the use of compact metal hydride accumulators for storage of high-purity repeated-action hydrogen [9, 10].

Hence, the development of an extremely space-saving and safe hydrogen storage technology in conditions close to those of the environment, with the possibility of providing effective on-site power generation with account of requirements of certain electric power consumers will enable hydrogen power supply systems to compete with those that are used currently by generators utilising natural and synthetic fuels or accumulators for being powered.

Literature review. Over the last years, wind power engineering has become a thriving branch of modern “clean” or, as it commonly called, “green” energy. Means for transforming the kinetic energy of wind flows to mechanical, heat and electric forms of energy are responsible for an increasing share in the worldwide energy sector. The reserves of this energy are inexhaustible because wind occurs due to solar activity, whereas the level of hazardous emissions with such generation is virtually zero. The volumes of hazardous emissions to the atmosphere and greenhouse gases during the combustion of conventional fuels affect climate changes and have an adverse impact on human health. Hence, the trend in successful and still greater development of renewable “clean” energy sources is obvious.

According to the data of the Global Wind Energy Council for 2018, the worldwide demand in electrical energy has increased by 3.7 %, which is one of the biggest growth indicators over the past 20 years. With China and India, which jointly account for about two-thirds of the electrical energy demand growth, the indicators increased to 81 %. The U.S.A. accounted for an especially big increase in electrical energy demand in 2018 when it had grown by 3.7 % due to weather conditions. Besides, according to estimates, carbon emissions in the power sector in 2018 increased by 2.7 %. This is the biggest growth rate over the last seven years, accounting for about one-half of worldwide carbon emissions [11].

The growth of electric power generation is due to the use of renewable energy sources. In the majority of developed countries, under conditions of state incentives, electric power generation based on renewable energy sources over the last years has achieved significant progress in building and use of wind power plants. Developing countries – India, China, Brazil, Egypt and others are assimilating wind energy on a broad scale. China is leading in the growth of renewable energy sources, accounting for 45 % of the worldwide increase in renewable energy generation [12].

Fuel cells are promising for building distributed power grids and setting up stand-alone power supply for many facilities [13]. Various systems built around hydrogen fuel cells for regular and standby power supply are used in 19 countries in the world. Together with other renewable energy sources, these technologies enable developing highly effective systems for stand-alone and distributed electric power generation, which will increase extremely the reliability and quality of electrical energy supply to consumers in all sectors of the economy.

Analysis of existing stand-alone electric power supply systems built around renewable energy sources has shown that electro-chemical accumulators are a critical component of such systems, though there are several problems related to their drawbacks. One of the ways of solving these problems is the search for and use of alternative storage devices [14].

The data analysed allows concluding that presently this problem is in the development stage because publications contain a relatively small amount of specific technical data on technologies of using fuel elements, hydrogen accumulation systems, as well as methods for connecting different subsystems.

Unsolved aspects of the problem. The research has shown that electrical energy supply systems built around fuel cells are interesting from different viewpoints: a high operating efficiency parameter [15], low environmental burden [16], flexible control of system parameters, and other parameters [17]. Systems for standby and stand-alone electrical energy supply built around fuel cells can also include renewable energy sources to create entirely closed systems. Besides, there is a big demand for automated systems of distributed and standby electrical supply for medical establishments, especially under conditions of the rapid spreading of the new COVID-19 coronavirus, and the need to support the serviceability of a huge number of artificial respiration units even under conditions of shutdown of centralised electric power supply. The suggested solution based on fuel cells has an advantage over all other modern standby electric power supply systems. Thus, as compared to present-day standby electric power supply systems based on storage batteries, fuel cells enable creating standby electric power supply systems with a 3 to 4 times longer time of operation in the stand-alone mode.

Besides, presently many small agricultural facilities are connected to centralised electric energy supply systems that encounter a host of problems, namely, voltage drops, critical conditions of electric power grids, and frequent and prolonged power blackouts.

Therefore, research focused to further refinement of hydrogen technologies is a topical issue today.

Purpose. To ensure the effective operation of a stand-alone electric power supply system, it is necessary to develop a methodology for researching the development of energy systems, which would meet the needs of a stand-alone consumer with account of a required load schedule. Hence, the key purpose of research is to develop a schematic arrangement of a wind-hydrogen energy technological complex for supplying hydrogen to fuel cells (FC) based on the schedules of the electric load of a concrete consumer.

Results. A schematic arrangement for a wind-energy installation (Fig. 1) was developed for research in metal-hydride technologies of accumulation and storage of hydrogen in alkaline FC.

During wind-driven generator operation, the generated electric power is delivered to the high-pressure electrolyser via

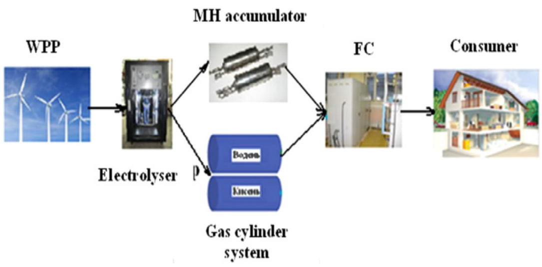


Fig. 1. Schematic arrangement of a stand-alone wind-hydrogen energy technological complex

the control system [4]. The reaction of electrochemical dissociation of the liquid alkaline electrolyte yields oxygen and hydrogen that are delivered to the gas storage system of cylinders and used subsequently for FC module operation. An invertor circuit is used to convert the DC voltage to alternating current. Then the converted electric power is delivered to the consumer. During hours when wind-driven generator power is excessive, hydrogen is stored in the metal hydride accumulator jointly with the gas cylinder storage system.

Hence, wind energy is accumulated to be used subsequently for stand-alone power supply to consumers. During peak load hours (morning and evening), as well as during an abrupt prolonged wind speed drop, hydrogen and oxygen in the storage system are used for generating additional electric power with the help of the alkaline FC module.

This requires developing an effective computational algorithm and using it to develop a program for modelling the evaluation of compliance (sufficiency) of energy capacities to meet the predicted electric power demand. This will allow addressing the issue of electric power supply for stand-alone systems.

To determine the amount of electric energy consumption, comprehensive analysis of electric power demand by households should be carried out (Fig. 2).

The methodology for determining the levels and conditions of electric energy consumption and scheduling electric loads provides for using electric power demand rates with the use of statistical data on electric power consumption conditions for domestic consumers. First, it is necessary to determine the composition of domestic electric appliances. This is done by using statistical data from several publications that allow determining key electric power consumers [18]. Next, the hourly and daily electric power consumption by a household is found to register the maximum household load. To provide comfortable living conditions and activities in a private house in the heating season, it is necessary to design a heating system and provide a heat energy source.

For the needs of a stand-alone house with an area of 100 m^2, we have found the monthly electric power consumption for lighting and domestic appliances (refrigerator, washing machine, TV set, PC, electric kettle, microwave oven, fan, toaster, and so on) and heating (Fig. 3).

Computational analysis shows that maximum electric power consumption is in the cold winter months when heating accounts for up to 95 % of the overall consumption. Significantly less electric power is consumed in the warm summer season when it is within 5 %.

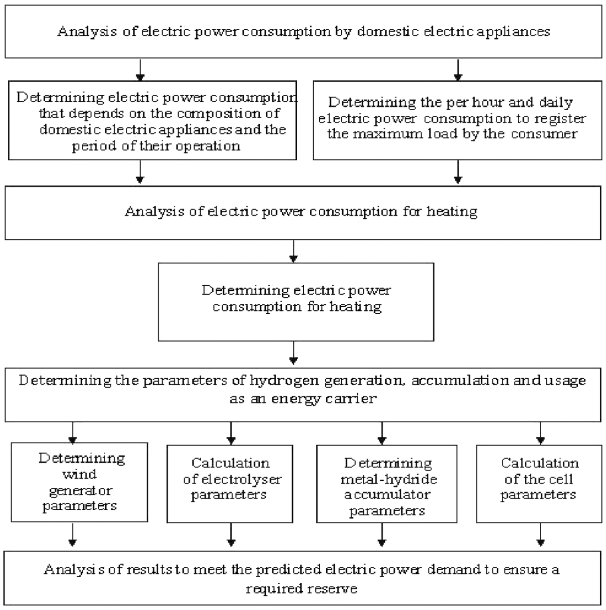


Fig. 2. General structure for determining the procedure for meeting electric power demand

Fig. 4 shows the average statistical daily electric power consumption for lighting, domestic appliances and heating depending on the season.

The maximum daily electric power consumption is in December due to heating and long daily dark periods. With an increasing daily light period and outdoor temperatures, the daily electric power consumption decreases, and this period can be called the transition one. Minimal electric power consumption is in the summer time. Thus, the level of daily electric power consumption by domestic appliances during the year is virtually invariable. The difference in electric power consumption depends only on lighting. Heating accounts for the bulk of consumption and it depends on outdoor temperature changes.

Fig. 5 shows the maximum daily load by lighting, domestic appliances and heating for a stand-alone house.

Hence, computations show that the energy consumption of a stand-alone house with an area of 100 m^2 is as follows: annual energy consumption – 9 651 kW/year, with lighting and domestic appliances accounting for 10 648.3 kW/year, and heating, for 8 002.7 kW/year. The maximum daily power load for lighting, domestic appliances and heating in December is at 18:00 hours and equals 4.5 kW/h. These computational data are required for choosing a fuel cell for generating electrical

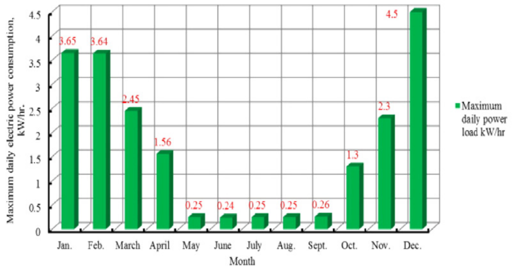


Fig. 3. Monthly electric power consumption by a stand-alone house

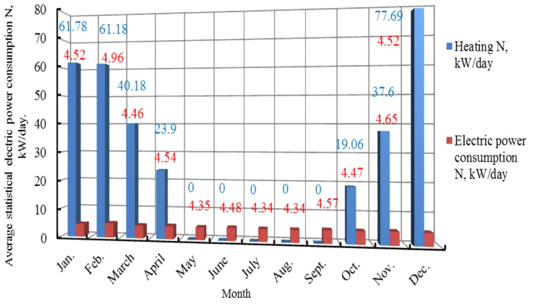


Fig. 4. Daily electric power consumption by a stand-alone house

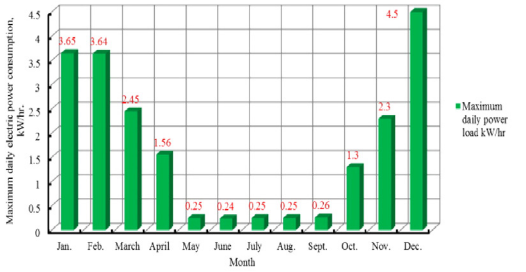


Fig. 5. Estimated maximum electric power load in a stand-alone house

energy to a consumer-defined schedule. Here it should be taken into account that the FC operating conditions must meet both the conditions for supplying electric power for lighting and domestic appliances and the conditions for supplying electric power for heating and the thermal load of the operating mode of the standby metal-hydride hydrogen storage system (Fig. 6).

In addition, looking forward, it is necessary to consider the possibility of using cogeneration systems for operating FC to meet the demand in hot water for domestic purposes and heating. This will reduce the electric power load for meeting these demands in summer by 80 % and more, and in winter, by 15–25 %.

Among the devices developed for hydrogen storage for stand-alone generation, the economically feasible and safe ones can be devices and systems based on metal hydrides, which can absorb hydrogen selectively and reversibly. Thereat, the bulk of hydrogen in the system is in the bound solid-phase state, ensuring increased operational safety [7, 8].

The reverse MH production reaction can be effected by direct interaction of the hydride-forming material with gaseous hydrogen or electrochemically

$$M_{(solid)} + H_{2(gas)} \leftrightarrow MH_{x(solid)} + Q \qquad (1)$$

$$M_{(solid)} + H_2O_{(liq.)} + e^- \leftrightarrow MH_{x(solid)} + OH^-_{(liq.)} \qquad (2)$$

where $M_{(solid)}$ is the metal or intermetallic compound.

Typically, the first process is implemented in hydrogen transportation and storage systems, and the second one is used in electrochemical processes and in chemical current sources with metal hydride electrodes. Depending on the type of hydride-forming material and ambient conditions, hydrogen sorption-desorption can be effected across a wide range of pressures and temperatures. Significant thermal effects (20–40 kJ/mol) result in hydrogen sorption being associated with heating, and desorption with MH cooling, whereas the direction of reaction (1) depends on hydrogen pressure and sorbent temperature [7]. This enables low-pressure hydrogen absorption at a low temperature, and with adequate heat supply to the MH, desorption of high-pressure hydrogen. This principle is used in the stand-alone power supply system, where the metal hydrides in a multiple-action hydrogen accumulator are capable of absorbing and producing hydrogen due to cold and hot water resources formed by FC operation.

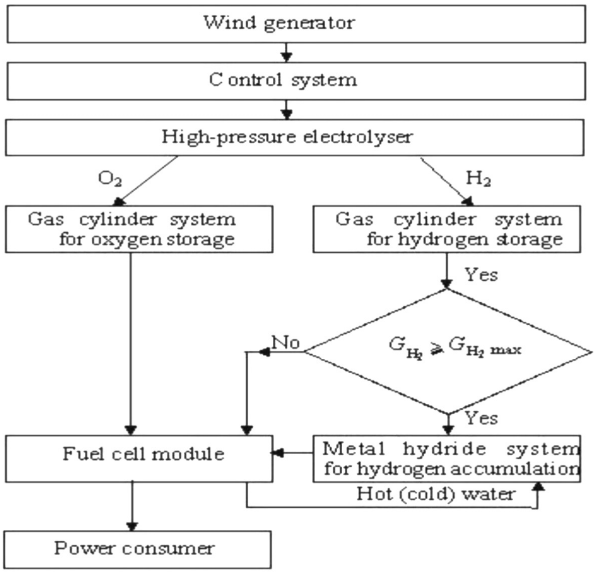


Fig. 6. Generalised algorithm for design of a stand-alone energy supply system

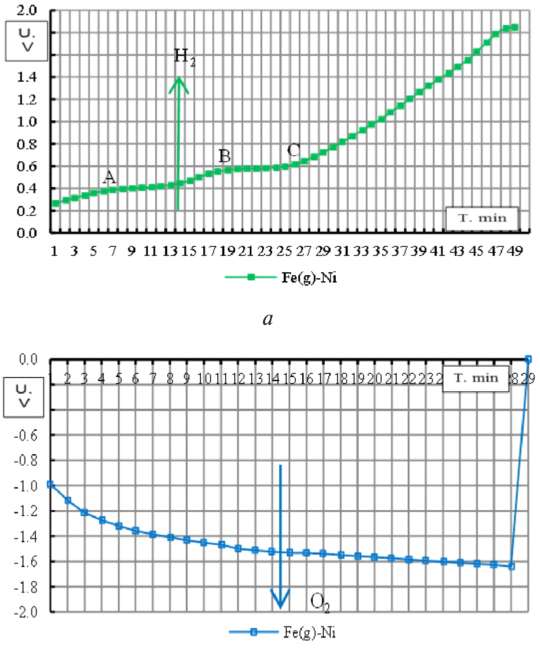
A mathematical model of thermosorption interaction of hydrogen with a metal hydride was used for modelling the operation of elements of hydrogen systems, studying their parametrical characteristics, and choosing effective operating conditions of systems of such type [19, 20]. $LaNi_5$ was chosen as the working material for metal hydride hydrogen accumulation. Its advantage involves cyclic stability, low sensitivity to oxygen admixtures and moisture, making it possible to use industrial-grade or electrolysis hydrogen.

Since the processes of sorption-desorption of hydrogen by metals involve significant thermal effects and are characterised by an essential dependence of equilibrium pressure on temperature, an important task during the design of metal hydride systems is ensuring the thermal state of the accumulating environment. Low effective thermal conductivity of an MH stands in the way of managing the thermal condition in the accumulator, which is required for ensuring specified consumptions of hydrogen supplied to the FC. Hence, a topical problem is identifying the optimal operating conditions of a metal hydride hydrogen accumulator according to specified characteristics and synchronising the operating modes of fuel cells with the accumulator's dynamic characteristics.

Design produced a metal hydride hydrogen accumulator with a length of $L = 0.15$ m and an inner diameter of 0.04 m, in which the heat exchange matrix is made of copper plates. For the chosen hydrogen accumulator design, the recommended distance between the finning plates must be within $5.0 \cdot 10^{-3}$ m with plate thickness of $d = 1.0 \cdot 10^{-4}$ m. The flow of the heat carrier that encircles the accumulator outer surfaces has the temperature 338 K, the desorption pressure $p = 0.36$ MPa, with hot water consumption $G = 0.017$ kg/s and productivity up to 0.035 g/s.

The electrochemical water splitting method developed at the A. Pidhornyi Institute for Mechanical Engineering Problems NAS of Ukraine is cyclic and comprises half-cycles of hydrogen and oxygen release (Fig. 7) [3, 4].

***Half-cycle of hydrogen liberation* (*Fig. 7, a*).** The electromechanical reaction of water splitting runs with voltage increase across the cathode-anode pair during gas production. Upon achieving the threshold voltage of 1.2 V, the polarity is



a

b

Fig. 7. The sequence diagram of the voltage change in the high-pressure hydrogen generator with a gas-emitting electrode, at $I = 0.02$ A/cm² with electrode pairs Fe(*g*)-Ni:

a – H_2 *generation*; *b* – O_2 *generation* reversed and the electromechanical gas-liquid flow switch is enabled, making the passive electrode the anode, and the active one a cathode.

***Half-cycle of oxygen liberation* (*Fig. 7, b*).** Gaseous oxygen is liberated at the passive electrode, and hydrogen regenerates the active mass of the gas absorption electrode on the cathode.

Upon achieving the threshold voltage of 1.6 V, the polarity of the electrodes is reversed and the cycle is repeated.

Using a material with a mixed valence (e.g., sponge iron), which chemically binds oxygen (Fig. 7, section A–B), follows the reaction

$$Fe + 2OH^- \leftrightarrow Fe(OH)_2 + 2e^- \quad (3)$$

With prolonged operation of the active mass of the electrode, the electrode mass is oxidised more intensely

$$Fe(OH)_2 + OH^- \leftrightarrow Fe(OH)_3 + e^- \quad (4)$$

The cyclogram section with an electrode potential change during electrochemical production of hydrogen and oxygen at the H_2 liberation half-cycles (Fig. 7, section B–C) corresponds to transition of Fe(II) to Fe(III), whereas the O_2 liberation half-cycle corresponds to electrochemical reduction of iron hydroxides. Oxidation of the active sponge iron electrode, as the basic electrochemical reaction, reduced power consumption for the production of 1 m^3 of hydrogen (and 0.5 m^3 of oxygen) to 3.85 kW per hour (typical electrolysers require power consumption from 4.3 to 5.2 $kW \cdot h/m^3$). This suggests that electrochemical high-pressure hydrogen generators will help address critical problems in power engineering, and in particular, the development of metal hydride accumulators with a fuel element when renewable energy sources characterised by irregular power supply are used [3, 4].

Wind generator outage time owing to low wind velocity can be 120 to 200 hours a month, and this is 5 to 8 days. Idle periods are limited to part of the day, or continue no more than 1–2 days in a row.

Since power plant operation depends on irregular wind force as an energy source, the key plant parameters (productivity of the electrochemical generator of high-pressure hydrogen and oxygen, and the hydrogen storage system parameters) are chosen with account of the power plant site.

The developed method for producing hydrogen is based on the integrated usage of the electric energy of the chemical potential of reaction resultants that interact with the materials of the gas sorption electrode, and the method was utilised for hydrogen production. In this method, electric energy is required only for initiating electrochemical reactions of electrolytical hydrogen production. For comparison, the Table gives the data for different technologies of electrolysis production.

As the Table shows, the energy effectiveness of electrolysis equipment that uses a gas sorption electrode is the highest. The working pressure and electric power consumption are better than in other types of electrolysis equipment.

Design showed that the maximum electric power demand for lighting, domestic appliances and heating in a stand-alone house is satisfied by using a wind generator with an output electric power of 5 $kW \cdot h$, the electrolyser EBT 1.0–150 with a productivity of 1 nm^3 H_2 and 0.5 nm^3 O_2, a metal-hydride hydrogen accumulator with a length of $L = 0.15$ m and an inner diameter of 0.04 m, and a productivity of up to 0.035 g/s. Alkaline fuel cells were considered and analysed. As a result, the FC DBX5000 with a power of 5.0 kW was chosen. It ensures the specified characteristics of the wind-power plant with a hydrogen energy accumulator.

Conclusions.

1. It is shown that the immediate task is to reduce natural gas consumption and place emphasis on using renewable energy sources, in particular, in power supply systems.

2. It is shown that, for stand-alone consumers, power supply systems built around low-temperature alkaline 20 kW FC are exceptionally interesting. The usage of a metal hydride hydrogen storage system in a wind energy technological complex meets the requirements to the installation of stand-alone power supply systems.

3. The schedules of electric power consumption by a stand-alone house were analysed. It was found that, for a house with an area of 100 m^2, the annual electric power consumption is 9 651 kW/year, specifically, for lighting and domestic appliances – 1 648.3 kW/year, and for heating – 8 002.7 kW/year. The maximum daily power load for lighting, domestic appliances and heating in December is at 18:00 hours and is equal to 4.5 kW/h.

4. The operation of fuel cells with a metal hydride hydrogen accumulation system was analysed for hydrogen storage accumulators and the schemes of their joint operation for a stand-alone cottage. The design chosen was that of a metal hydride hydrogen accumulator with a length of $L = 0.15$ m and an inner diameter of 0.04 m, and a productivity of up to 0.035 g/s.

5. It was shown that, using oxidation of an active sponge electrode as the basic electrochemical reaction, reduced electric power consumption for the production of 1 nm^3 of hydrogen (and 0.5 nm^3 of oxygen) to 3.85 $kW \cdot h$ (conventional electrolysers consume within 4.3 to 5.2 $kW \cdot h/m^3$).

6. Based on design, the electrolyser EBT 1.0–150 with the productivity of 1 nm^3 H_2 and 0.5 nm^3 O_2 was chosen. It produces high-pressure hydrogen and oxygen at 15.0 MPa without using a compressor and entirely meets the technical demands of a gas tank system for hydrogen and oxygen storage.

7. The fuel cell of choice was DBX5000 with a power of 5.0 kW that provides the maximum electric power load of a stand-alone house.

Hence, the combined application of advanced technologies for the production, storage and usage of hydrogen increases energy conversion effectiveness and significantly expands its application areas, especially for stand-alone power supply systems with a wind-driven power plant and a hydrogen energy accumulator.

The next research stage will be the technical and economical comparison of the proposed stand-alone system for electric power supply of a stand-alone consumer by a centralised electric power supply system and a diesel electric power plant.

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Table

Electrolysis technology for hydrogen production

Type of electrolyser	Energy consumption, $kW \cdot h/m^3$	Temperature, K	Productivity H_2, m^3/h	Pressure, MPa	Efficiency %
Alkaline	4.5–6.0	320–370	Max. 500	0.1–25	50–70
With a solid polymer electrolyte (SPE)	4.3–5.0	350–370	Max. 100	0.1–15	80–90
With a solid oxide electrolyte	2.5–4	1.070–1.270	–	0.1–3	≥ 85
With a gas sorption electrode	3.9–4.0	320–370	Max. 10	0.1–35	≥ 90

target program of scientific studies at the NAS of Ukraine "Development of the scientific fundamentals of production, storage and usage of hydrogen in stand-alone power supply systems".

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Застосування високоефективних систем генерування та зберігання водню для автономного енергозабезпечення

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Мета. Розробка науково-технічних рішень, що забезпечують підвищення надійності енергозабезпечення автономних систем і зменшення екологічного навантаження на оточуюче середовище за рахунок використання водневих технологій акумулювання енергії.

Методика. Методика розрахунку забезпечує отримання сукупності оптимальних технічних рішень задля визначення ефективних режимів роботи автономної системи енергозабезпечення для подачі водню до паливної комірки, виходячи із графіків електричного навантаження конкретного споживача за допомогою обчислювального експерименту.

Результати. На підставі проведеного дослідження розроблена технологічна схема автономної системи енергозабезпечення на базі паливних комірок, обґрунтовано підхід до створення металогідридної системи акумулювання водню та його подачі до паливних комірок. Розроблено алгоритм розрахунку, що дозволяє розраховувати річний баланс енергії конкретного споживача й підібрати необхідне обладнання для реалізації схеми, виходячи з річного графіка теплового та електричного навантаження.

Наукова новизна. Запропонована альтернативна схема гарантованого електро- й теплопостачання автономного будинку без використання привізного палива. Перевагою такої схеми є її замкнутість, оскільки водень для живлення паливної комірки виробляється на місці, при цьому металогідридна система зберігання водню здатна забезпечити проведення процесів поглинання та його виділення за рахунок наявних у системі ресурсів гарячої й холодної води.

Практична значимість. Застосування технології перетворення енергії первинних джерел шляхом створення вітроводневого енерготехнологічного комплексу із застосуванням електролізної установки й металогідридної системи акумулювання водню дозволить вирішити проблему згладжування нерівномірності надходження енергії від поновлюваних джерел.

Ключові слова: *енергозабезпечення, енергоустановка, водень, паливні комірки, металогідридний акумулятор*

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