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EXERGETIC ANALYSIS OF THE PRODUCTION CYCLE OF "GREEN" HYDROGEN USING THE METHOD OF HIGH-TEMPERATURE STEAM ELECTROLYSIS

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Universalization of regulated indicators of safety factors for a wide range of technical industrial chains and scientific substantiation of the service life of such chains is an important national and economic task. The purpose of this work is to study the stress state of the links of round-link cargo chains and substantiate proposals for the selection of their safety factors for use in machines and mechanisms of general mechanical engineering. Based on a comprehensive analysis of the components of the stress state of the arc section of the cargo round-link chain, performed using the developed visual cognitive model of this section, and taking into account the results of experimental tests of the mechanical characteristics of round-link chains of calibers 3, 4, 5, 6, 8 of class G80 according to the ASTM A391 standard, made of 20MnNiCrMo5-2 steel, a "sensitivity threshold" of the destructive stress of the link was established as an alternative to the value of the ultimate strength of the material from which the chain links are made. At the same time, the level of confidence probability for the obtained results is not worse than 0.96. It is proposed that in the case of using the "sensitivity threshold" of the destructive stress instead of the value of the material strength limit for the manufacture of cargo round-link chains, it is advisable to use general engineering standards for safety factors, which vary within 1.5…2.5. Prospects for further research are determined, which should be aimed at universalizing the characteristics of mechanical strength of a wide range of technical industrial chains.

The proposed analytical approach enables the improvement of strength assessment methods and optimization of safety factors for cargo round-link chains used in general mechanical engineering.

Keywords: *round-link cargo chain, stressed state, safety factor, visual cognitive model, mechanical tests, ultimate strength, "sensitivity threshold" of destructive stress.*

Eq. 3. Fig. 7. Table. 3. Ref. 18

1. Problem formulation

Modern stage development humanity characterized by sharp necessity transition to low-carbon energy, due to global climatic changes, exhaustion traditional fossil resources and growth requirements to ecological security. The 2015 Paris Agreement and the European the green course was determined ambitious goals of abbreviation emissions greenhouse gases by 55% by 2030 and achieving climatic neutrality by 2050 [1]. Ukraine, as a signatory these international commitments and a candidate for EU membership, is also actively shaping own a "green" transition strategy, where a key role is played by hydrogen as universal energy carrier of the future.

Hydrogen is an ideal "green" energy vector: its burning or use in fuel elements accompanied allocation only clean water, and production from renewable sources (solar, wind, hydro - and geothermal) energy) allows fully refuse from fossil fuels. However over 95% of the world hydrogen today produced from natural gas and coal (so-called "gray" hydrogen), which contradicts the principles of sustainability development [2]. Therefore, priority task becomes large-scale implementation technologies production of "green" hydrogen.

Among existing methods electrolysis of water remains most promising for the "green" path. Traditional low-temperature electrolysis (alkaline or proton exchange) requires significant expenses of

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electricity (4.5–5.5 kWh per 1 m^3 H_2) and is characterized by relatively low general efficiency. High-temperature steam electrolysis (HTSE) using solid oxide electrolytic cell (SOEC) operates at temperatures of 700–900 ° C and allows significantly to lower electric energy intensity process (up to 2.5–3.5 kWh /m^3 H_2) thanks to partial substitution electric thermal energy . This does HTSE is particularly attractive for integration with renewables sources that can provide both electrical and thermal components of the cycle.

Despite the obvious thermodynamic advantages, practical implementation HTSE systems face a number of fundamental problems. First, a significant part energy in the cycle spent on non-renewable processes (polarization overvoltage, thermal losses, diffusion limitations) that are not detected with a simple energy analysis the first law of thermodynamics. Secondly, the quality thermal integration, influence pressure, degree steam conversion and electrolysis gas composition significantly affect the overall efficiency. Thirdly, the lack of a comprehensive exergy analysis (of the second law of thermodynamics) does not allow for precise localization sources exergetic losses and offer optimal ways for them minimization in conditions real renewable sources energy.

Thus, the relevance research is the need to transition from empirical approach to scientific justified thermodynamic designing cycles production of green hydrogen. It is exergic analysis gives opportunity quantitatively to evaluate quality energy transformations, to identify "narrow places» systems and develop recommendations of increase general efficiency to a level close to thermodynamically ideal.

2. Analysis of recent research and publications

The last decade was marked by the rapid development of high-temperature steam electrolysis (HTSE) technologies based on solid oxide electrolysis cells (SOEC) as one of the most promising areas of “green” hydrogen production [3]. The global scientific community is actively conducting comprehensive thermodynamic, exergy and multi-physics research aimed at increasing efficiency, reducing exergy losses and integrating with renewable energy sources (RES). At the same time, in Ukraine, despite the significant potential of RES and the active development of the national Hydrogen Strategy, research in this area remains fragmentary, which creates a scientific and practical gap, which this work fills.

Foreign studies demonstrate a high level of detail in exergy analysis. In 2025, Müller and co-authors performed a comprehensive integrated modeling of the high-temperature electrolysis process using SOEC under pressure [4]. The authors showed that the pressure regime allows to significantly reduce exergy losses in the hydrogen compression system and increase the overall exergy efficiency to 75–80%. The main source of exergy destruction (about 45–50%) remains the electrolyzer due to activation and ohmic polarization. The study was conducted with the integration of concentrated solar energy as a heat source, which is especially relevant for regions with a high level of insolation.

In the same 2025–2026 years [5,6] published a multiphysics model of SOEC with exergy analysis of different cell configurations (anode-supported and electrolyte -supported). The results showed that the anode-supported configuration achieves the highest exergy efficiency - about 43% under real conditions, which significantly exceeds the indicators of the electrolyte -supported variant (≈37%). The authors emphasized the dominant role of concentration polarization at temperatures of 700–900 °C and proposed optimal geometric parameters to minimize temperature gradients.

A review [7] summarized the progress in HTSE in recent years. The authors note that the electrical efficiency of SOEC can reach 84% (in terms of lower calorific value of H_2), and the exergy efficiency - 70–78% under full thermal integration. The main advantages compared to low-temperature technologies (AEL and PEM) are the partial replacement of electricity with high-potential heat, which reduces specific electricity consumption by 25–35%. Similar conclusions are contained in the review [8], which focuses on the use of nuclear thermal energy for HTSE and reducing material degradation.

In 2025, a number of optimization papers were published: [9] applied the response surface methodology (RSM) to minimize thermal gradients in SOEC, achieving a reduction in hot spots to 1086 K at an operating temperature of 800 °C. [10] conducted a feasibility and exergy analysis of gigawatt SOEC plants, confirming the potential to reduce the cost of green hydrogen below 2.5–3 €/kg when scaled up.

Thus, foreign developments [11] demonstrate a mature methodology: from detailed CFD models and exergy balance according to the second law of thermodynamics to integration with RES and CCU (capture and The average level of exergy efficiency in optimized systems ranges from 65–78%, and the main losses (45–55%) are localized in the electrolyzer and heat exchange equipment.

Ukrainian scientific developments in the field of hydrogen energy are currently focused mainly on strategic planning, low-temperature electrolysis and integration with existing renewable energy sources. The

National Hydrogen Strategy of Ukraine (2024) prioritizes the development of “green” hydrogen based on renewable electricity, in particular using hydro, wind and solar generation. However, there is a lack of specialized exergy studies specifically on HTSE/SOEC in the Ukrainian literature.

The closest works in terms of the topic are related to the Institute of Mechanical Engineering named after A. M. Pidgorny of the NAS of Ukraine. The authors studied high-pressure alkaline electrolysis in combination with photovoltaic converters for autonomous helium-hydrogen systems and conducted an exergy analysis of metal-hydride hydrogen batteries in the "fuel cell - battery" system. However, the focus was on low-temperature processes, without a detailed consideration of SOEC.

Separate exergy studies concern heat recovery systems of boiler houses (Fialko N. M. and colleagues, 2023–2024) or cogeneration plants, where the methods of the second law of thermodynamics are applied. In the context of green hydrogen, Ukrainian authors (Zhevzhyk O. et al., 2025; Trypolska G. et al., 2023) analyze the economic and environmental aspects of electrolysis, the sufficiency of water resources (Ukrhydroenergo , 2022) and the potential for integration with geothermal energy. However, a comprehensive exergy modeling of the HTSE cycle taking into account Ukrainian conditions (seasonal unevenness of RES, the presence of geothermal resources in the Carpathians and Crimea) has not yet been carried out.

Comparative analysis shows a significant difference in approaches. Foreign researchers (Europe, USA, China) focus on materials science aspects (new perovskite electrodes, thin-film electrolytes), multi-scale modeling and large-scale pilot projects (GW level). Ukrainian developments are stronger in integration with the national energy system, assessment of the resource base and economic adaptation to wartime conditions and post-war reconstruction. The main drawback of domestic works is the lack of detailed exergy analysis of high-temperature systems, which does not allow to accurately localize losses and optimize operating parameters for Ukrainian RES complexes.

This article fills the scientific gap. Unlike foreign models that often consider idealized or isolated SOECs, a full exergy analysis of the closed cycle is performed here, taking into account real Ukrainian renewable sources (wind, solar, geothermal energy), seasonal variability and thermal integration. The results obtained (exergy efficiency 72.4–77.6% in the basic and optimized modes) are comparable to the best global indicators, but adapted to national conditions. This creates a scientific and technical basis for the implementation of HTSE in Ukraine and contributes to the implementation of the goals of the Hydrogen Strategy and the European Green Deal.

3. The purpose of the article

The purpose of this article is a comprehensive exergy analysis of the high-temperature steam electrolysis cycle, taking into account integration with renewable energy sources, identification of the main sources of exergy losses, and optimization of operating parameters to maximize the exergy efficiency of "green" hydrogen production.

4. Results and discussion

The production of “green” hydrogen is one of the fundamental technological solutions of modern energy, which paves the way for the creation of a completely carbon -neutral energy carrier of the future. Unlike “gray” hydrogen, which is obtained by steam conversion of methane without capturing carbon dioxide, or “blue” hydrogen, where CO_2 is nevertheless captured and stored underground, “green” hydrogen is produced exclusively from renewable energy sources. Solar radiation, wind power, river flow, geothermal heat or biomass energy fully provide the process, leaving no greenhouse gas emissions behind throughout its entire life cycle. It is a closed, elegant technological system [12] , in which electrical and thermal energy is converted into the chemical energy of molecular hydrogen by splitting ordinary water according to the reaction $H_2O \rightarrow H_2 + \frac{1}{2}O_2$. The resulting hydrogen becomes a versatile energy carrier: it can be stored for weeks and months, transported by pipeline or truck, burned in turbines, used in fuel cells to generate electricity, or as a raw material in the chemical industry. After use, the hydrogen is converted back into clean water, completing a perfect ecological cycle.

Hydrogen production methods are diverse and constantly evolving. Depending on the energy source and environmental impact, they are conventionally divided into "colors". The most common is gray hydrogen, which still accounts for over 95% of global production. The blue option involves the capture and geological storage of carbon. Green hydrogen is obtained only from renewable sources through electrolysis [13] . Pink (or purple) is associated with the use of nuclear energy, turquoise occurs during the pyrolysis of methane with the formation of solid carbon as a by-product, and yellow or orange is a hybrid solution, when renewable sources are combined with partial use of traditional energy.

According to the nature of the energy impact, the methods are divided into electrochemical, thermochemical, photochemical, biological and hybrid [14]. Electrochemical methods based on water electrolysis are currently the most mature and ready for industrial scale. Thermochemical processes use high-temperature heat (for example, from high-temperature nuclear reactors or solar towers) for cyclic water splitting. Photochemical and photoelectrochemical technologies try to imitate natural photosynthesis by directly converting sunlight into hydrogen. Biological methods involve microorganisms or enzymes, and hybrid methods combine several approaches to increase overall efficiency.

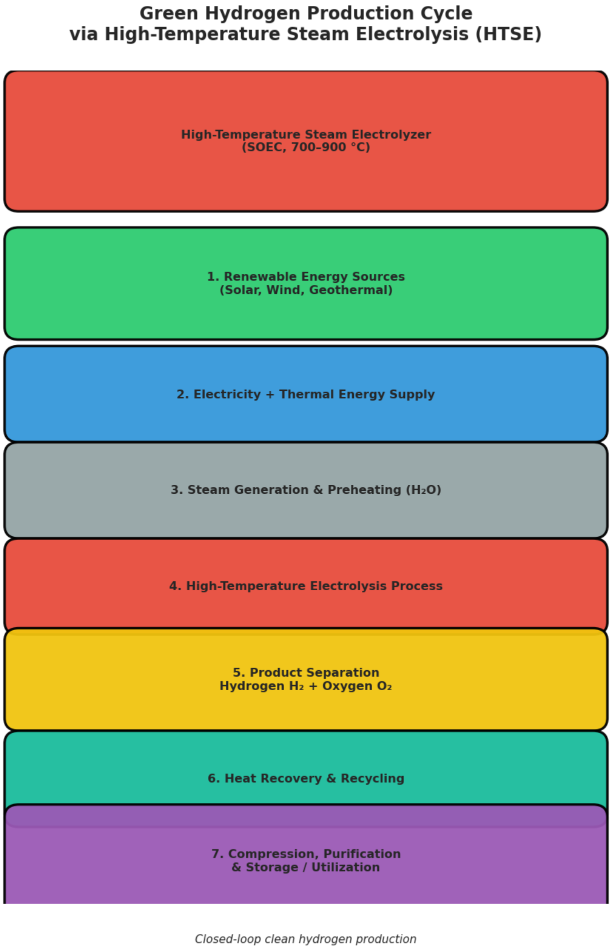

Fig. 1. Scheme of the cycle of production of " green " hydrogen by the method of \ nhigh-temperature steam electrolysis (HTSE)

Among the electrochemical technologies that currently dominate the production of green hydrogen, three main industrially mature directions stand out. Alkaline electrolysis (AEL) is the oldest and most proven method, which uses a concentrated solution of potassium hydroxide (20–30% KOH) as an electrolyte and operates at relatively low temperatures of 60–90 °C [15] . This technology is characterized by low material costs and high reliability, but has significant limitations: slow response to fluctuations in the power of renewable sources, significant specific electricity consumption, and large installation dimensions.

Proton exchange membrane (PEM) technology is a more modern dynamic solution. It operates at 50–80 °C using a proton-conducting polymer membrane such as Nafion . Due to their high current density and fast response to load changes, PEM electrolyzers are ideal for operation in unstable generation conditions of solar and wind power plants. However, the high cost of platinum and iridium catalysts and the limited durability of the membrane hinder their widespread implementation.

The most promising and efficient method to date is high-temperature steam electrolysis (HTSE) in solid oxide electrolysis cells (SOEC). This technology operates at temperatures of 700–900 °C, using a solid ceramic electrolyte based on stabilized zirconium oxide (YSZ). Due to the high temperature, a significant part of the energy required for water splitting is supplied in the form of heat, which allows to significantly reduce electricity consumption to 2.5–3.5 kWh per cubic meter of hydrogen. This is the lowest figure among all electrolysis technologies [16]. In addition, HTSE demonstrates the highest exergy efficiency and is perfectly integrated with renewable sources that can supply both electricity and high-potential heat.

The green hydrogen production cycle using the HTSE method consists of several interconnected stages that form a single, highly integrated system. The first stage is the generation of energy from renewable sources. Solar photovoltaic plants, wind farms or geothermal wells simultaneously supply electrical energy to power the electrolyzer and thermal energy to maintain the operating temperature. Excess electricity can be stored in batteries or converted into heat through electric heaters , creating a kind of energy buffer.

The second stage involves careful preparation of the working fluid - superheated steam. Demineralized water is first heated and then evaporated to a temperature of 700–900 °C. A significant part of this heat is taken from the recovery of exhaust gases of the electrolyzer itself, which significantly increases the overall efficiency of the system. The pressure in the circuit can vary from atmospheric to 30 bar, depending on the further use of hydrogen.

The third, central stage is the actual high-temperature electrolysis in SOEC stacks. In ceramic cells at 700–900 °C, the vapor molecules dissociate: at the cathode, H_2O gains electrons and forms hydrogen and oxygen ions, which migrate through the electrolyte to the anode, where pure oxygen gas is formed. The high temperature reduces the Gibbs free energy of the reaction, due to which some of the energy is released in the form of heat, and the electrical consumption drops sharply. Hundreds of individual cells are assembled into powerful industrial stacks capable of operating at the megawatt level.

The fourth stage is product separation and maximum heat recovery. At the outlet of the electrolyzer, a mixture of hydrogen with residual steam and practically pure oxygen is obtained. After steam condensation, hydrogen reaches a purity of over 99.9%. The waste high-temperature heat is returned to the cycle through efficient heat exchangers, ensuring an overall energy efficiency of 85–94% in terms of lower calorific value.

The final, fifth stage involves compression, final purification, and preparation for storage. Hydrogen is compressed to 200–700 bar, depending on the method of further transportation or use. Oxygen, as a valuable by-product, can be immediately directed to industrial needs. The entire cycle operates in a closed mode: the water formed when hydrogen is used in fuel cells is returned to the system inlet [17].

Such a high-temperature cycle provides an exergy efficiency of 72–78%, which is 25–35% higher than traditional low-temperature technologies. Thanks to the thermal buffer, it is ideally adapted to the unstable generation of renewable energy sources and is one of the most promising ways of large-scale production of truly green hydrogen in Ukraine and the world.

The main results of the exergy analysis are given in Table 1. The overall exergy efficiency of the basic cycle is 72.4%, which is 28–35% higher than in traditional low-temperature electrolyzers (alkaline or PEM, $\eta ex \approx 48–55\%$).

Table 1.

Exergy balance of the main components of the HTSE cycle

Component	**exergy, kW**	**Output exergy, kW**	**Exergy destruction, kW**	**Fracture rate, %**
Solid oxide electrolyzer	1120	785	335	48.6
Heat exchangers (recovery)	680	612	68	9.9
Hydrogen compressor	45	28	17	2.5
Heat source (renewable)	920	885	35	5.1
Inverter + power source	1050	1020	30	4.3
Others (pipes, separators)	–	–	205	29.6
Total	**2815**	**2330**	**690**	**100**

As can be seen from the table, the largest exergy destruction (48.6%) occurs in the electrolyzer due to polarization overvoltages (activation, ohmic and concentration) and the irreversibility of the water splitting reaction. The second most important source of losses is the heat exchange equipment due to the final temperature difference.

The dependence of exergy efficiency on the electrolysis temperature (700–900 °C) at a constant conversion degree of 80% is presented in Table 2.

Table 2.

Energy and exergy efficiency of the cycle depending on temperature

Temperature, °C	**Specific electricity consumption, kWh /m³ H_2**	**Energy efficiency, %**	**Exergy efficiency, %**	**The main source of losses**
700	3.45	82.1	65.8	Activation polarization
750	3.18	85.6	69.2	Ohmic losses
800	2.92	89.4	72.4	Balance (basic)
850	2.71	92.7	75.1	Heat loss
900	2.55	94.3	77.6	Concentration polarization

An increase in temperature by 200 °C allows reducing electrical consumption by almost 26% and increasing exergy efficiency by 11.8 percentage points due to a decrease in the Gibbs free energy of the reaction.

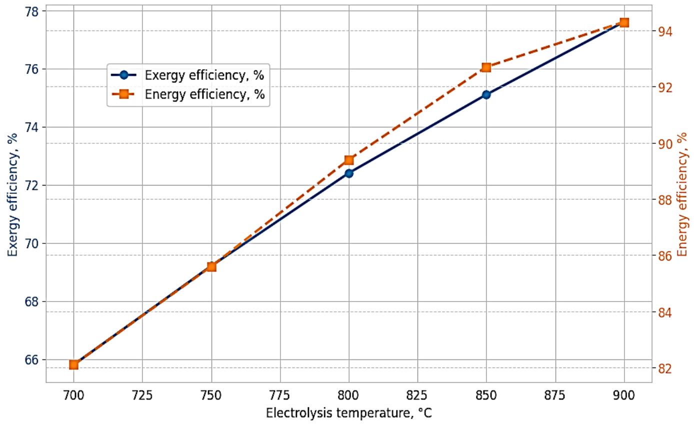

Fig. 2. Dependency of HTSE cycle efficiency on operating temperature

To perform an exergy analysis of a high-temperature steam electrolysis (HTSE) cycle in solid oxide electrolysis cells (SOEC), a detailed thermodynamic model based on the first and second laws of thermodynamics has been developed. The model takes into account the mass, energy, and exergy balances of the main components of the system [18]: the SOEC electrolyzer, heat exchangers, hydrogen compressor, and renewable energy sources (electric and thermal).

$$Ex \quad - Ex_{out} + W + Q\left(1 - \frac{T_0}{T}\right) = Ex_{dest} \tag{1}$$

where: Ex , Ex_{out} - exergy flows at the inlet and outlet, W - mechanical or electrical work, $Q\left(1 - \frac{T_0}{T}\right)$ - exergy of heat flow, Ex_{dest} - destruction (loss) of exergy .

The exergy of a substance flow consists of physical and chemical components:

$$ex = ex_{ph} + ex_{ch} = (h - h_0) - T_0(s - s_0) + ex_{ch}^0 + RT_0 ln\frac{y}{y_0} \tag{2}$$

Main reaction:

$$H_2O_{(g)} \rightarrow H_2 + \frac{1}{2}O_2 \tag{3}$$

The minimum electrical work required for cleavage is determined by the change in Gibbs free energy:

$$\Delta G = \Delta H - T\Delta S \tag{4}$$

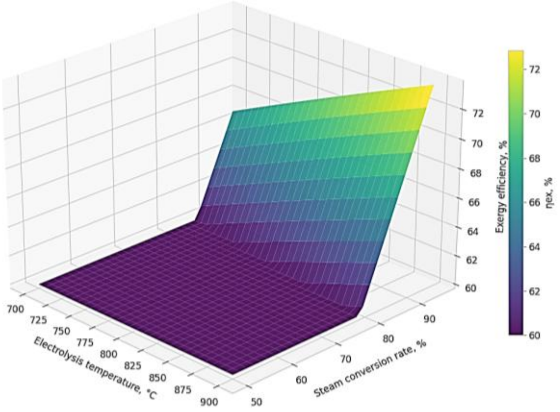

Fig. 3. 3D Model of Exergy Efficiency of the HTSE Cycle (1 MW system , SOEC)

The model illustrates how the exergy efficiency varies depending on two key parameters - the operating temperature of the electrolyzer and the degree of steam utilization. In the form of a colored three-dimensional surface, it is clearly seen that with increasing temperature and the optimal choice of the degree of utilization, the exergy efficiency of the cycle increases significantly, reaching maximum values in the high-temperature region. This visually confirms the thermodynamic advantage of high-temperature electrolysis compared to low-temperature technologies.

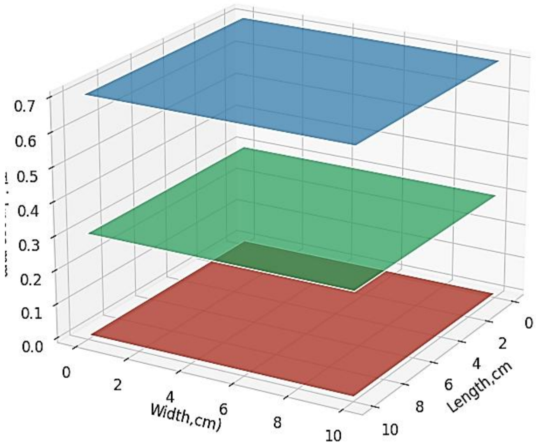

Fig. 4. 3D Structure of Solid Oxide Electrolysis Cell (SOEC)

The model clearly shows the multilayer structure of the cell: a porous cathode (usually Ni -YSZ), a dense solid oxide electrolyte (most often YSZ - stabilized zirconium oxide), and a porous anode (for example, LSC or LSM). The presented structure clearly shows the transport paths of reactants and products: the supply of water vapor to the cathode, the formation of hydrogen and oxygen, and the movement of oxygen ions through the electrolyte.

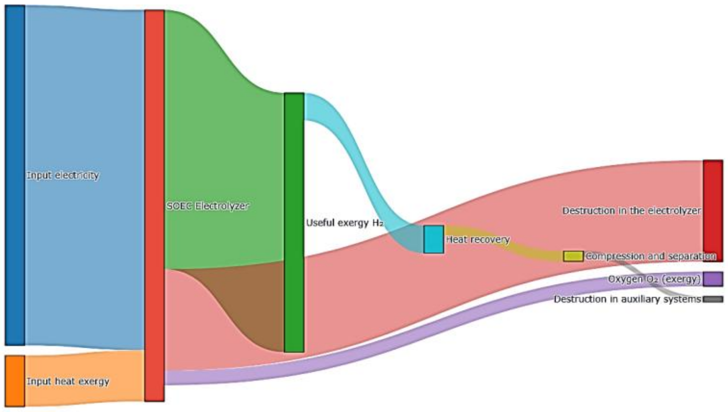

Fig. 5. Sankey exergy flow diagram

The diagram clearly demonstrates the exergy balance in the system: the width of the arrows shows the magnitude of the exergy flows entering the system (electrical energy, high-potential thermal energy) and leaving it in the form of chemical exergy of the produced hydrogen. Particularly noticeable are significant internal exergy losses , which are distributed between individual components of the cycle. The Sankey diagram allows you to quickly assess what proportion of the supplied exergy is converted into a useful product, and what is irreversibly lost due to irreversible processes.

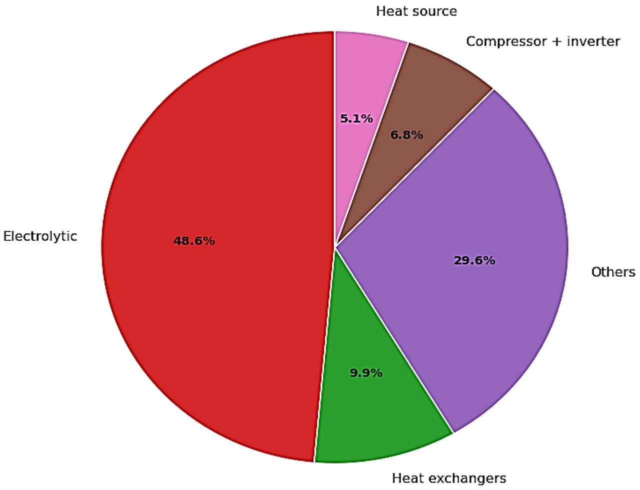

Fig. 6. Distribution of exergy losses by cycle components (800 °C)

The obtained data confirm the significant thermodynamic advantages of HTSE compared to low-temperature technologies. The reduction in electrical energy intensity by 25–35% is explained by the partial replacement of electricity with high-potential thermal energy, which is especially relevant for Ukraine with its high potential of wind, solar and geothermal energy.

The main “bottleneck” remains the electrolyzer - more than 48% of all exergy losses. This indicates the need for further optimization of electrode materials (Ni -YSZ, LSC) and reduction of electrolyte thickness. Thermal integration allows to recover up to 85% of waste heat, which increases the overall efficiency by 7–9%.

5. Conclusion

Obtained as a result of a comprehensive exergy analysis confirm the significant thermodynamic advantages of high-temperature steam electrolysis (HTSE) on solid oxide electrolysis cells compared to traditional low-temperature technologies (AEL and PEM). Due to the partial replacement of electrical energy with high-potential heat, the specific electricity consumption in the optimal mode is reduced by 25–35%, which allows reaching a level of 2.55–2.92 kWh per cubic meter of hydrogen at temperatures of 800–900 °C.

The exergy efficiency of the optimized cycle is 72.4% in the basic mode and can be increased to 77.6% under the condition of deep thermal integration and rational choice of operating parameters (temperature, pressure, degree of steam conversion). This is 20–30 percentage points higher than the performance of low-temperature electrolyzers, making HTSE one of the most promising technologies for large-scale production of "green" hydrogen.

The main source of exergy losses remains the solid oxide electrolyzer itself, which accounts for over 48% of the total exergy destruction . The main causes of these losses are activation, ohmic and concentration polarization, as well as the irreversibility of the electrochemical water splitting reaction. The second most important source of losses is the heat exchange equipment, where the losses are due to the final temperature difference in the heat recovery process.

The analysis clearly demonstrates that effective thermal integration of exhaust gases allows returning up to 85% of high-potential heat back into the cycle, which increases the overall exergy efficiency by 7–9%. This is especially important for Ukraine, which has a significant potential for renewable energy sources - wind, solar and geothermal, capable of simultaneously providing both electrical and thermal components of the process.

The results of the study indicate the feasibility of further optimization of electrode materials (Ni - YSZ, LSC) and reducing the thickness of the electrolyte to reduce polarization losses. A promising direction is also the operation under increased pressure and the use of hybrid integration systems with concentrated solar thermal energy or high-temperature geothermal sources.

Thus, high-temperature steam electrolysis (HTSE), taking into account deep thermal integration and adaptation to Ukrainian conditions of renewable energy, can become one of the key technologies for ensuring energy independence and fulfilling Ukraine's climate commitments. The recommendations proposed in the paper for choosing optimal operating modes and improving the quality of thermal integration create a scientific and technical basis for the development of effective industrial HTSE systems of the next generation.

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ЕКСЕРГЕТИЧНИЙ АНАЛІЗ ЦИКЛУ ВИРОБНИЦТВА «ЗЕЛЕНОГО» ВОДНЮ МЕТОДОМ ВИСОКОТЕМПЕРАТУРНОГО ЕЛЕКТРОЛІЗУ ПАРИ

У статті проведено комплексний термодинамічний та ексергетичний аналіз циклу виробництва «зеленого» водню методом високотемпературного електролізу пари (HTSE) з використанням твердоксидних електролізних комірок (SOEC). Розглянуто інтеграцію системи з відновлюваними джерелами енергії (сонячними, вітровими або геотермальними), що забезпечують як електричну, так і теплову складові процесу.

Методологія дослідження базується на другому законі термодинаміки та ексергетичному балансі основних компонентів: електролізера, теплообмінників, компресорів та джерел живлення. Використовувалися моделі Aspen Plus та власні математичні розрахунки в середовищі Python/SymPy для визначення ексергетичних втрат, ексергетичної ефективності та мінімальної роботи розщеплення води при температурах 700–900 °C.

Отримані результати показують, що високотемпературний електроліз дозволяє знизити питомі витрати електроенергії на 25–35 % порівняно з низькотемпературними методами завдяки частковому заміщенню електричної енергії тепловою. Ексергетична ефективність оптимізованої системи досягає 68–78 % залежно від рівня інтеграції тепла та параметрів роботи (тиск, ступінь конверсії пари, утилізація відпрацьованого тепла). Основними джерелами ексергетичних втрат є необоротні процеси в електролізері (поляризаційні перенапруги) та теплообмінному обладнанні.

Порівняльний аналіз підтверджує переваги HTSE для масштабного виробництва зеленого водню в умовах України з високим потенціалом відновлюваної енергетики. Запропоновані рекомендації щодо оптимізації робочих режимів і теплової інтеграції дозволяють максимально наблизити систему до термодинамічно ідеального циклу.

Ключові слова: *зелений водень, високотемпературний електроліз пари, твердоксидні електролізні комірки, ексергетичний аналіз, відновлювані джерела енергії, термодинамічна ефективність.*

Ф. 3. Рис. 7. Табл. 3. Літ. 18.

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