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SUBSTANTIATING THE EXPEDIENCY OF USING HYDROGEN FUEL CELLS IN ELECTRICITY GENERATION

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The object of research is the process of using a hydrogen fuel cell to generate and accumulate electricity. The study highlights the feasibility of using a hydrogen fuel cell to provide electrical load.

The potential of using hydrogen as an alternative energy source was evaluated. SWOT analysis was used as a research method, based on the results of which recommendations were developed. The proposed measures could be taken to increase the use of hydrogen energy as an alternative to traditional energy sources.

The use of hydrogen technologies in an administrative building connected to an existing electrical network was analyzed.

The economic and environmental aspects of the use of hydrogen fuel cells to meet the demand for electrical load were investigated. Six schemes of energy supply of the building and comparing them to select the optimal solution have been developed. In the study, the assessment tool was the Hybrid Optimization of Multiple Energy Resources (HOMER) software.

The considered schemes were evaluated in accordance with a single generalized indicator. As a result, it was determined that the use of a hydrogen fuel cell could increase the efficiency of the traditional system by 85 %. For renewable energy systems, there was an increase in efficiency of 7 % (for the wind generator) and 10 % (for the photocell).

The practical use of the results will contribute to the efficiency of the process of electricity production by equalizing the stability of energy supply in hybrid systems. The economic and environmental assessment conducted demonstrates the prospects of using a hydrogen fuel cell. This assessment is designed to strengthen consumer confidence in the use of hydrogen fuel cells and hydrogen in general

Keywords: hydrogen fuel cell, hydrogen potential, green hydrogen, hydrogen economy, SWOT analysis

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1. Introduction

According to the current energy paradigm, hydrogen energy should become the most promising direction for replacing traditional energy from fossil sources [1].

One of the potential solutions for electricity generation is the use of hybrid energy systems with a hydrogen fuel cell (HFC).

Now in the world there is a rapid increase in the share of renewable energy in the energy sector [2]. This is due to a number of factors, including the competitiveness of renewable energy technologies, targeted policy initiatives, access to finance and affordable government credit, environmental issues, the ever-growing demand for energy and the rising cost of it. However, first of all, the growth in the percentage of alternative energy is due to the desire of countries to gain energy independence through diversification of fuel and energy resources. The events of recent years, including military conflicts, have demonstrated that fuel resources can act as a factor of manipulation for making political or socially important decisions. In order to avoid this, it is necessary to maintain a vector for energy independence, which can be achieved by obtaining energy from local resources, such as water, land, wind, sun, organics, etc.

Alternative renewable energy has many advantages and is a necessity for Ukraine. However, it has significant drawbacks. The main disadvantage is its intermittent nature since almost all renewable energy is characterized by serious random fluctuations and interruptions at different times of the day and seasons.

Therefore, electricity generated using renewable energy that is directly connected to the grid will lead to problems with the quality of electricity, such as voltage and frequency fluctuations. To overcome this limitation, hybrid energy systems (which include one or more renewable energy-based generating plants) are combined with a backup battery to meet the demand for energy load. One of the options for equalizing the stability of energy supply is to use a combination of an electrolyzer, a hydrogen storage device, and a hydrogen fuel cell, but it has not been studied in detail up to now.

This predetermines the problem of our study – to increase the stability of the supply of alternative renewable energy through the use of hydrogen fuel cells.

Given the current situation in the global energy sector and the advantages of using hydrogen energy, we can say that the study of the potential of using a hydrogen fuel cell is extremely relevant.

2. Literature review and problem statement

According to experts, the hydrogen sector will constantly grow and diversify in Ukraine. Ukraine is expected to become a leader in hydrogen technologies at the EU level. According to the assumption by the energy association «Ukrainian Hydrogen Council», in 2050 Ukraine will have a reputation as a hydrogen hub in Europe, will rapidly expand the hydrogen market, in particular its export component [1]. In addition, according to the Timmermans Recovery Plan, the reconstruction of the energy sector in Ukraine will take place with an emphasis on its renewable energy sources. Therefore, it is important to assess the prospects for hydrogen energy.

In study [3], a mathematical model of the irradiation flow scheme of the photovoltaic matrix of the panel and the electrolyzer was built, which was confirmed experimentally. Through the use of a V-shaped concentrator, it was possible to increase the efficiency of converting solar energy into hydrogen energy from 5.62 % to 6.18 %. But the authors do not indicate how the hub contributes to the rise in the cost of the energy scheme.

The possibility of connecting an electrolyzer for hydrogen production is considered in [4]. The paper develops systems for combining photocells with a PV-electrolyzer with a Buck DC-DC converter interface, which helps regulate hydrogen generation. Experimental studies on the ground and laboratories were performed to obtain the characteristics of the electrolyzer. However, the question remains unresolved how the efficiency of the system varies depending on the speed within the range of solar irradiation from 440 to 975 W/m^2 under consideration. It is also not specified whether it is appropriate to use the system at an exposure level of less than 440 W/m^2.

In [5], the work of a hybrid model of a photovoltaic/fuel cell system is evaluated. In the study, the main components, the electrolyzer and fuel cell, were simplified to an equivalent circuit model, and these were not confirmed by experimental results. Therefore, quantitatively calculating the effectiveness of the system was difficult.

However, in works [3–5] there is no calculation of economic impact. The efficiency of the power plant is, first of all, the ratio of the costs of implementing and operating the system to the load received and the financial benefits received. Therefore, it is not advisable to talk about increasing efficiency without taking into account the economic side of the issue in the energy sector.

The issue of green electricity production is discussed in [6]. The study analyzed the production of green hydrogen by electrolysis of water in combination with photovoltaic cells under different climatic conditions in Morocco.

The authors simulated the operation of four solar power plants with a nominal capacity of 100 mW from different PEM electrolyzer technologies. It is recognized that the proposed hybrid system is the cheapest for the country and competitive in relation to other countries. Thus, for the production of green hydrogen, the cost is USD 5.57/kg, against USD 5.96/kg in southern Spain, and USD 6.51/kg in South Africa. However, the cited paper does not consider the possibility of adding elements of a different capacity and the limited territorial area of research.

In work [7], a hybrid energy system consisting of photovoltaic and solid oxide fuel cells (PV-SOFC) for electricity production and hydrogen production is designed. According to the optimization of the system, the electrolyzer is capable of producing 238.8 thousand kg of hydrogen that can be used as fuel in SOFC to compensate for energy shortages at night and during peak season, which is an extremely good optimization result.

Study [8] simulated a hybrid system consisting of a solar photocell, a hydrogen energy storage, a heat recovery system on fuel cells, an integrated electric heater, and a solar thermal system. Theoretical simulation of the system is carried out in the MATLAB software package.

However, the reported studies [6–8] have territorial limitations: one city in northern Algeria and in Australia. This makes it impossible to assess the holistic situation regarding the use of HFC since it has not been investigated how the same hybrid system would behave under other climatic conditions.

In the process of implementing any project, investors focus on the benefits that can be profitable. These can be direct financial investments, or environmental benefits that save money from paying taxes on emissions, etc. However, assessing the technical and economic performance of energy systems is a difficult task. In connection with the increased use of renewable energy systems, much attention is also paid to their feasibility assessment.

Despite the fact that a comprehensive indicator can be used to analyze the performance of systems in detail from some aspects, it is still not enough to synthetically determine their feasibility in real projects. Few studies have comprehensively identified various aspects, including economic benefits, resource conservation and environmental impacts, so limited scientific research has hindered the practical application of renewable energy. Intense attention to the environment has led to ongoing concerns about sustainable energy, and a number of systems have been put into practice.

Quantifying the technical and economic performance of renewable energy systems is important, but it is challenging because the state of resources, system investment and subsidy policies vary from place to place.

We can conclude that there are almost no studies evaluating a hybrid system with a combination of solar photovoltaic cells, wind stations in combination with hydrogen fuel cells. There are many studies evaluating systems that would combine the operation of photocells and fuel cells as an auxiliary element. However, all studies are focused on use in areas with a high level of light radiation and it is not clear how alternative sources can be used in temperate climates.

It should be noted that the considered studies [3–8] are focused on a specific area, on climate features, and do not emphasize the benefits of local resources. In addition, studies concern the separate analysis of one type of energy in a particular region without comparative evaluation of other resources. The choice of resources for the application of the system had to be very important. It is difficult to choose the best system configuration in a particular region if there is no single quantitative standard.

Also, an important factor is the possibility of standardizing the system, its consideration regardless of the territory of application. Therefore, it is advisable to develop a comprehensive generalized indicator that would combine the main technical, economic and environmental indicators of the impact of the energy system. To do this, the most correct is the use of computer-aided design with a large database.

There are many computer-aided design tools available to study renewable energy use. However, there is no perfect energy tool that could solve all the problems of grid design [9]. The choice of tool largely depends on the specific goals that actually need to be achieved. The study evaluated schemes for different configurations of renewable and non-renewable resources, isolated and connected to the grid. To solve this, it is correct to use the computer tool Hybrid Optimization Model for Electric Renewable Energy (HOMER), developed by the National Renewable Energy Laboratory (NREL). HOMER evaluates optimal and close to optimal solutions. After modeling all possible system configurations, HOMER ranks possible configurations from most to least efficient for comparing different design options.

This suggests that it is expedient to conduct research on the design, planning, and optimization of energy system management from traditional and alternative sources with a hydrogen fuel cell, as a promising direction for stabilizing the energy system.

Therefore, our study proposes to evaluate the possibility of combining power equipment in combination with a hydrogen fuel cell. To this end, it is advisable to use computer simulation.

3. The aim and objectives of the study

The aim of this study is to substantiate the feasibility of using hydrogen fuel cells in energy supply systems, in particular by assessing the economic and environmental benefits of implementing hydrogen projects. This will make it possible to increase the efficiency of electricity production and help ensure optimal flow distribution between energy sources and consumers.

To accomplish the aim, the following tasks have been set:

– to assess the potential of hydrogen fuel cells using SWOT analysis;

– to carry out the simulation of energy supply schemes;

– to perform a comprehensive economic and environmental assessment of the hybrid energy system using hydrogen fuel cells as a replacement for traditional electricity.

4. The study materials and methods

The object of research is the process of using a hydrogen fuel cell to generate and accumulate electricity.

The hypothesis of the study is the assumption that combining hydrogen fuel cells in a hybrid system with elements of alternative or traditional energy in electricity production will reduce costs and contribute to the stability of the system.

To assess the potential of using hydrogen fuel cells as an alternative energy source, SWOT analysis was used as a research method. The data were obtained based on reports of international organizations on the practical implementation of fuel cells, the Hydrogen Strategy of Ukraine, the Draft Roadmap for the production and use of hydrogen in Ukraine. Data from presentations of participants in the cycle of professional highly specialized discussions «Ways to develop the hydrogen economy in Ukraine» from the Energy Club were also used.

The study reports a comprehensive analysis of economic and environmental indicators of a set of scenarios associated with the use of hydrogen for electricity production.

We studied the economic conditions necessary for a hybrid system with hydrogen fuel cells to be competitive compared to traditional systems based on the use of grid electricity.

The study was conducted on the example of a typical administrative building in the city of Kyiv (Ukraine). The building is seen as a self-contained system, and the electrical grid is only an emergency device that works when the fuel cell is not working (for breakdowns or maintenance). After assessing the available resources, several scenarios for the building's power supply have been developed.

In the first phase, the existing load was investigated to formulate the exact behavior of energy demand. The combination of power systems was selected in accordance with several combinations of devices (electrical network, fuel cell, photovoltaic panels, wind turbines, boiler, etc.) depending on the proposed scheme. The renewable energy system design tool was used to model different scenarios and find the optimal one.

The second stage involved the evaluation and optimization of selected schemes. In the current study, there are six schemes of energy supply systems: two traditional and four alternative systems that work with hydrogen.

Simulation of the selected schemes and calculation of the configuration of several economic and environmental parameters were carried out in the software package HOMER. The use of this software made it possible to compile the energy balance of the system and its components, the hourly operation of each system, and calculate the economic and environmental parameters.

The main economic indicator used to compare the system is the «net present value» (NPV), which is the current cost of investing and operating the system over its lifetime.

CO_2, CO, NO_x, SO_2, unburned hydrocarbons and particulate matter are indicators used to analyze the environmental performance of each system.

According to the obtained economic and environmental indicators, a comprehensive generalized indicator was calculated using the method of mathematical normalization to compare the application of schemes with traditional, renewable, and hydrogen elements.

The calculation of a single generalized indicator was carried out by the method of normalization by standard deviation according to formulas (1) to (6) from [10].

Calculation of a positive indicator:

$$Z_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)}, \quad (1)$$

where x_{ij} is the initial value of the variable j for unit i; $\min(x_j)$ and $\max(x_j)$ are, respectively, the minimum and maximum values representing the possible range of the variable j.

Calculation of the negative indicator:

$$Z_{ij} = \frac{\max(x_j) - x_{ij}}{\max(x_j) - \min(x_j)}. \quad (2)$$

The standard values of the indicators were calculated based on the data of positive and negative normalized indicators obtained in (1), (2):

$$Z = E(Z_i) = \frac{1}{n}\sum_{i=1}^{n} Z_{ij}, \quad (3)$$

where n is the number of values in the numeric series.

Calculation of standard deviation by standard values:

$$\beta_j = \sqrt{\sum\nolimits_{i=1}^{n}\left(Z_{ij} - E(Z_j)\right)^2}. \quad (4)$$

The weight of each indicator was obtained taking into account the standard deviation indicator for standard values, obtained in (4):

$$W_j = \frac{\beta_j}{\sum\nolimits_{j=1}^{m}\beta_j}. \quad (5)$$

Using (3), (5), the calculation of a single generalized indicator by the method of valuation, which falls into the interval [0, 1], is obtained:

$$SGI = \sum_{i=1}^{n} Z_i \cdot W_i. \quad (6)$$

Features of the study were as follows. First, the administrative building has never been investigated as an example in the design of a hybrid energy system. Secondly, in this study, the impact of the hydrogen fuel cell operation is taken into account when considering the system. The substantiation was made using a computer tool for modeling renewable energy, with the collected load profile, climatic and financial data as input data.

5. Results of studying the use of hydrogen fuel cells in energy supply schemes

5. 1. Estimating the potential of hydrogen fuel cells using SWOT analysis

The SWOT matrix of the fuel cell station, which indicates the specific main characteristic elements of hydrogen fuel cell technology, is given in Table 1.

Table 1

SWOT matrix of fuel cell station

Strengths	Weaknesses
S1. Support from the government. S2. High performance. S3. Versatility and wide range of applications. S4. Low energy distribution costs. S5. Environmental benefits	W1. Poorly developed hydrogen infrastructure. W2. Implementation risks. W3. System integration. W4. High costs
Opportunities	**Threats**
O1. Development potential. O2. Addressing the issue of improving energy security. O3. New business opportunities	T1. Low technical component of existing solutions. T2. Social unpreparedness. T3. Economic challenges

Strengths.

S1. Support from the government:

– beginning of cooperation between political bodies and professional associations in the field of hydrogen energy and business entities, manufacturers of hydrogen fuel cell technologies;

– support for the hydrogen economy at the national level [11];

– action in Ukraine of programs to support hydrogen energy, for example, the H2PILLARS project, which is part of European Horizon 2020 Program;

– a draft Roadmap for the production and use of hydrogen in Ukraine was developed; discussion of the draft Hydrogen Strategy until 2030 [2];

– availability of targeted research and development work from large companies for the development of hydrogen management equipment.

S2. High performance indicators:

– hydrogen has the highest high specific energy per unit mass among all known traditional and alternative fuels [12];

– fuel cell technology has a high overall efficiency of up to 60 % and does not depend on their power;

– it is possible to integrate the fuel cell with the Smart Grid to stabilize power fluctuations in the power grid. The use of HFC with renewable sources of electricity allows accumulating energy in the form of hydrogen during a decrease in consumption, and reproducing it during load peaks;

– extended period of trouble-free and uninterrupted operation of fuel cells: working hours of HFC are on average 7000 hours.

S3. Versatility and wide range of applications:

– fuel cells have a wide power range – from 3 W to 100 MW, which indicates the versatility of application: from a private house to a powerful enterprise;

– simple process technology: a fuel cell converts hydrogen directly into electricity and heat through an electrochemical reaction;

– it makes it possible to compete with traditional battery devices [13].

S4. Low energy distribution costs:

– portable HFC make it possible to produce electricity in close proximity to the consumer [14];

– hydrogen can be transported at a distance through pipes under safe conditions;

– when using HFC, the cost of electricity distribution is reduced by reducing the length of networks [15];

– hydrogen has the potential to integrate existing fuel transportation infrastructure.

S5. Environmental benefits:

– hydrogen is a conditionally inexhaustible environmentally friendly natural source of energy since it is obtained from water by electrolysis;

– hydrogen production and consumption are a closed cycle that promotes the ecological use of energy resources; hydrogen can be produced by recycling waste as a by-product [16, 17];

– hydrogen combustion is almost completely devoid of pollutant emissions; hydrogen is a non-toxic energy carrier;

– hydrogen production does not pose a threat to production workers;

– the operation of HFC is not accompanied by noise pollution. Noise can come from a cooling system, compressors for fuel supply, etc.; its level is insignificant [18];

– work safety and resistance to adverse effects. For example, the ability to withstand earthquakes, various natural phenomena, or strong man-made impacts. The design of the fuel cell does not involve the use of massive rotating parts and there is no clear fixation of the position, which ensures high process safety.

Weaknesses.

W1. Poorly developed hydrogen infrastructure:

– lack of hydrogen production points;

– lack of efficient transportation and distribution systems;

– incomplete network hydrogen infrastructure;

– the need to change the current electricity distribution system in residential buildings;

– absence of official representative offices of large manufacturers of HFC in Ukraine: Ballard Power Systems, Plug Power, Bloom Energy, etc.;

– lack of clear plans for the development and implementation of the hydrogen economy.

W2. Implementation risks:

– non-detailed technology: there are no regulations and technical standards, implementation procedure; the complexity of the hydrogen economy;

– integration of hydrogen as an energy carrier into the energy system has not been tested on an industrial scale;

– lack of effective tools for introducing hydrogen into existing natural gas transport and distribution networks;

– unexplored problem of operational safety: hydrogen burns in the presence of air;

– electricity from hydrogen, as a new type of electric energy, can cause public resistance associated with uncertainty and lack of information about operating problems.

W3. System integration:

– lack of broad awareness of the possibilities and potential benefits of hydrogen fuel cell technologies used to supply clean energy;

– weak development of the hydrogen supply network;

– lack of a clear marketing policy and strategies to promote hydrogen energy as clean energy;

– unclear plans for the future economy based on hydrogen energy.

W4. High costs:

– high initial investment costs;

– high cost of electricity production from green hydrogen compared to traditional fuel resources;

– high costs of adapting the hydrogen economy.

Opportunities.

O1. Development potential:

– electricity generation from hydrogen will contribute to the energy security of the region and the country (hydrogen can be considered as a conditionally infinite source of energy);

– it makes it possible to reduce dependence on fossil classic fuels and diversify sources of autonomous power supply;

– hydrogen energy can be considered as an object of innovation and technological advancement in the direction of energy efficiency [15];

– HFCs have the potential to solve the problem of balancing the network with large volumes of unstable renewable electricity;

– this direction stimulates and creates new jobs;

– there is a possibility of expanding the power supply network without high capital investments, the possibility of autonomous applications in remote areas;

– HFCs have the potential to integrate non-permanent renewable energy sources into the energy system to increase the stability of its operation;

– hydrogen and fuel cell technology stimulates research, innovation, and development in the field of energy systems.

O2. Addressing the issue of improving energy security:

– energy carrier contributes to stabilization of energy security and prices, generating competition between different energy sources, promotes energy diversification;

– improving energy efficiency through efficient use of energy resources throughout the energy cycle – storage, distribution, and final consumption, distribution and final consumption;

– decarbonization of the energy sector at minimal cost;

– integration of hydrogen into the energy balance, which corresponds to the desire for sustainable development and reduces dependence on energy imports [19].

O3. New business opportunities:

– emergence of the hydrogen market;

– emergence of new commercialization plans and new business models;

– emergence of potential suppliers, consumers and end users;

– the possibility of doing business in remote non-electrified areas;

– the emergence of new jobs.

Threats.

T1. Low technical component of existing solutions:

– immaturity of some technologies for converting hydrogen into energy;

– lack of specialists and experts in the field; limited practical experience of both producers and consumers;

– insufficient capacity to store large volumes of hydrogen, there is no network, which would ensure the reliability and flexibility of the network;

– immature solutions for massive hydrogen storage, which have not passed extensive tests;

– the need to improve technical elements: detectors for hydrogen search; odorization; selection of materials for pipelines; transport containers for hydrogen delivery; limited practical experience of both producers and consumers;

– lack of technical information from potential investors on hydrogen technologies, which leads to low interest on their part.

T2. Social unpreparedness:

– negative impact from other actors in the energy sector;

– public perception of the widespread use of hydrogen is unclear;

– immaturity of legislation: lack of relevant laws and regulations;

– non-recognition of hydrogen energy as a strategic infrastructure.

T3. Economic challenges:

– lack of potential suppliers, potential investors, and consumers;

– competition with other renewable resources;

– the complexity of competition with the current fossil fuel market;

– strong positions of fossil fuel producers;

– imperfection of organization and financing of the hydrogen economy.

The SWOT model has made it possible to analyze the advantages, disadvantages, capabilities, and threats of fuel cell systems. It is a comprehensive analysis of current development strategies and difficulties in order to put forward future strategies and provide theoretical support.

So, while there are some bottlenecks, fuel cell systems in Ukraine are on the rise. It is advisable that the use of fuel cells as soon as possible comes out of the research stage and enters the energy supply market by diversifying it. Therefore, according to the current economic situation and social needs, there are some suggestions for hydrogen fuel cell systems:

1) the government should continue the constant vector of support for the hydrogen strategy. In addition, it is necessary to pay attention to the unification of research institutions and enterprises in order to lay the foundation for in-depth research of hydrogen as an energy factor. It is important to create competitive, key technologies. This is possible with further integration of business and scientific community, as well as the creation of new training programs for specialists in the field of hydrogen and alternative energy;

2) the hydrogen infrastructure network should be improved. In particular, installing hydrogen stations and battery replacement stations. Ukraine should establish a full set of auxiliary capacities and then consider reducing the industrial stages of fuel cell system implementation;

3) fuel cell systems must meet international standards and increase the adoption of foreign advanced technologies to reduce differences with developed countries. In combination with the development of fuel cell systems, Ukraine should actively participate in international exchanges and cooperation to accelerate industrial development. Only in this way will hydrogen energy in the country be able to become competitive as soon as possible.

5. 2. Modeling of energy supply schemes

5. 2. 1. Data collection

Energy consumption. The load on the office building has been precisely determined and the HRES developed in this study is expected to correspond to a maximum load of 27.54 kW and 200 kWh/day. Due to energy consumption, artificial lighting systems, computers, and a complex of auxiliary electronic devices and equipment are powered.

For the purposes of estimating, the values of variability between steps in time and variability from day to day were established as 12.2 % and 8 %, respectively. The maximum, medium, and minimum loads are 27.54 kW, 15 kW, and 3 kW, respectively.

The daily and seasonal load distribution profile is shown in Fig. 1 (drawn in the HOMER software package).

The need for loading varies throughout the day, and the maximum need falls from 8:00 to 17:00. Load requirements depend on each month.

Climatic data. Both energy supply and demand change frequently, so real-time adjustments require full data availability. Since the availability and amount of solar and wind energy depends on climatic conditions, a preliminary feasibility study is needed to investigate site-specific weather data. For example, both the electrical efficiency and the output power of a photovoltaic module are linearly dependent on the operating temperature. Therefore, the development of an optimal hybrid system requires appropriate climate data.

The coefficients of daily variability and incremental variability over time, equal to 2 %, were introduced into the assessment to make load data more realistic.

Data on solar radiation and hourly wind speed are taken into account according to information from the Central Geophysical Observatory [20]. Solar radiation for Kyiv varies in the range of 0.69–0.83 kW/m^2. The distribution of wind speed varies from 2 to 3 m/s, the average wind speed in the region is about 2.5 m/s.

Based on all assumptions, regional energy demand, using the HOMER simulation software, is calculated at approximately 200 kWh/day (or 73.00 MWh/year).

The tariff component for calculating the economic indicator is established by law [21]. Thus, the «green» tariff for electricity for 2020–2024 for energy produced from solar radiation energy is 4.74 UAH/kWh (0.13 USD/kWh), for wind energy 4.04 UAH/kWh (0.11 USD/kWh).

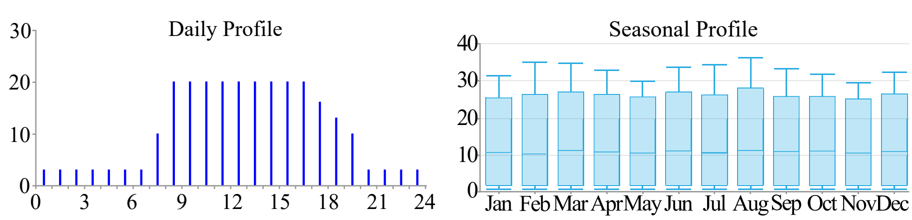
In addition to buying power from the grid to meet the load consumption, the excess electricity generated by the system itself can be sold back to the grid. The service life of the proposed schemes is designed for 25 years. The annual real interest rate for Ukraine is set at 3 % according to the subsidization of expenditures from the Government of Ukraine.

5. 2. 2. Determining power system schemes

To solve the set tasks, various schemes of energy supply of the building were evaluated: the traditional scheme of energy supply, the scheme of energy supply from renewable sources, and the comparison of their characteristics in combination with the hydrogen fuel cell. According to the traditional system, two schemes are supposed to be used:

Scheme 1. 1. Traditional basic scheme (Fig. 2, *a*). The building's electricity needs are met by the general urban network. As an additional source of energy, a gasoline generator running on natural gas is used.

Scheme 1. 2. The need for electricity for devices and lighting devices can be provided either by the network or by HFC (Fig. 2, *b*). The fuel cell is designed to supply all the necessary electricity, so that the network only works when HFC is not working (as in the case of a breakdown or maintenance). Hydrogen is delivered via pipeline and is supposed to be produced by electrolysis from renewable sources.



a *b*

Fig. 1. Load distribution profile for a typical administrative building in the city of Kyiv: *a* – daily; *b* – seasonal

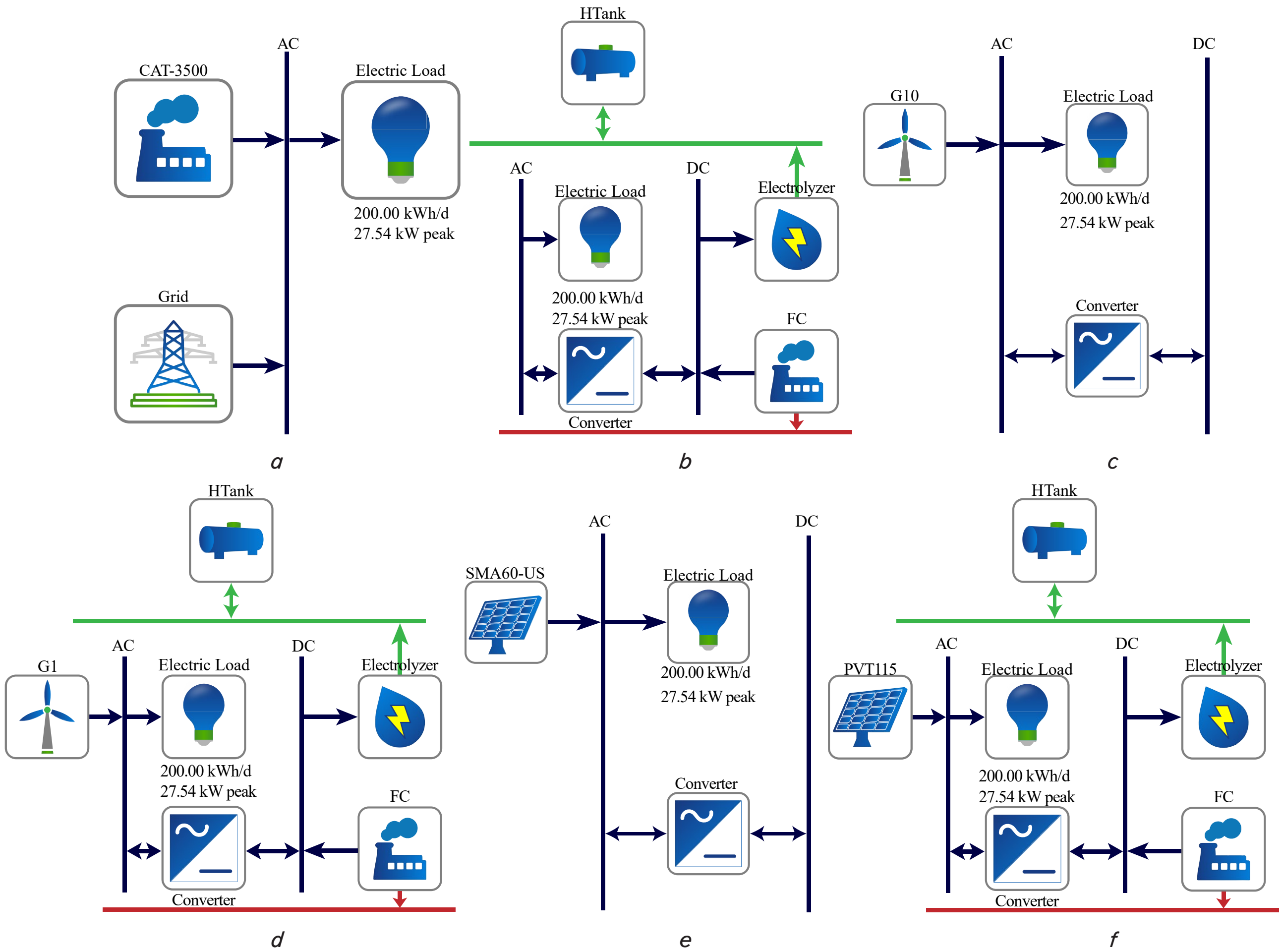


Fig. 2. Developed schemes of energy supply: *a* — Scheme 1. 1; *b* — Scheme 1. 2; *c* — Scheme No. 2. 1; *d* — Scheme 2. 2; *e* — Scheme 3. 1; *f* — Scheme 3. 2 (built in PC HOMER, screen image)

Scheme 2. 1. Energy supply is generated from alternative sources using a wind generator (Fig. 2, *c*).

Scheme 2. 2. In the system, the normal demand for electricity is satisfied by HFC and the wind generator (Fig. 2, *d*). Hydrogen is supplied to the HFC, which is produced as a result of electrolysis and distributed through the pipeline.

Scheme 3. 1. Energy supply is generated from alternative sources using photocells (Fig. 2, *e*).

Scheme 3. 2. In the system (Fig. 2, *f*), the demand for electricity includes energy for household appliances and lighting. It is fully satisfied with the photovoltaic installation and HFC. The fuel cell works when solar radiation is low or zero. Electrolytic hydrogen is used to power the fuel cell.

Since the electrolyzer and fuel cell almost always work at different points, circuits 2. 2 and 3. 2 provide for the installation of a hydrogen tank, so the hydrogen produced is temporarily stored in it.

The main technical data of the selected equipment are given in Table 2.

The dimensions of photovoltaic panels, wind turbines, electrolyzer, and hydrogen tank are selected minimum necessary to ensure system autonomy.

The dimensions of fuel cells and inverters are selected from peak power.

The minimum size of other equipment was determined by optimization.

The energy balance for each of the 8760 h in a typical year was compiled to simulate the operation of all circuits. The results were used for further economic and environmental assessment.

Table 2

Technical data of the selected equipment used

Elements	Cost, thousand UAH/kW	Cost of operation, % of capital expenditures	Service life
Electrolyzer	200–500	2 %	30,000 hours
Hydrogen fuel cell	120	2 %	40,000 hours
Hydrogen tank	1 thousand UAH/m^3	0.5 %	25 years
Photocells	260,5	0 %	15 years
Wind generator	823,9	0 %	25 years

5. 3. Economic and environmental assessment results for hydrogen fuel cell energy schemes

5. 3. 1. Selection of economic indicators

To evaluate energy systems, the result of modeling in the HOMER software package was used. The obtained data necessary for the study: net present cost (NPV), normalized cost of energy (LCOE), the amount of operating costs.

The main economic indicators obtained by optimizing circuits in the HOMER software are given in Table 3.

Data on equipment performance and costs were taken from market reviews.

The input parameters are the cost of equipment, technical parameters, the cost of fuel (hydrogen and natural gas), the demand for electricity and heat. The impact of pollutant emissions, global solar radiation, and annual wind speed time profiles is also taken into account.

It is worth noting that the configuration of scheme 1. 2 is one of the best configurations. In particular, it has NPV significantly higher than when using the scheme of combining HFC with photovoltaic cells (scheme 3. 2) or wind generator (scheme 2. 2). This fact suggests that, at assumed running costs, hydrogen is the best option for energy production.

Comparing alternative power supply schemes, it can be noted that the configuration of the combination of photocell, electrolyzer, tank, and HFC (scheme 3. 2) has significantly higher NPV than the combination scheme of a wind generator, electrolyzer, tank, and HFC (scheme 2. 2). This indicates its greater attractiveness for investment. The implementation of this scheme is also supported by the lower cost of electricity – LCOE of scheme 3. 2.

It should be noted that the traditional system (scheme 1. 1) is much more economical. Such a system has the lowest investment and LCOE but, unlike the proposed schemes 1. 2–3. 2, the traditional system cannot be profitable and increase NPV. It can be noted that alternative systems are competitive to the traditional system only if there is a very significant reduction in capital costs and fuel costs. The increase in electricity prices will entail a very small target reduction in investment costs for configurations of scheme 2. 2 and scheme 3. 2.

Since the cost of hydrogen-related devices (electrolyzer, HFC) is the same for these two systems, the difference in their NPV is related to the investment costs of devices that generate electricity (photovoltaic cells and wind generator).

5. 3. 2. Selection of environmental indicators

To assess the environmental impact of the developed schemes of energy systems on the environment, emissions of major pollutants were calculated. The assessment was carried out using built-in HOMER tools.

The main harmful substances analyzed are CO_2, CO, NOx, SO_2, unburned hydrocarbons, and particulate matter.

The emissions of each pollutant are calculated taking into account the relative emission coefficients [17, 22].

Systems that use fewer or no fossil fuels have the lowest emissions of greenhouse gases and toxic pollutants. In particular, systems that use only hydrogen are the most environmentally friendly systems.

The components whose operation causes emissions are the electrical grid (according to the mixture of fuel used in power plants) and the gasoline generator. A fuel cell does not emit kinds of pollutants because it only emits water when it operates in a normal temperature range. Therefore, hydrogen fuel cells have zero emissions.

Emissions from various systems are mainly related to local resources. Compared to traditional energy such as oil and coal, renewable energy is not only sustainable but also environmentally friendly. Therefore, carbon emissions should also be considered as an important indicator for an environmental assessment of a sustainable energy system.

Emissions of harmful substances from the use of various energy schemes are given in Table 4.

It is obvious that when using a hydrogen fuel cell in a traditional energy supply scheme (scheme 1. 2), emissions of both carbon and other harmful substances are significantly reduced. However, this trend continues when compared with alternative power supply schemes (scheme 2. 2 and scheme 3. 2), which indicates that hydrogen systems can effectively mitigate the adverse effects of global warming.

Table 3

Economic indicators of energy schemes

Indicat.	Scheme 1. 1	Scheme 1. 2	Scheme 2. 1	Scheme 2. 2	Scheme 3. 1	Scheme 3. 2
NPV, UAH thousand	837	24 123	14 406	16 948	17 407	20 479
O&M, UAH	53 285 350	257 243	354 995	308 691	428 952	373 002
LCOE, UAH	4.97	4.37	6.03	5.24	8.44	7.34

Table 4

Emissions of harmful substances

Scheme number	Scheme 1. 1	Scheme 1. 2	Scheme 2. 1	Scheme 2. 2	Scheme 3. 1	Scheme 3. 2
Carbon Dioxide	2 831.13	31.31	31.36	0.00	31.44	0.00
Carbon Monoxide	403.00	0.23	0.28	0.00	0.36	0.00
Unburned Hydrocarbons	159.00	0.00	0.05	0.00	0.13	0.00
Particulate Matter	31.9	0.00	0.05	0.00	0.13	0.00
Sulfur Dioxide	7.06	0.00	0.05	0.00	0.13	0.00
Nitrogen Oxides	24.63	0.32	0.37	0.37	0.45	0.29

5. 3. 3. Calculation of the efficiency of selected energy supply schemes using a single generalized indicator

In order to critically evaluate the performance of hybrid systems, which are very different from each other, an assessment was applied using a single generalized indicator.

Six main economic and environmental indicators are selected: Net present value, Levelized cost of energy, O&M, Sulfur Dioxide, Carbon dioxide, Nitrogen Oxides, as aspects used to calculate a complex generalized indicator by normalization. The final summary index is represented by the real numbers of the interval [0, 1].

System configuration simulation and optimization is completed using HOMER software. Long-term simulations of wind and solar power generation systems in combination with a hydrogen fuel cell were performed. With the help of software modeling, data on energy saving and environmental efficiency, which are widely used in modeling a renewable energy system, have been obtained.

The selected six main estimated indicators represent the six axes of the real number in the interval [0, 1]. The full performance of the proposed schemes of energy production systems is obtained by the normalized method after calculating all weight values.

A complex generalized indicator is shown in Fig. 3.

The complex efficiency of the system is better for the circuit with a larger chart area. For example, it is obvious that «Scheme 1. 2» has the largest area, while the area of «Scheme 1. 12 is approaching zero.

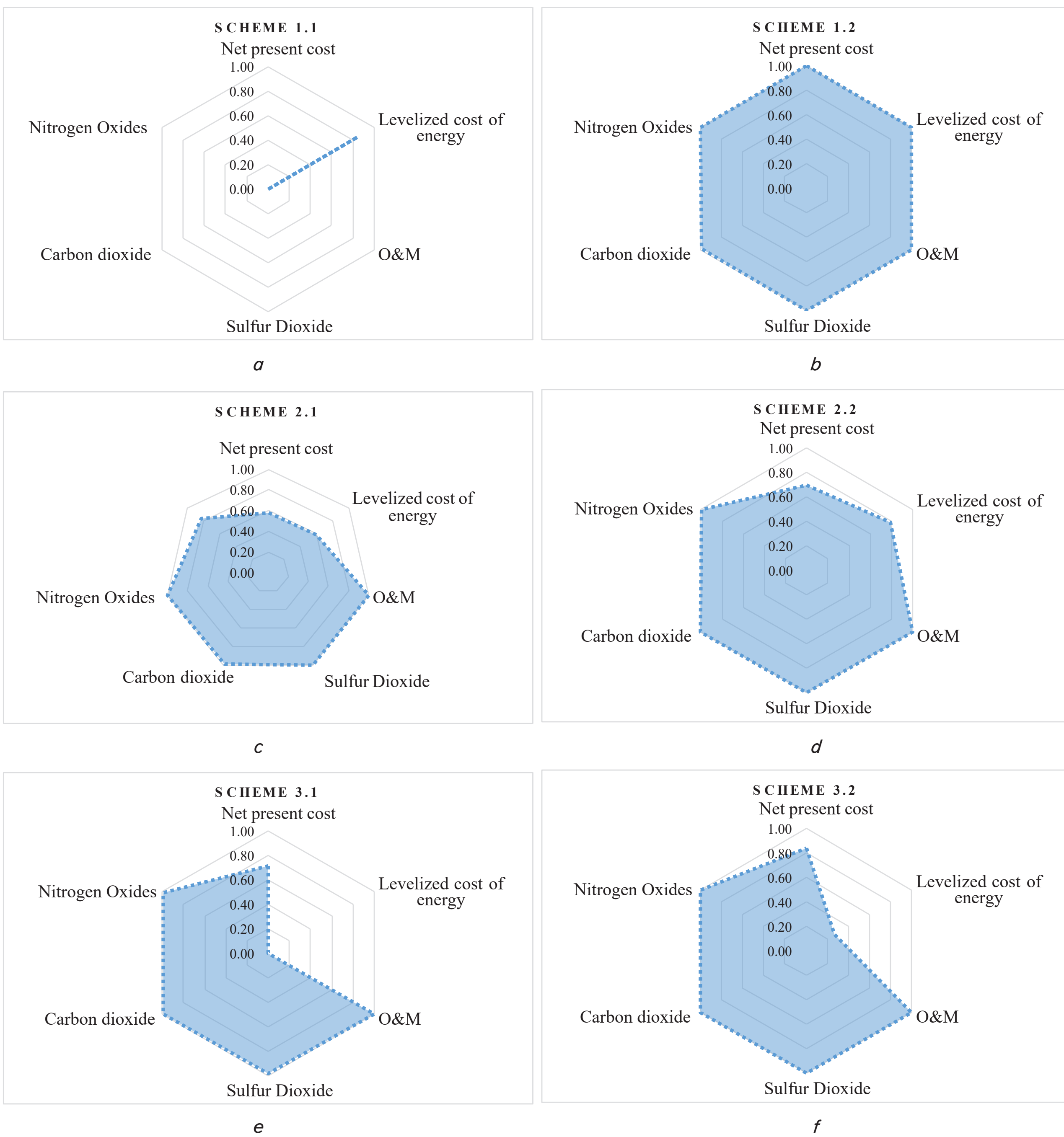


Fig. 3. Key indicators for evaluating energy schemes:
a – Scheme 1. 1; *b* – Scheme 1. 2; *c* – Scheme 2. 1; *d* – Scheme 2. 2; *e* – Scheme 3. 1; *f* – Scheme 3. 2

At the same time, when individual indicators approach 1, which means that every aspect of the system has the maximum possible value, and the system is optimal for use. For «Scheme 1. 1» indices approach 0, which means that its use is not recommended.

Table 5 shows the selection of equipment for energy supply schemes. The complex generalized indicator is calculated in Table 6.

In all three combinations of schemes, the use of HFC gives an increase in efficiency in terms of economic and environmental aspects. Its best use (by more than 85 %) predetermines its use in a scheme with a city network. However, even with alternative energy schemes, the use of HFC increases its efficiency.

If we compare the traditional scheme, the advantage of using HFC is that emissions of harmful substances and operating costs are greatly reduced, which are quite significant in scheme 1.1 due to the operation of a gasoline generator.

In comparison with alternative energy schemes, the use of HFC has little impact (from 7 to 10 %). It is due to the increase in the economic indicator NPV. The fact is that due to voltage fluctuations and frequency of alternative circuits, there is an urgent need to use photovoltaic cells and wind generators 1.5–2 times more power than necessary. This technical feature, in turn, leads to a significant increase in the cost of equipment. The use of an additional accumulating energy source in the form of an electrolyzer and HFC makes it possible to reduce initial investment.

The most acceptable, but also the most expensive is the system of combining a powerful electrolyzer, a hydrogen fuel cell and a hydrogen storage tank with a generalized indicator of 1.0.

If we evaluate alternative schemes, then it is preferable to use a wind generator with HFC in scheme 2. 2 (indicator 0.9). The average value of the system for combining a wind generator with a hydrogen fuel cell (0.90) is obviously higher than that of a system with photovoltaic cells (0.82). Scheme 2. 2 gives an advantage of 7.68 % compared to Scheme 3. 2, in which solar photovoltaic cells are used and it is suitable for consumers in the city of Kyiv.

Summing up, it can be argued that the most effective is the system of combining the city network with an electrolyzer and a hydrogen fuel cell, which is used in scheme 1. 2.

However, for alternative schemes, the use of HFC can increase the efficiency of their work and reduce the cost of initial investment. At the same time, the scheme of combining a wind generator in combination with a hydrogen fuel cell has an extremely high potential for application for Ukrainian cities. Photovoltaic systems, however, are limited by resources and initial investment, and can only be used as a supplement to the system to sell generated electricity beyond the required need, but not to maintain a stable energy supply to the building.

Table 5

Characteristics of equipment for power supply schemes

Scheme number	Type of energy supply scheme	Power generation equipment
Scheme 1. 1	Traditional scheme	City network; gasoline generator (35 kW) [23]
Scheme 1. 2	The traditional scheme in combination with HFC	City network; SOFC type HFC – 6 modules, (5 kW) [24]; electrolyzer of type PEM (Proton Exchange Membrane) [25]; hydrogen tank
Scheme 2. 1	Alternative scheme	Wind generator, (50 kV); inverter
Scheme 2. 2	Alternative scheme in combination with HFC	Wind generator, (30 kV); SOFC type HFC – 3 modules, (5 kW); PEM type electrolyzer; hydrogen tank
Scheme 3. 1	Alternative scheme	Photovoltaic installation, (60 kW); inverter
Scheme 3. 2	Alternative scheme in combination with HFC	Photovoltaic installation, (30 kW); SOFC type HFC – 2 modules, (5 kW); PEM type electrolyzer; hydrogen tank

Table 6

Calculation of the effectiveness of the scheme using a single generalized indicator

Scheme number	Scheme 1.1	Scheme 1.2	Scheme 2.1	Scheme 2.2	Scheme 3.1	Scheme 3.2
Net present value	0.00	1.00	0.58	0.69	0.71	0.84
Levelized cost of energy	0.85	1.00	0.59	0.79	0.00	0.27
O&M	0.00	1.00	1.00	1.00	1.00	1.00
Sulfur Dioxide	0.00	1.00	0.99	1.00	0.98	1.00
Carbon dioxide	0.00	0.99	0.99	1.00	0.99	1.00
Nitrogen Oxides	0.00	1.00	1.00	1.00	0.99	1.00
Single generalized indicator	0.15	1.00	0.83	0.90	0.72	0.82
Change in efficiency in the application of HFC	Growth by 85 %		Growth by 0.07 %		Growth by 0.10 %	

6. Discussion of results of the use of hydrogen fuel cells in energy supply schemes

The SWOT analysis of the use of hydrogen fuel cells in the energy supply of the private sector as an important factor in the development of the hydrogen economy of Ukraine was carried out. It is determined that the key factors influencing its development include energy and climate policy, fuel cell financing programs, parallel technologies, the presence of manufacturers of fuel cell systems, and energy costs (Table 1). Also, the SWOT analysis conducted in this study emphasizes that for the development of hydrogen energy in Ukraine, the legislative framework should be improved, the influence of decision-makers in the energy sector should be promoted. An important factor may be the level of awareness and interest of final beneficiaries, potential investors. It is also necessary to promote the development of professional competencies of existing specialists in this field and increase the number of future specialists.

It is determined that there are some bottlenecks of the system, but Ukraine has every opportunity for its development. The hydrogen fuel cell system must exit the research stage as soon as possible and enter a market with diversified development.

The main directions of development are improvement of the legislative framework, expansion of the hydrogen infrastructure network and regulation of the energy system in accordance with international standards.

Only in this way will hydrogen energy in the country be able to become competitive as soon as possible.

In order to justify the feasibility of using hydrogen fuel cells, the design of systems for providing the building with electrical energy was carried out.

An example was the energy needs of an administrative building located in the city of Kyiv. A comparison of the traditional scheme of energy supply, the scheme of renewable energy sources and their comparison when using hydrogen fuel cells is carried out. For this purpose, 6 energy schemes were developed (Fig. 2, *a–f*), the equipment necessary for energy supply was selected, and the main economic (Table 3) and environmental indicators (Table 4) were calculated.

Thus, economic indicators in the scheme of combining the wind power system with a hydrogen fuel cell in the city of Kyiv are much better than in the scheme of combining photovoltaic panels with HFC. It should be noted that the photovoltaic system (scheme 3. 2) is much less economical, it does not bring profit from the sale of energy to the grid and leads to certain losses of investment. Profitable are wind energy systems (scheme 2. 2) and hydrogen use systems (scheme 1. 2).

Due to climate, the use of photovoltaic cells in the city of Kyiv involves the use of large solar photovoltaic panels to collect a sufficient amount of solar radiation, which significantly increases investment costs. However, the city has abundant wind resources. Therefore, the city's wind energy system has greater advantages.

The capacity of Kyiv to produce wind energy is much higher than the electricity purchased by the grid, and most of the remaining electricity is sold back to the grid. Despite the fact that the preferential tariff for wind energy is significantly lower than for other renewable sources, the wind energy system has a high profit from the sale of electricity. For the photovoltaic system in the city of Kyiv, due to high investments in photovoltaic panels and lack of solar radiation resources, it is still difficult to recover the costs due to the higher price per unit of electricity sales.

Our study demonstrates that LCOE decreases with increasing energy production by the system. The LCOE of the photovoltaic system compared to the set sales rate is too high. There is an urgent need for sufficient lighting to reduce the cost of the system, which is difficult to achieve in the city of Kyiv. Since the components of energy systems are the same and investments in them are the same in any country, their economic advantage can only be determined by revenues related to the electricity tariff set by law.

When evaluating the environmental friendliness of energy systems, it should be noted that the traditional scheme (scheme 2. 1) produces the most waste emissions. This is primarily due to the high level of carbon dioxide produced during the operation of the gasoline generator (Table 4).

According to the «CO_2» parameter, wind and hydrogen generation schemes (scheme 2. 2) and solar and hydrogen (scheme 3. 2) are the best clean energy options both in the current period and in the medium term.

The proposed complex generalized indicator is implemented by the method of normalization taking into account six main aspects (Table 6). The most effective is the system of a powerful hydrogen cell (scheme 1. 2) with an indicator of 1.00. Also effective is the operation of wind power systems combined in a hydrogen fuel cell (scheme 2. 2) with an indicator of 0.90.

It should be noted that the study demonstrated that the use of HFC can increase the efficiency of the energy system in accordance with economic and environmental indicators. Thus, in comparison with the traditional scheme, the use of HFC can increase efficiency by 85 %. And when combined in alternative energy systems: in combination with hybrid wind energy – by 7 %; in combination with hybrid solar – by 10 %, which is a good result. The result obtained does not contradict existing studies [3].

Insufficient exposure and large initial investments lead to low economic efficiency of alternative energy supply systems, although they can make a significant contribution to energy conservation and emission reduction. The use of HFC makes it possible to overcome these problems, reduce economic costs, and generally increase the efficiency of the system.

The comprehensive aggregated indicator proposed in this study provided a more in-depth assessment for energy investors and government decision-making. Its application made it possible to compare different energy supply schemes – traditional and alternative, which is extremely difficult to evaluate among themselves according to different characteristics since each has its own advantages and disadvantages.

In contrast to studies [3–8], which considered specific situations of application of HFC, the assessment obtained in our study allows comparing both traditional and hybrid energy supply systems in combination with HFC. This becomes possible through the use of a single generalized indicator of economic and environmental assessment, with the help of which you can not only evaluate the effectiveness of a particular scheme but also choose the optimal configuration of equipment for it. Also, the use of a single generalized indicator makes it possible to overcome the territorial limitations of research [6–8] since the use of a single generalized indicator makes it possible to normalize the system, its consideration regardless of the territory of application.

The limitations of the study are the evaluation of equipment only at the stage of operation. That is, our study does not take into account emissions and waste during the life cycle of equipment: namely, at the stages of production and disposal, which in global terms can significantly affect the result.

The disadvantage of the study is the probability of a sufficiently large error in optimizing the energy system, which is caused by the use of the software package.

Other mathematical methods can be used to calculate the comprehensive indicator in future studies, and it is possible to analyze and discuss more types of power generation systems.

The practical use of the results will contribute to the stability of the hybrid energy supply system, reduce energy costs, and increase the use of alternative and renewable energy sources. The results of the study are intended to provide household consumers with objective and complete information about the impact and effect of the energy project, to strengthen consumer confidence in the use of hydrogen fuel cells, and hydrogen in general.

Further research will aim at finding dependences for the impact of the hydrogen fuel cell in the hybrid energy system in regions with different climatic features.

7. Conclusions

1. The potential of using hydrogen fuel cells analysis was evaluated by using SWOT analysis. The SWOT analysis conducted in this study emphasizes that the implementation of the hydrogen economy crucially depends on the legislative framework and decision-makers in the energy sector. Awareness and interest of final beneficiaries, potential investors, and availability of specialists in the industry also have a significant impact. The main factors influencing the development identified during the analysis are the government's energy and climate policy, hydrogen project financing programs, technology development, the presence of HFC producers in the country's market, and the cost of energy.

It is substantiated that hydrogen is not only a carbon-free fuel but also an energy storage medium for renewable sources. In addition, the feasibility and advantages of the system in Ukraine were examined, combined with meteorological conditions in the area, such as daily solar radiation and wind speed. It is substantiated that hybrid renewable energy supply systems for consumers with energy storage by a hydrogen fuel cell will help reduce energy costs, reduce emissions, and increase the use of alternative and renewable energy sources.

2. Simulation of power supply schemes was carried out. A practical example of application was the selection of an energy supply scheme to meet the needs of a typical administrative building located in the city of Kyiv. Simulation of six types of power generation systems was performed. These are two types of traditional scheme: connection to a common network (scheme 1. 1); connection to a common network in combination with HFC (scheme 1. 2). As well as two alternative schemes: wind (scheme 2. 1) and solar energy (scheme 3. 1). Two types of combination of alternative schemes with the operation of a hydrogen fuel cell (scheme 2. 2 and scheme 3. 2) are also considered.

The analysis was carried out using the HOMER software package. Thus, from an economic point of view, scheme 1. 2 is defined as investment attractive (NPV is UAH 24,123 thousand), as well as scheme 3. 2 (NPV – UAH 20,479 thousand). The least attractive investment is scheme 1. 1. However, the normalized energy cost for scheme 3. 2 is 1.5 times higher than the cost of energy obtained using the circuit system 1. 1. Assessing the environmental sustainability of the schemes, we obtained the following result: virtually zero emissions produced by the equipment used in scheme 3. 2. The most environmentally unstable is scheme 1. 1 with indicators: CO_2 – 2,831.13 kg/year, CO – 403.00 kg/year, and unburned hydrocarbons –159.00 kg/year.

3. A comprehensive economic and environmental assessment of the hybrid energy system using hydrogen fuel cells as a replacement for traditional electricity was carried out.

The proposed hybrid and traditional schemes of energy supply, implemented by modeling long-term realization, are evaluated according to a complex generalized indicator using the method of mathematical normalization. Its application involved the synthesis of the obtained numerical results and bringing the results to a single indicator for the possibility of comparing the effectiveness of the application. The proposed normalized indicator takes into account the weight of independent economic and environmental indicators.

The generalized indicator has no territorial reference, it can be applied all over the world. The study has made it possible to find the ideal configuration that would meet the load needs and be effective from an economic and environmental point of view.

The obtained data showed that the most effective is the system of combining the city network and a hydrogen fuel cell (scheme 1. 2). In this scheme, the HFC acts as a factor in reducing CO_2 emissions at the cost of energy and increases efficiency by 85 % compared to the traditional scheme (scheme 1. 1). Also, the use of HFC generally increases the efficiency of alternative energy supply schemes. It was possible to increase efficiency by 7 % when using HFC in a hybrid wind system (schemes 2. 1 and 2. 2), and by 10 % in a hybrid solar system (schemes 3. 1 and 3. 2).

The simulation results should provide household consumers and the energy sector with information on return on investment, on CO_2 emissions from the energy system under current and future climatic conditions. This can strengthen consumer confidence in the use of hydrogen fuel cells and hydrogen in general. The results of our study illustrate the feasibility and efficiency of using HFC in the energy sector.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

References

1. Shraiber, O. A., Dubrovskyi, V. V., Teslenko, O. I. (2021). Current state and prospects of hydrogen energy development in the world. Scientific notes of Taurida National V.I. Vernadsky University. Series: Technical Sciences, 32 (71 (5)), 199–209. doi: https://doi.org/10.32838/2663-5941/2021.5/30

2. Vodneva stratehiya Ukrainy: proekt (2021). Kyiv, 91. Available at: https://hydrogen.ua/images/about/Vodneva-Strategia-Cover.pdf
3. Su, Z., Ding, S., Gan, Z., Yang, X. (2016). Analysis of a photovoltaic-electrolyser direct-coupling system with a V-trough concentrator. Energy Conversion and Management, 108, 400–410. doi: https://doi.org/10.1016/j.enconman.2015.10.078
4. Ganeshan, I. S., Manikandan, V. V. S., Ram Sundhar, V., Sajiv, R., Shanthi, C., Kottayil, S. K., Ramachandran, T. (2016). Regulated hydrogen production using solar powered electrolyser. International Journal of Hydrogen Energy, 41 (24), 10322–10326. doi: https://doi.org/10.1016/j.ijhydene.2015.05.048
5. Jayalakshmi, N. S. (2019). Study of Hybrid Photovoltaic/Fuel Cell System for Stand-Alone Applications. Current Trends and Future Developments on (Bio-) Membranes, 213–234. doi: https://doi.org/10.1016/b978-0-12-813545-7.00009-x
6. Touili, S., Alami Merrouni, A., El Hassouani, Y., Amrani, A., Rachidi, S. (2020). Analysis of the yield and production cost of large-scale electrolytic hydrogen from different solar technologies and under several Moroccan climate zones. International Journal of Hydrogen Energy, 45 (51), 26785–26799. doi: https://doi.org/10.1016/j.ijhydene.2020.07.118
7. Melzi, B., Kefif, N., El Haj Assad, M., Delnava, H., Hamid, A. (2021). Modelling and Optimal Design of Hybrid Power System Photovoltaic/Solid Oxide Fuel Cell for a Mediterranean City. Energy Engineering, 118 (6), 1767–1781. doi: https://doi.org/10.32604/ee.2021.017270
8. Assaf, J., Shabani, B. (2019). A novel hybrid renewable solar energy solution for continuous heat and power supply to stand-alone-alone applications with ultimate reliability and cost effectiveness. Renewable Energy, 138, 509–520. doi: https://doi.org/10.1016/j.renene.2019.01.099
9. Veremiychuk, Yu. A., Opryshko, V. P., Prytyskach, I. V., Yarmoliuk, O. S. (2020). Optymizatsiya funktsionuvannia intehrovanykh system enerhozabezpechennia spozhyvachiv. Kyiv: Vydavnychyi dim «Kyi», 186. Available at: https://ela.kpi.ua/handle/123456789/36475
10. Curran-Everett, D. (2013). Explorations in statistics: the analysis of ratios and normalized data. Advances in Physiology Education, 37 (3), 213–219. doi: https://doi.org/10.1152/advan.00053.2013
11. Tashcheiev, Y. V., Voitko, S. V., Trofymenko, O. O., Riepkin, O. O., Kudria, T. S. (2020). Global Trends in the Development of Hydrogen Technologies in Industry. Business Inform, 8 (511), 103–114. doi: https://doi.org/10.32983/2222-4459-2020-8-103-114
12. Boichenko S., Kalmykova N. (2020). Benchmarking of efficiency of accumulation and storage of hydrogen as a motor fuel. Science-Based Technologies, 48 (4), 496–512. doi: https://doi.org/10.18372/2310-5461.48.15093
13. Boichenko, S., Tarasiuk, O. (2022). World Practicies and Prospects of Using Hydrogen As a Motor Fuel. 2022 IEEE 8th International Conference on Energy Smart Systems (ESS). doi: https://doi.org/10.1109/ess57819.2022.9969276
14. Boichenko, S., Shkilniuk, I., Tselishchev, O., Matviyi, I., Tarasiuk, O., Jaworski, A., Wos, P. (2022). Modern technologies of hydrogen generation and accumulation. Analytic overview of theoretical and practical experience. POWER ENGINEERING: Economics, Technique, Ecology, 1. doi: https://doi.org/10.20535/1813-5420.1.2022.259125
15. Tulchynska, S., Shevchuk, N., Chornii, V. (2018). Using a methodical approach to the evaluation of attractiveness investment resources for electricity distribution companies. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2, 130–135. doi: https://doi.org/10.29202/nvngu/2018-2/23
16. Bondarenko, I., Dudar, I., Yavorovska, O., Ziuz, O., Boichenko, S., Kuberskyi, I. et al. (2021). Devising the technology for localizing environmental pollution during fires at spontaneous landfills and testing it in the laboratory. Eastern-European Journal of Enterprise Technologies, 6 (10 (114)), 40–48. doi: https://doi.org/10.15587/1729-4061.2021.248252
17. Baikalov, Y., Dzhygyrey, I., Bendiuh, V., Proskurnin, O., Berezenko, K., Boichenko, S. et al. (2022). Improvement of quarry and slagheap reclamation technology. Eastern-European Journal of Enterprise Technologies, 4 (10 (118)), 38–50. doi: https://doi.org/10.15587/1729-4061.2022.263513
18. Loriia, M., Tselishchev, O., Eliseyev, P., Porkuian, O., Hurin, O., Abramova, A., Boichenko, S. (2022). Principles and stages of creation of automatic control systems with a model of complex technological processes. Eastern-European Journal of Enterprise Technologies, 6 (6 (120)), 20–29. doi: https://doi.org/10.15587/1729-4061.2022.270519
19. Bendiuh, V., Markina, L., Matsai, N., Kyrpychova, I., Boichenko, S., Priadko, S. et al. (2023). Integrated method for planning waste management based on the material flow analysis and life cycle assessment. Eastern-European Journal of Enterprise Technologies, 1 (10 (121)), 6–18. doi: https://doi.org/10.15587/1729-4061.2023.273930
20. Boris Sresnevsky Central Geophysical Observatory. Available at: http://cgo-sreznevskyi.kyiv.ua/en/diialnist/klimatolohichna/klimatychni-dani-po-kyievu
21. Pro vstanovlennia «zelenykh» taryfiv na elektrychnu enerhiyu, vyroblenu heneruiuchymy ustanovkamy spozhyvachiv, u tomu chysli enerhetychnykh kooperatyviv, vstanovlena potuzhnist yakykh ne perevyshchuie 150 kVt. Postanova 30.12.2022 No. 1960. Available at: https://zakon.rada.gov.ua/rada/show/v1960874-22#Text
22. Iqbal, A., Arif, M. S. B., Ayob, S. M., Siddiqui, K. (2015). Analysis of a solar PV/battery/DG set-based hybrid system for a typical telecom load: a case study. International Journal of Sustainable Energy, 36 (3), 259–276. doi: https://doi.org/10.1080/14786451.2015.1017497
23. CATERPILLAR. Available at: https://www.caterpillar.com/ru/news/media-information/press-reel.html
24. Ballard: Fuel Cell Solutions. Available at: https://www.ballard.com/fuel-cell-solutions/fuel-cell-power-products/backup-power-systems
25. Heneratory vodniu Proton PEM. Available at: https://www.elkt.com.ua/products/-proton-pem