

Prospects For The Production Of High-Pure Hydrogen By Water Electrolysis Using Solar Energy

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ABSTRACT: The paper considers various methods for obtaining hydrogen from water using solar energy. After a comparative analysis of all these methods, preference is given to conventional alkaline electrolysis of water, carried out from a photovoltaic current source (PCS) with a maximum power of 750 W and a solar radiation intensity (SRI) of 1000 W/m². The moments of violation of the operation mode of the cell with changes in the SRI over a wide range and ways to eliminate these problems are considered. Methods for obtaining high-purity hydrogen and oxygen by maintaining the pressure of these gases in equality are also analyzed.

KEY WORDS: photovoltaic current source, solar radiation, filter press electrolyzer, hydrogen and oxygen, water decomposition voltage, voltage per cell, maximum power, gas pressure regulator, automatic switching devices.

I. INTRODUCTION

It is known that all domestic types of fuel will be depleted in the near future. Today, in many countries of the world, even in developed European countries, this is clearly felt. Despite the fact that Azerbaijan is an oil and gas producing country, even without taking into account the annual growth rate of exports, our oil reserves will run out in 25-30 years, and gas reserves in 100 years [1]. In addition, the ever-increasing pollution of the near-Earth atmosphere with greenhouse and other toxic gases emitted by the use of domestic fuels raises the question of how to avoid this problem? Obviously, the only way out of this situation is both the search for new, environmentally friendly and

inexhaustible types of synthetic fuels and renewable energy sources (RES). In this aspect, as a fuel, special attention is paid to hydrogen and hydrogen-containing combustible gas mixtures (CGM), methanol, ethanol, etc., and as energy sources - solar, wind, geothermal, wave energies, as well as to the energy of biomass, rivers etc. Among these energy sources, the most affordable and with large reserves are solar and wind energy. As for the energy reserves of rivers, studies show that in recent times there have been severe droughts even for relatively large rivers. For example, in the Azerbaijani mouthwaters of the Kura River, there is a significant drought, which is even more felt from year to year. This year alone, the water level in the Kura delta has dropped by about one meter. Similar situations are also observed in other, relatively small mountain rivers, such as Damaraparanchay, Aksuchay, Gokchay, Dashagilchay, etc. There are some geothermal sources of energy in Azerbaijan, but not enough work is being done on the use of these resources, due to the lack of specialists in this field. Particular attention is paid to the use of solar and wind energy. During the periods 2004-2022, numerous solar (SPS) and wind power (WPS) stations with various capacities were developed and built, which operate in parallel with the centralized power supply system, which is not always the best option [2,3]. This is primarily due to the fact that in the vast majority of cases, the modes of electricity consumption do not coincide with the modes of receipt of solar and wind energy, which in most cases are stochastic (arbitrary) in nature. This is especially true for the mode of change of wind power. To eliminate these shortcomings, it is

necessary to accumulate the energy of the sun and wind under good weather conditions, and non-solar and non-wind weather conditions, as well as use the accumulated energy at night. By this, it is possible to ensure continuous and sustainable power supply to consumers of various types. The following types of storage systems (SS) can be used to accumulate solar and wind energy: electrochemical (in the form of electrical energy, using batteries (B)), chemical (in the form of chemical energy of combustible gas), pneumatic (in the form of compressed air), hydraulic (in the form of water raised above ground level) and thermal (in the form of thermal energy). However, pneumatic and thermal speakers cannot be used for the accumulation of large amounts of energy, as well as for long-term accumulation.

Electrochemical batteries are also not designed for high power, they require special maintenance. In addition, due to the high cost, short service life, large overall dimensions and heavy weight, the use of such batteries is not always advisable. A comparative analysis of all possible types of accumulation shows that among these methods, the best and most promising is the accumulation in the form of the chemical energy of hydrogen and hydrogen-containing gases. In this regard, the production of hydrogen by electrolysis of water is of particular importance. This is primarily due to the fact that in the electrolysis process, firstly, high-purity hydrogen is obtained, in addition, in addition to hydrogen, another, strategically very important product, oxygen, is also obtained. The only disadvantage of the electrolysis process is the relative energy intensity of the process, since to obtain a unit volume of gas ($1.0 \text{ m}^3 \text{ H}_2$ and $0.5 \text{ m}^3 \text{ O}_2$) it is required to spend at best 4.2-4.5 kWh of electricity. Other minor disadvantages of this process are the need for bidistillate, as well as additional equipment for obtaining direct current. Therefore, at this time, the use of solar energy to carry out the process of electrolysis of water, especially solar photovoltaic current sources (SPVCS), is considered the most correct solution to the problem. Since 1976, the laboratory "Conversion of Renewable Energy" of the Institute of Radiation Problems of the Ministry of Science and Education of the Republic of Azerbaijan (MSERA) has been conducting research on the use of solar and wind energy to produce high-purity hydrogen and oxygen under pressure by electrolysis of water [4-11].

Below is a comparison of possible methods for obtaining hydrogen, as well as hydrogen-containing gases from water, using solar energy, and also provides information on the work

carried out on water electrolysis and the results obtained.

II. COMPARATIVE ANALYSIS OF POSSIBLE METHODS FOR OBTAINING HYDROGEN FROM WATER USING SOLAR ENERGY

Currently, the following main methods for obtaining hydrogen from water using solar energy are known [6]:

- 1) thermal decomposition of water, using high-temperature solar furnaces (thermolysis of water), which are used as parabolic concentrators;
- 2) thermochemical method of water decomposition using parabolic concentrators;
- 3) direct decomposition of water, under the action of a $h\nu$ quantum of sunlight (photolysis);
- 4) direct photocatalytic decomposition of water under the action of the radiant energy of the sun;
- 5) photoelectrochemical methods of water decomposition:
 - a) using hybrid anodes;
 - b) using photosensitive dyes that intensively absorb light radiation;
- 6) photochemical method, with the use of dyes that intensively absorb the radiant energy of the sun;
- 7) biochemical method;
- 8) electrochemical decomposition of water, using various types of SPS, including SPVCS.

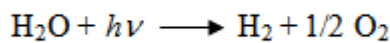
From a comparison of all these methods of obtaining hydrogen from water using solar energy, we can draw the following conclusions [6].

To implement the thermal method of water decomposition, a large amount of heat is required, since the minimum temperature in the reaction chamber should be $\sim 2500^{\circ}\text{K}$, and its equilibrium constant equal to unity corresponds to $\sim 4500^{\circ}\text{K}$. Therefore, carrying out this reaction in a high-temperature solar furnace is a complex and explosive process. To eliminate the explosion hazard, it is necessary to select hydrogen from the reaction chamber so that an explosive mixture of gases does not form. There are also a number of other technological problems that limit the practical application of this method, at least in the near future.

The thermochemical method of water decomposition, in comparison with thermal dissociation, is more acceptable, since it requires a relatively low temperature ($<1800^{\circ}\text{C}$) and does not impose a special requirement related to the selection of hydrogen from the system. This method is well studied in the works [12-14], in which the authors carried out thermodynamic calculations of the process, determined the possibilities of using solar energy to implement this

process, developed thermochemical reactors have been developed in some modifications [12–13] and a mathematical model of an installation with a parabolic concentrator [14] designed to produce hydrogen-containing combustible gas mixtures from coals, hydrocarbons, and plant biomass. The composition of combustible gas mixtures, in the optimal mode, is 50% H₂, 30% CO and 20% other gases (CO₂, CH₄, N₂, etc.).

The essence of photolysis lies in the fact that in this method, water molecules undergo direct decomposition under the action of a quantum of absorbed light according to the reaction:



In this case, the quantum energy sufficient to decompose a water molecule is 292.6 kJ/mol, which corresponds to wavelengths of <4000 Å. In this case, the optimal photolysis regime is achieved at wavelengths less than 1900 Å. However, the energy of even the shortest wavelength part of the solar radiation spectrum, reaching the Earth's surface, also does not approach the indicated value and is insufficient for the process of water photolysis. To reduce energy consumption, i.e. to carry out the photolysis process at a relatively long-wavelength part of the solar radiation spectrum, in some cases, various photocatalysts are proposed to be used. However, this method also has no prospects, because the energy of the short-wave part of the solar radiation spectrum is only 3% of the total energy of solar radiation. Therefore, the efficiency of this method does not exceed 0.001%. Another obstacle to the widespread use of this process is the reverse reaction of the resulting products. To eliminate this shortcoming, it is proposed to use asymmetric membranes that serve to separate the products of direct reduction and oxidation reactions.

As for the photo electrolysis of water, this process is carried out using semiconductor electrodes. However, there are a number of problems preventing the wider application of this method of water decomposition.

The photoelectrochemical method of water decomposition with the use of hybrid electrodes has great prospects. In this case, the anode is made from a thin (~5000 Å) TiO₂ film deposited on a silicon film. This design of electrodes has the following advantages: 1) the solar cell creates an anode bias on the TiO₂ film, which sharply increases its catalytic effect in the process of water decomposition; 2) photons with energies above 3 eV are absorbed in the TiO₂ film, and with energies from 1.2 to 3.0 eV - in the cell itself, which increases the efficiency of photochemical

decomposition; 3) The stability of TiO₂ film removes the problems of electrode corrosion. However, studies show that at present the efficiency of this process does not exceed 0.1%, and its required value, according to economic calculations, can reach up to 5-10%.

Of great interest is the use of microbiological facilities for the production of hydrogen using solar energy. These objects primarily include anaerobes, bacteria that capture hydrogen (pathogenic and other types of intestinal bacteria), bacteria that contain and capture nitrogen compounds, and photosynthetic organisms (photosynthetic bacteria, blue-green algae, green algae). It was determined that systems, including the use of blue-green bacteria and synthetic systems, have greater potential than all others, and these systems are similar to microbiological systems. However, this method requires a wide range of studies to increase the efficiency of the process.

In comparison with the above methods, the photobiochemical method at first glance looks like the most promising method for the production of H₂, using solar energy. However, it can be seen from the literature analysis that for the production of 10⁴ m³ of hydrogen per year, by the photobiochemical method, more than 10⁶ m² of area is required, which significantly reduces the practical value of this method.

Unlike all the above methods, the production of hydrogen by electrolysis of water has a number of advantages, which are as follows:

- in the final product, the purity of hydrogen is 99.99%, and oxygen - 99.85%;
 - automatic control of the technological process is much simpler and there are no moving parts on the electrolytic cells;
 - in addition to the main product (hydrogen), another strategically important product, oxygen, is also obtained;
 - the supply of water used as a raw material is, firstly, unlimited, and secondly, in the production of electricity using fuel cells, as a result of a chemical reaction between hydrogen and oxygen, only pure water vapor is formed, which is reused in the electrolysis process and thus, the following environmentally friendly closed cycle is learned: “- water - electrolysis - hydrogen and oxygen - chemical reaction in the fuel cell - water -”;
 - to reduce the consumption of electrical energy, the process can be carried out at high pressures;
- Another important advantage of the electrolysis method is that, since this method is carried out using electric energy, not only SPVCS, as well as other types of RES, including WPS.

III. EXPERIMENTAL SOLAR ELECTROLYSIS PLANT FOR THE PRODUCTION OF HIGH-PURITY HYDROGEN AND OXYGEN FROM PRESSURIZED WATER

Intensive work on the production of electrolytic hydrogen and oxygen from water using solar energy began in the 70s of the last century. Thus, the first experimental electrolysis plant with direct power supply from SPVCS was created in 1974 in the USA. The installation was developed in the laboratory of jet engines of the California Institute of Technology, which consists of SPVCS, with a maximum power of 175 W, at a voltage of 35 V and a portable hydrogen generator (electrolyzer). The practically output power of the SPVCS is 143 W, and the voltage per one cell of the electrolyzer is $U_{CELL} = 2.3 \pm 0.2$ V. The joint current-voltage characteristics (CVC) of the setup taken at different times on a clear sunny day are given. This setup operated at normal pressure [6].

Following this, we developed the first solar electrolysis plant for the production of high-purity hydrogen and oxygen from water, operating

under pressure up to 0.6 MPa [5,6]. The plant was powered by SPVCS with a maximum power of 100 W at an SRI of 900 W/m², and two types of electrolyzers conventionally named E-1 and E-2 were used as a hydrogen generator. In this case, the E-1 type electrolyzer is made in the form of two metal cylinders, concentrically located one inside the other, the outer cylinder of which simultaneously plays the role of a housing and an anode, and the inner cylinder - a cathode. Between the anode and the cathode there is a perforated, on the lower side, partition made of a dielectric material. A 32.5% KOH solution in distilled water was used as an electrolyte. The E-2 type electrolyzer is a multi-cell, filter-press type, the cells of which are connected in parallel along gas and electrolyte lines, and in series along the electric power lines from the SPVCS. The optimal number of E-2 cells, which allows maximum hydrogen productivity in a wide range of SRI changes, is determined taking into account the family of joint load CVCs of the SFVCS, taken at different values of the SRI and the electrolyzer - taken at different numbers of electrolytic cells.

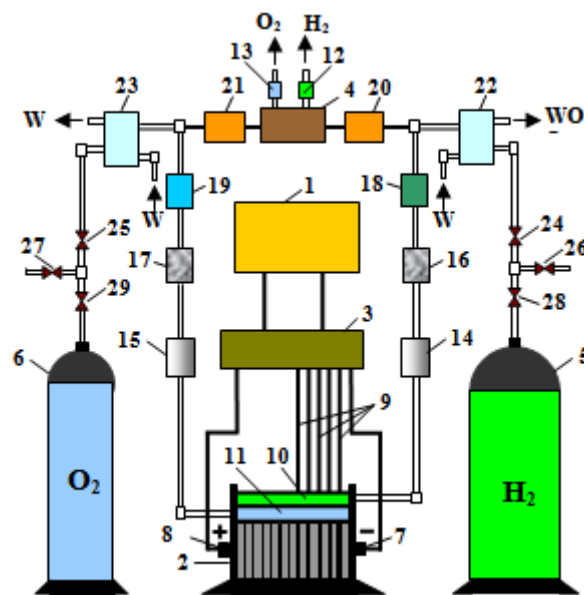


Figure 1. Functional diagram of a solar electrolysis plant for obtaining high-purity hydrogen and oxygen from pressurized water:

1- SPVCS; 2-electrolyzer type E-2; 3-automatically switching device (ASD); 4- pressure difference regulator (PDR) H₂ and O₂; 5 and 6 - receivers for H₂ and O₂; 7 and 8 outputs taken from the extreme monopolar electrodes of the cell; 9 - outputs taken from individual bipolar electrodes of the electrolyzer; 10 and 11 - gas collection manifolds for H₂ and O₂; 12 and 13 - solenoid valves installed on gas lines H₂ and O₂ PDR; 14 and 15 - separation columns for H₂ and O₂; 16 and 17 filters for H₂ and O₂; 18 and 19 - drying chambers for H₂ and O₂; 20 and 21 - flame arresters installed at the PDR inlets for H₂ and O₂; 22 and 23 - cold rooms for H₂ and O₂; 24, 25, 26, 27, 28 and 29 valves; W- water line

To study the electrolysis process, at different values of SRI and the number of operating cells of the electrolyzer, as well as to ensure both the high purity and quality of the gases obtained, as well as the explosion safety of the installation, a simplified functional diagram of the experimental solar electrolysis installation was developed, which is shown in Figure 1.

Although the diagram shown in Figure 1 is simplified, in this diagram all the main components necessary to obtain high-purity gases (gas pressure difference regulators), to improve the quality of both gases (filters, dryers, and gas coolers) and the explosion safety of the entire device, in in general (flame arresters) are taken into account. In Figure 1, a multi-cell filter-press electrolyzer of the E-2 type is used, which, in addition to the main outlets taken from the extreme monopolar electrodes, also has additional outlets taken from a number of intermediate, bipolar electrodes. An electrolyser with such a design was first developed in the laboratory “Conversion of Renewable Energy Types” of the Institute of Radiation Problems of the MSERA, which passed long-term field tests in the climatic conditions of Baku.

However, the first experiments were carried out on an electrolyzer of the E-1 type, which was able to operate at pressures of the vapor-gas mixture up to 0.6 MPa (~ 6 atm). To maintain the pressure of hydrogen and oxygen in equality, in the anode and cathode spaces of this cell, a pressure difference controller (PDC) was used, consisting of a gas pressure difference sensor (GPDS), consisting of a highly sensitive (operating with an accuracy of not more than 15-20 mm of water column), a small-

sized U-shaped differential pressure gauge and an electrovalve installed on the oxygen line of the cell. At the same time, the U-shaped differential pressure gauge was made of rectangular plexiglass with dimensions of 5x10x20 cm, inside which two channels are made parallel to each other in the vertical direction, which are connected to each other from the bottom in the form of communicating vessels, and from the upper side, both channels are equipped with branch pipes, one of which is connected to the hydrogen and the other to the oxygen lines of the electrolyzer. An electrovalve is installed on the oxygen line to release excess gas (in this case oxygen) into the atmosphere. A long needle electrode is installed on the oxygen elbow of the U-shaped differential manometer, and a short needle electrode is installed on the hydrogen elbow. To create electrical conductivity, the internal cavity of the U-shaped differential manometer is also filled with a 32.5% KOH solution in distilled water. Using this type of RDR, hydrogen was obtained with a purity of 99.99%, but since it worked on the “to itself” principle, the accumulation of oxygen was not provided for in it and oxygen was released into the atmosphere. The main disadvantage of the U-shaped differential pressure gauge of this type is that its operation occurs by sparking, which creates an explosive situation, with possible mutual mixing of gases inside the electrolyzer for random reasons. With this in mind, other explosion-proof versions of the RDR were subsequently developed, conditionally named RDR-2, RDR-3 and RDR-4, RDR-5, which were discussed in detail in [6,7,9,10] .

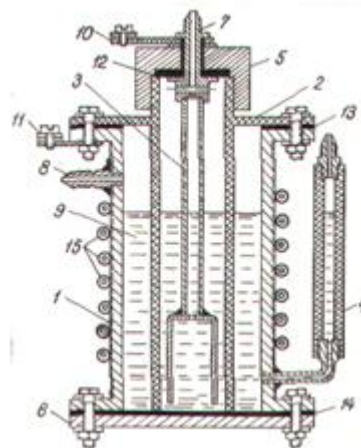


Figure 2. Structural diagram of the electrolyzer type E-1:

- 1- case; 2- perforated partition; 3- cathode; 4-level gauge; 5- top cover; 6 - bottom cover; 7- output for H₂; 8 - outlet for O₂; 9 - electrolyte (KOH); 10-anode tire; 11-cathode bus; 12, 13 and 14 sealing gaskets

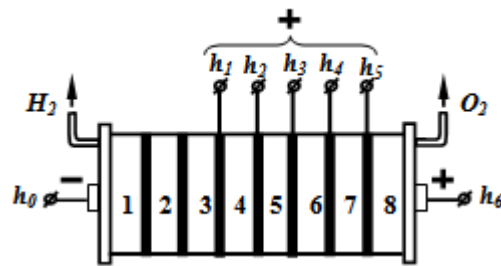


Figure 3. Conventional diagram of the E-2 type electrolyzer:

1-3 - constantly on cells; 4-8-switch-able cells; h_0 and h_6 are outputs taken from the outermost monopolar electrodes; $h_1 - h_5$ - outputs taken from intermediate bipolar electrodes; H_2 and O_2 - cell output for H_2 and O_2 , respectively

Figure 2 shows a structural diagram of an electrolytic cell, type E-1, and Figure 3 is a schematic diagram of an electrolytic cell of type E-2.

It has been experimentally established that when using an electrolyzer, type E-1, at the same values of current density on the electrodes, the value of the water decomposition voltage increases significantly. When two electrolyzers of the E-1 type are switched on in series, the electrolyzer operates in the immediate vicinity of the point of maximum power x CVC SFVCS. At the same time, the productivity of the plant in terms of H_2 also approximately doubles. However, the serial connection of more than two electrolyzers, in this case, is impractical, since, with a wide range of SRI, especially with SRI over 500 W/m^2 , the operating mode of the installation goes beyond the maximum power point, and its density on the electrodes of the electrolyzer become lower than the minimum value, as a result of which the electrolysis process stops. This is more clearly seen from the joint CVC characteristics of the SPVCS, taken, respectively, at the SRI of 900 W/m^2 and 300 W/m^2 (curves 1 and 2) and the electrolyzer taken when one and two electrolyzers of the E-1 type were switched on (curves 3 and 4, respectively), which are shown in Figure 4. As can be seen from Fig. 4, for SRI 900 W/m^2 when one cell is powered by SPVCS, the load current is $I_1 = 8.35 \text{ A}$, and when two cells are powered $I_1 = 6.8 \text{ A}$. Knowing these load current values from the following equation, it is possible to determine the amount of hydrogen produced for unit of time (in this case one minute):

$$V_{H_2} = 6,833 \cdot \dot{I}_n \cdot nt \text{ (ml/min)}$$

where, \dot{I}_n - is the load current flowing through the cell, A; n - the number of E-1 type electrolyzers connected in series with each other, pcs; t - the time of continuous operation of the electrolyzer.

Taking $t = 1$ hour, from the equation, we find the amount of hydrogen produced for both cases. So for the operation of one cell $V_{H_2} = 6.833 \cdot 8.35 = 57.06 \text{ ml/min}$, and for two cells $V_{H_2} = 6.833 \cdot 6.8 \cdot 2 = 92.93 \text{ ml/min}$. Thus, during the operation of one and two electrolyzers, within one hour, 3.42 l/h and 5.58 l/h of H_2 are obtained, respectively. From the CVC family of SPVCS for both SRI values, we find the voltage and current values at the points x of the maximum power of these CVCs. So, with an ISR of 900 W/m^2 - $U_{\max} = 15.7 \text{ V}$; $I_{\max} = 6.3 \text{ A}$, and with an SRI of 300 W/m^2 - $U_{\max} = 14.8 \text{ V}$; $I_{\max} = 1.85 \text{ A}$. And the maximum developed power of the SPVCS with an SRI of 900 W/m^2 and 300 W/m^2 is $P_{\max}^{900} = 15.7 \cdot 6.3 = 98.9 \text{ W}$ and $P_{\max}^{300} = 14.8 \cdot 1.85 = 27.4 \text{ W}$. It should be taken into account that during the operation of one cell, only $P_{\text{loses}}^{SPVCS} = 1.1 \text{ W}$ of the maximum power of the SPVCS is lost, and when one cell is turned on, $P_{\text{loses}}^{SPVCS} = 100 - 27.4 = 72.6 \text{ W}$ of power. These losses are mainly thermal losses. Now, for the operation of the SPVCS at an SRI of 900 W/m^2 , we determine the amount of electricity consumption for the production of a unit volume of gases ($1.0 \text{ m}^3 \text{ H}_2$ and $0.5 \text{ m}^3 \text{ O}_2$), which for the operation of one electrolyzer is $E = 100 / 3.42 = 29.2 \text{ kW} \cdot \text{h}$ and for the operation of two electrolyzers - $E = 100 / 5.58 = 17.9 \text{ kW} \cdot \text{h}$. Thus,

in the first case, in comparison with industrial electrolyzers, the production of 1 m³ of hydrogen consumes $E / E_{ind} = 29.2/4.5 = 6.49$ times, and in the second case, 4 times more energy. All this is due to the discrepancy between the sizes of the

anode and cathode of the E-1 electrolytic cell and the location between them of a partition, with a lower part provided with perforation, for the passage of anions and cations in the appropriate direction.

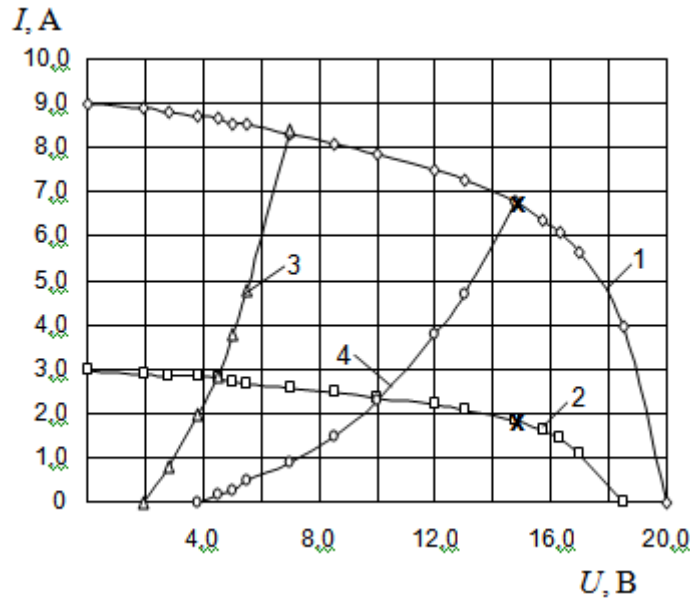


Figure 4. Families of joint current-voltage characteristics of the SPIT (curves 1 and 2) and electrolyzer type E-1 (curves 3 and 4):

curves 1 and 2 were taken, respectively, at ISR 900 W/m² and 300 W/m², and curves 3 and 4 were taken, respectively, when one and two electrolyzers of the E-1 type were operating one and two electrolyzers type E-1

IV. ANALYSIS OF THE POSSIBILITIES OF USING THE E-2 TYPE ELECTROLYZER IN A SOLAR ELECTROLYSIS PLANT FOR THE PRODUCTION OF HYDROGEN AND OXYGEN FROM WATER

The work begun in 1976 of the last century on the electrolysis of water, using SPVCS as a current source, to obtain high-purity hydrogen and oxygen, was continued in subsequent years. For this purpose, in 2019, at the Institute of Radiation Research of the MNOAR, an SPVCS

was built with a maximum power of 750 W, with a SRI of 1000 W/m², the real value of the output power of which, with an SRI of 900 W/m², is up to 500-600 W. A further task is the development and creation of an electrolysis plant for the production of hydrogen and oxygen from water, under a pressure of up to 0.6 MPa, fed from the above SPVCS. Taking into account a number of disadvantages of the E-1 type electrolyzer, in this case, a multi-cell fresh electrolyzer of the E-2 type is used as an electrolyzer, the design of which is shown in Figure 5.

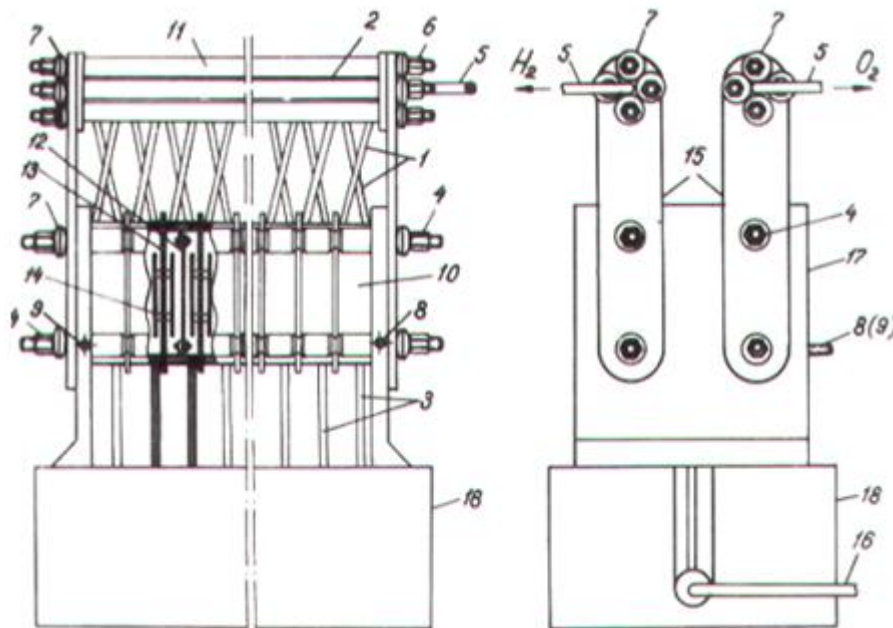


Figure 5. General design scheme of the E-2 type filter-press electrolyzer:

1- output for H_2 v O_2 ; 2- gas separation chambers; 3 - electrolyte lines; 4 - fixing bolts; 5- common collectors for the outlet of gases; 6- bolts for fastening gas separators; 7- disc washers; 8 - cathode bus; 9 - anode bus; 10 - electrolytic cell; 11- tubular guide insulators; 12- diaphragm; 13 - the main sheet of the bipolar electrode; 14 - additional sheet taken from the bipolar electrode; 15- sealing gaskets; 16 - feed channel for electro-lite; 17 - ext-rème monopolar electrode; 18- concrete base

To determine the optimal number of electrolytic cells of the electrolytic cell, ensuring its operation in the immediate vicinity of the maximum power points of the CVC of the SPVCS,

load CVCs were taken, both of the SPVCS, at ISR of 900, 600 and 300 W/m^2 , and of the electrolyzer, type E-2, for different quantities operating electrolytic cells, which are shown in Figure 6.

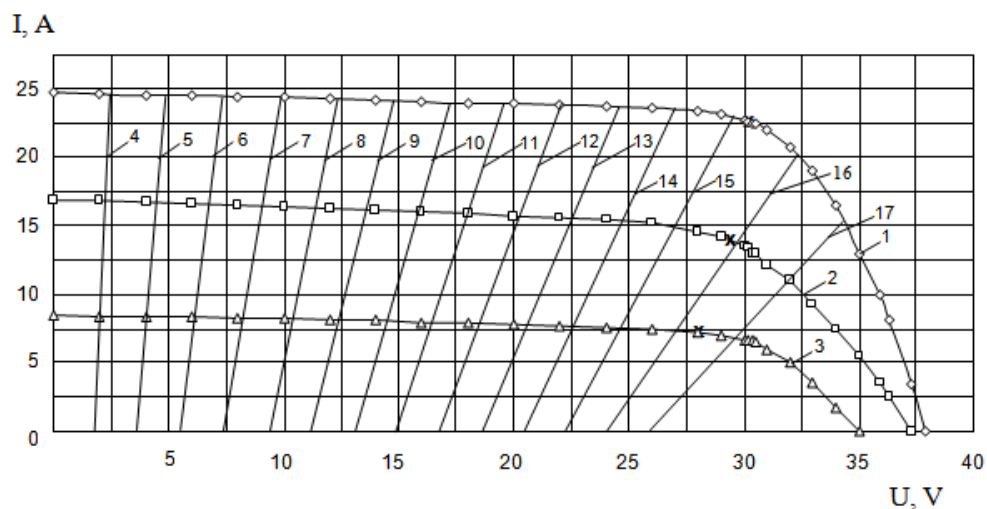


Figure 6. Load CVC, SFIT (curves 1-3), taken at different values of ISR and electroly-zer, type E-2 (curves 4-17) for different numbers of operating electrolytic cells: curves 1-3 refer, respectively, for the values of ISR 900, 600 and 300 W/m^2 , and curves 4-17, respectively, for the number of working cells of the electrolyzer $n = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13$ and 14 pieces

As can be seen from Figure 6, in comparison with the E-1 type electrolyzer, in this case, due to the improvement in the design of the electrolytic cells of the electrolyzer, the water decomposition voltage is significantly reduced and varies within $U_{CELL} = 1, 85-2.45$ V. This leads to a similar reduction in the consumption of electrical energy for the production of a unit volume of hydrogen. So, if under normal conditions the amount of electrical energy consumption for the production of a unit volume of hydrogen is taken $E = 4.5$ kW·h, then as a result of the electrolysis process powered by SPVCS, with a power of 750 W, in 1 hour you can get $0.75 \cdot 1000 / 4.5 = 155.6$ l H_2 and 77.8 l O_2 . Here the number 1000 means the conversion factor from m^3 to liter. As indicated in the previous section of this article, for the E-1 type electrolyzer, the maximum amount of hydrogen produced in 1 hour is $V_{H_2}^{E-1} = 5.58$ liters, although using the E-2 type electrolyzer, $V_{H_2}^{E-2} = 0.1 \cdot 1000 / 4.5 = 22.2$ liters of hydrogen. As you can see, the difference is $V_{H_2}^{E-2} / V_{H_2}^{E-1} = 22.2 / 5.58 = 3.98$ times. And this is a serious disadvantage of the electrolyzer, type E-1. Naturally, in real conditions of operation of the SPVCS, taking into account the temperature regime and other climatic conditions, pollution and partial shading of the surface of solar panels, inconsistencies in the CVC of individual modules and panels, etc., when using both types of electrolyzer, the actual amount of hydrogen produced, for unit of time are somewhat lower.

From the CVC of the SPVCS, we determine the following values of voltage, current and power: with an SRI of $900 \text{ W/m}^2 - U_{no-load} =$

37.9 V , $I_{sh.cir} = 24.75 \text{ A}$, $U_{max} = 30.5 \text{ V}$, $I_{max} = 22.5 \text{ A}$, $P_{max} = 30.5 \cdot 22.5 = 686.3 \text{ W}$, $\gamma = 0.73$; at $ISR \ 600 \text{ W/m}^2 - U_{no-load} = 37.0 \text{ V}$, $I_{sh.cir} = 16.9 \text{ A}$, $U_{max} = 29.0 \text{ V}$, $I_{max} = 14.6 \text{ A}$, $P_{max} = 29.0 \cdot 14.6 = 423.4 \text{ W}$; at $ISR \ 300 \text{ W/m}^2 - U_{no-load} = 35.0 \text{ V}$, $I_{sh.cir} = 8.45 \text{ A}$, $U_{max} = 28.0 \text{ V}$, $I_{max} = 7.2 \text{ A}$, $P_{max} = 28.0 \cdot 7.2 = 201.6 \text{ W}$ [17].

As can be seen from Fig. 6, depending on the decrease in the SRI value from 900 W/m^2 to 300 W/m^2 , the points of maximum power of the CVC of the SPVCS move non-linearly to the left side. At the same time, the optimal value of the load resistance of the SPVCS increases from $R_{opt}^{SPVCS} = 1.36 \text{ Ohm}$ (at the SRI of 900 W/m^2) to $R_{opt}^{SPVCS} = 3.89 \text{ Ohm}$ (at the SRI of 300 W/m^2). And with an SRI value of 600 W/m^2 , it is $R_{opt}^{SPVCS} = 1.99 \text{ ohms}$. And the resistance of the external circuit, i.e. the electrolyzer, at the same time, depending on the number of working electrolytic cells, varies from $R_{ext.cir.} = 0.099 \text{ Ohm}$ (with an SRI of 900 W/m^2 and the number of working cells $n = 1$), to $R_{ext.cir.} = 5.044 \text{ Ohm}$ (with an SRI of 300 W/m^2 and the number of working cells $n = 14$), i.e., in a very wide range.

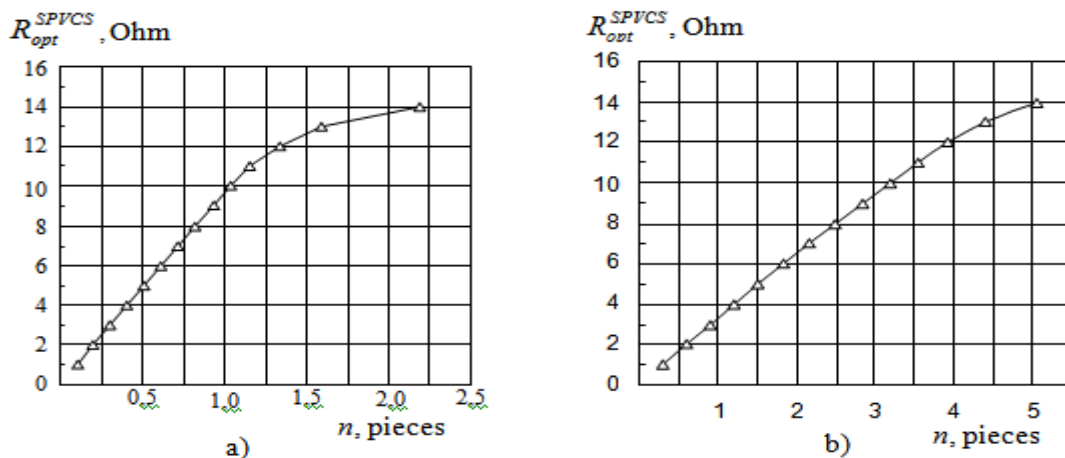


Figure 7. Graphical dependences of the optimal resistance of the external circuit, from the number of operating cells of the E-2 type electrolyzer: a) for an SRI value of 900 W/m^2 ; b) for SRI value 300 W/m^2

This is more clearly seen from Figure 7, where the graphical dependences of the resistance of the external circuit on the number of operating cells of the E-2 type electrolyzer are presented. When the SRI is below 300 W/m², both the optimal resistance of the SPVCS and the electrolyzer increases sharply, which leads to a similar decrease in the load current and density current on both electrodes and the termination of the electrolysis process with the release of target products - hydrogen and oxygen. This is explained by the fact that due to the low current density, gas bubbles formed on the surfaces of the corresponding electrodes cannot overcome the resistance of the electrolyte to go out of the anode and cathode spaces of the cell. Therefore, inside the cell, the process of filling the electrolyte with small bubbles of both gases and a significant increase in the resistance of the electrolyte, which prevents the further occurrence of the electrolysis process, is formed. Therefore, when the SRI is below 300 W/m², it is necessary to reduce the number of operating cells of the electrolytic cell, corresponding to the decrease in the SRI value. For this purpose, the electrolyzer E-2 is equipped with additional taps taken from separate bipolar electrodes from the side of the anode or cathode (see Fig. 3).

It can be seen from Figure 6 that with an SRI of 900 W/m², the optimal number of operating cells is 12 pcs, and in the SRI range of 300-600 W/m² it is 13 pcs. Another, no less important point, when designing an electrolysis plant with an E-2 type electrolyser, is to determine both the active surfaces of both electrodes (anode and cathode), which have the same dimensions when performed with a round configuration, and the total outer diameters of the electrolytic cells and electrodes, also having the same dimensions. So, according to Faraday's law, the maximum value of the current density in the electrodes of the electrolyzer, without overheating, should be no more than 0.084 A/sm² (840 A/m²). Based on this, and taking into account that in our case the maximum value of the load current, with the number of operating cells of the electrolyzer $n = 12$ and RPS 900 W/m², is $I_{l.cur.}^{el} = 23$ A, we find the areas of the active part of the electrodes which are: $S_{El}^{act.sur.} = 23/0.084 = 273.8$ sm². Then the diameters of the active part of the electrodes can be determined as follows:

$$D_{El}^{act} = \sqrt{4S_{El}^{act.sur} / \pi} = 18.68 + 2 \cdot 1.25 \approx 21.2 \text{ sm.}$$

Then the diameters of the active part of the electrodes can be determined as follows:

$$D_{El}^{act} = \sqrt{4S_{El}^{act.sur} / \pi} = 4 \cdot 273,8 / 3,14 = 18.68 \text{ sm.}$$

Taking the width of the intermediate sealing gaskets $\delta = 1.25$ cm (for a cell wall thickness of ~ 0.8 cm, this is quite normal), we determine the outer diameters of the electrolytic cells, also electrodes, with the same dimensions:

$$D_{El}^{out} = D_{Cell}^{out} = D_{El}^{act.sur} + 2 \cdot \delta = 18.68 + 2 \cdot 1.25 \approx 21, 2 \text{ sm.}$$

This is a completely normal diameter for an experimental electrolyzer, type E-2. As for the width of the cells, in this case, the maximum width can be taken $\delta_{Cell} = 2.5$ cm (for the optimal value, we take 2.0 cm). It should be taken into account that the smaller the width of the electrolytic cells, the lower the electrolyte resistance and the path length of charged particles in the directions of the corresponding electrodes, and the lower the voltage of water decomposition and the energy consumption to obtain a unit volume of hydrogen and oxygen. However, it is also not possible to reduce the cell width too much, since in this case design difficulties appear, in particular, when connecting the communication lines of hydrogen and oxygen.

The families of load CVC characteristics of the SPVCS, shown in Figure 6, were taken without taking into account additional losses. And in real conditions, the point of maximum power of the CVC of the SPVCS moves more sharply to the left side, depending on the decrease in the SRI value. From this it follows that, during the day, depending on the change in the value of the SRI, the number of operating cells of the electrolyzer should be automatically changed. All these processes are discussed in detail in [6,10,16]. For this purpose, automatic switching devices (ASD) have been developed in two modifications, which were conditionally called ASD -1 and ASD -2. At the same time, ASD -2 is the most advanced version of ASD -1, for the use of which the electrolyzer must be made as separate groups of cells connected to each other in series through blocking power thrusters. Another significant difference between ASD -1 and ASD -2 is that ASD -1 uses a separate light sensor and a separate relay to switch each cell. Thus, to switch only 5 intermediate and one extreme cells, 6 photo sensors and the same number of control relays are used. In ASD -2, to switch 15 cells in the form of various options, it is enough to use only 3 intermediate and 3 main relays. And the light sensors, at the same time, are made in the form of photo sensors tuned to different SRI values, by means of intermediate relays connected to the automatic control unit,

which consists of contact plates, a contactor and a micro motor for advancing the contactor along the contact plates in both directions. Moreover, in the first group there is only one cell, and in each subsequent group - twice as much as the previous group.

However, automatic change in the number of working cells of the electrolyzer is only beneficial for optimizing more powerful solar electrolysis plants, since the operation of the automation unit also requires a certain amount of energy. We have considered another option: a simultaneous change, both in the number of working cells of the electrolytic cell, and in the ratio of the number of serially and parallel-connected SPVCS solar panels. This option makes it possible to more accurately match the electrolytic cell with the SPVCS at each time during daylight hours. And when the sky is cloudy, it is not advisable to use both the first and the second of the above optimization methods. Since this leads to a frequent change in the number of working cells of the electrolyzer, in the direction of decreasing and increasing, which is unacceptable. Optimization with the use of ASD -1 and ASD -2, as well as a simultaneous change in the number of operating cells of the electrolyzer and SPVCS solar panels connected in series and in parallel, is beneficial only in clear and cloudy weather conditions. And in weather conditions with variable cloudiness, it is better to use electrochemical batteries operating in a buffer mode together with SPVCS.

V. CONCLUSION

From an analysis of the results obtained from experiments carried out on a laboratory electrolysis installation powered by a 100 W SFIT, it was found that the use of a rechargeable battery has the following main advantages: 1) the installation circuit is simplified; 2) makes it possible to use a conventional electrolyzer of type E-2, without additional taps and with an established optimal number of electrolyzers; 3) does not require the use of additional devices to automatically change the option of matching the electrolyser with the SPVC; 4) the current density in both electrodes changes in very small intervals, which makes it easier to control the electrolysis process over a wide range of ISO changes; 5) it becomes possible to ensure the safe operation of the system as a whole; 6) makes it possible to work at night [6].

However, the use of rechargeable batteries also has some disadvantages, which are as follows: 1) service life is short; 2) cannot be used in powerful electrolysis plants; 3) have large

dimensions and weight; 4) require constant maintenance of the state of work; 5) for a group of batteries to work together (this is usually the case), the energy characteristics of all of them must be the same, which is not always possible; 6) a separate room with good ventilation is required to place the battery; 7) to control operating modes and automatically regulate charge and discharge processes, an appropriate controller should be used.

In conclusion, it should be noted that in order to create the most powerful and stable electrolysis installations, it is advisable to simultaneously use wind energy sources of appropriate power together with SEPVA. Thanks to this, it is possible to achieve continuous operation of the electrolyzer, including at night.

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