The optimization technique for a hybrid renewable energy system based on solar-hydrogen generation

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ABSTRACT

This paper provides an in-depth analysis of the challenges associated with the commonly used optimization methods for determining the configuration of hybrid renewable energy systems that rely on solar generation and hydrogen technologies. It highlights the key research directions in this field and includes a brief overview of the number of publications related to the subject. The standard topology employed in the implementation of these studied complexes is clearly defined and described. The paper also presents a comprehensive examination of various modern optimization methods and approaches employed to determine the optimal structure of these complexes. The paper thoroughly discusses the advantages and disadvantages of these methods, while also proposing future development directions that suggest specific adjustments to existing approaches. These adjustments aim to enhance decision-making efficiency and maximize economic benefits. Overall, the paper emphasizes the significance of research in renewable energy sources and hydrogen technologies, underlining their relevance and potential for sustainable energy solutions. In a concise manner, this paper addresses identified problems, highlights research directions, analyzes optimization methods, proposes improvements, and argues for the importance of this research field.

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1. INTRODUCTION

As the global population, industrialization, and urbanization surge, the demand for electricity grows. Yet, meeting this demand poses challenges. Traditional energy sources worsen the environment and deplete resources, hindering the provision of safe and affordable energy [1], [2]. The growth of energy consumption, as well as the population, is exponential, and according to forecasts, by 2050 the year may increase by almost 50% [3]. The course on the combined use of various energy sources, both traditional and renewable, is becoming one of the most important aspects of modern energy in achieving the Sustainable Development Goals, as it directly affects the indicators of resource use and environmental impact. One of the reasons for the emissions of a large amount of greenhouse gases, such as CO_2, SO_2, NO, etc. is the extraction of minerals (natural gas, coal, oil), which account for more than 80% of all primary energy [4], [5]. Figures 1 and 2 show global energy-related CO_2 emissions for 1990-2021 and changes in global CO_2 emissions by fuel type for the same period, respectively.

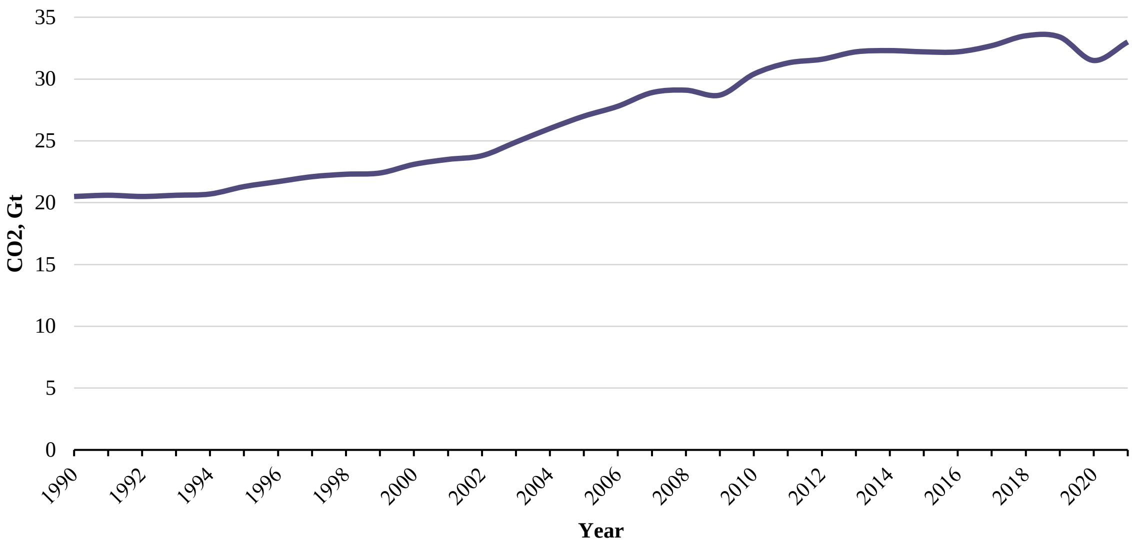

Figure 1. Global energy-related CO_2 emissions from 1990 to 2021 [6]

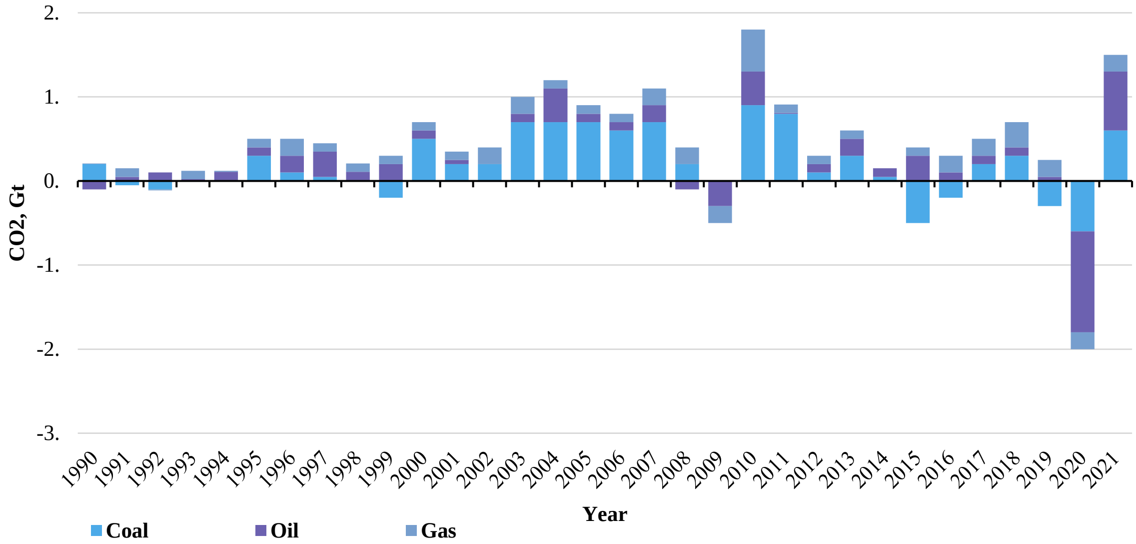

Figure 2. Change in CO_2 emissions by fuel type, 1990-2021 [6]

In 2020, global carbon dioxide emissions decreased from 33.4 Gt in 2019 to 31.5 Gt, or about 6%. This is the largest reduction in CO_2 emissions in the last 30 years, while it is 5 times more than during the global financial crisis of 2009. At the same time, the demand for electricity has not changed so significantly. This is due to the impact of the pandemic: the demand for fossil fuels decreased at that time, and for renewable energy sources increased. The fact is that during this period, the production capacities of the countries were forced to reduce their energy consumption due to the suspension of their activities and the cessation of production, which affected the need for the same amount of energy and raw materials. The recovery of the economies of world countries contributed to the return of demand for coal, oil and gas, therefore, in 2021 there was an increase in CO_2 emissions by 4.8% [7]. Moreover, the burning of fossil fuels is the main reason for the increasing pace of climate change.

According to the International Energy Agency, the growth rate of modern renewable energy infrastructure by 2050 will lead to a 40% reduction in CO_2 emissions compared to 2021 [8], [9]. In this regard, there is a development and spread of low-carbon technologies, which have taken a leading position in the list of priorities to meet global energy needs and reduce greenhouse gas emissions [10]–[12].

Wind and solar energy are the most well-known renewable sources of electricity, and their combinations are used to improve the reliability of energy systems [13]–[15]. We should not forget about other, non-traditional sources of renewable energy, such as biomass, geotherms and tides, which, in general, are more often used to cover basic needs. The problem encountered when using these sources is the unstable and stochastic nature of generation caused by local weather conditions and the geography of the location of the energy facility [16]. Energy storage systems are used to solve this problem [17], [18]. Rechargeable batteries, usually used for storing electricity, have a number of disadvantages, such as low energy density and a decrease in the storage resource over time. These aspects do not allow them to be used on an industrial scale together with renewable energy sources [19]. Therefore, the use of hydrogen as an energy carrier is considered as a new stage in the development of storage technologies in the use of hybrid complexes built on the basis of hydrogen and renewable energy [20], [21].

The widespread use of energy systems based on hydrogen fuel is complicated by the fact that this gas is not available on Earth in free form and in large quantities and it must be obtained from hydrocarbons or water, while expending energy [22]. Approximately 96% of the hydrogen produced is accompanied by significant greenhouse gas emissions due to the use of methods such as steam reforming of methane and natural gas, pyrolysis or coal gasification [23], [24]. On the other hand, hydrogen generation by water electrolysis is an alternative environmentally friendly method of obtaining this gas if the electricity supplied to the electrolyzer was produced by renewable energy sources (RES) [25], [26]. As a result, the use of hydrogen in combination with wind and solar energy can increase the reliability of energy complexes based on renewable energy sources.

Compared to traditional energy sources, hydrogen has a significantly higher energy density [27]–[29]. During periods of surplus of electricity from renewable energy sources, it can be conveniently converted into hydrogen and stored in the accumulation system, without releasing emissions harmful to the environment [30]–[32]. At the same time, when there is a shortage of electricity in the power system, hydrogen enters the fuel cell from the storage system, in which hydrogen molecules decay, and the missing electricity enters the grid. Today, with the development of fuel cell technologies, storage and transportation systems, hydrogen energy is attracting more and more attention of researchers, which means it has prospects for further development. Figure 3 shows a general idea of the structure of hybrid renewable energy systems and hydrogen technologies.

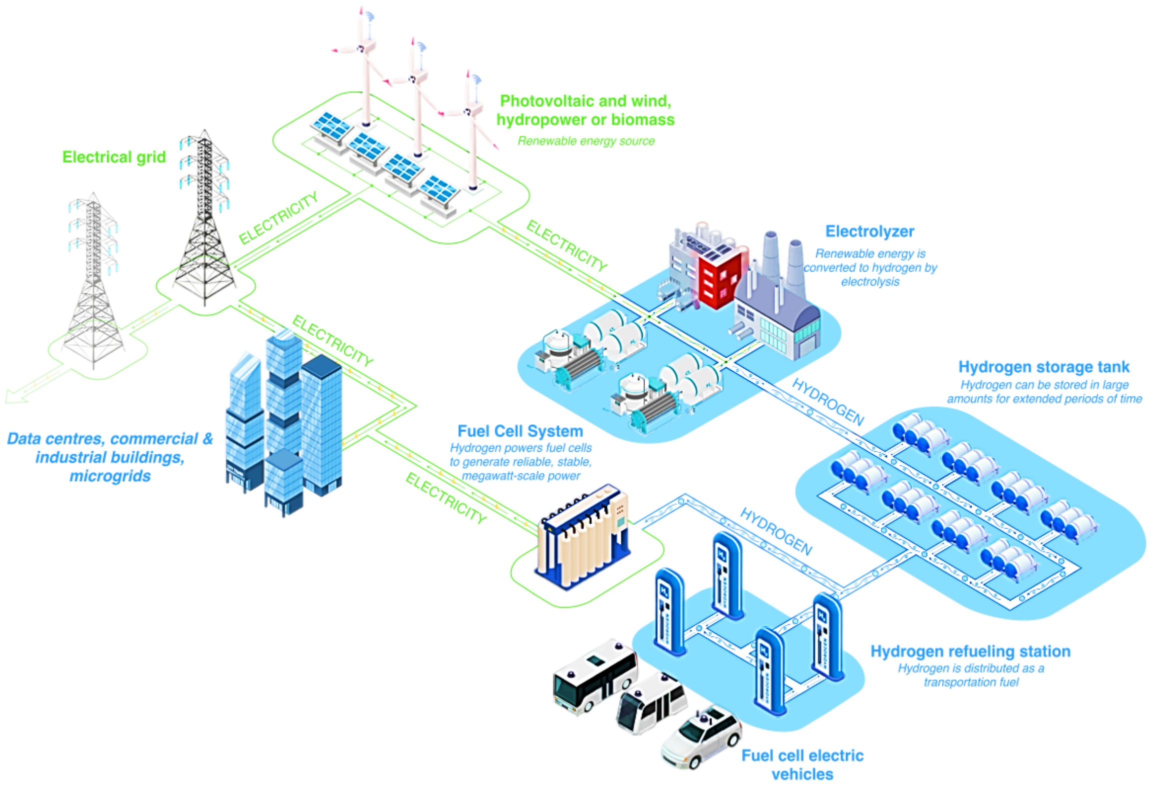

Figure 3. Illustration of a hybrid energy system containing renewable energy sources and hydrogen technologies for energy storage and generation [33]

In addition to the positive qualities inherent in this system, it is also accompanied by a number of disadvantages: significant initial investments, the high cost of operating energy conversion devices throughout their service life, reduced reliability in the event of a transition to autonomous operation and social restrictions. The described disadvantages require careful optimization to supply consumers with electricity at reasonable prices. This procedure is a task of increased complexity due to the fact that in the calculation process it must take into account a lot of factors, such as load schedules, the specifics of the operation of the units used, meteorological data and technological features [34]–[36].

The purpose of the work presented in this article is to analyze the energy feasibility of hybrid solar-hydrogen systems and to research articles related to topics such as choosing the optimal size of hybrid solar-hydrogen systems, analyzing their energy and economic feasibility, and managing the energy accumulated by them. In addition, the paper explores the issues of multi-criteria analysis of performance and optimization of the operating modes of the system from the perspective of increasing energy efficiency, economic benefits, reliability and reducing the negative impact on the environment.

The main source of research literature was the unified abstract and bibliographic database Scopus, which contains journals in various disciplines, including topics of interest to this study. To search for articles, various keywords and phrases related to research topics were used, such as "technical and economic analysis", "solar-hydrogen energy system", "optimization of the size of a hybrid complex", and "optimal management strategy". Literature sources were selected no older than 5-7 years. During the initial search using the generalized phrase "solar-hydrogen hybrid power system" (SHES) in the Scopus database, the number of articles published from 2016 to 2023 numbered about 79 thousand. The bulk of the scientific papers from the sample received were research articles (almost 60 thousand), immediately after them, there were review publications (11 thousand) and book chapters (7 thousand). The remaining number refers to such types of articles as encyclopedic, conference abstracts, summary reports or research announcements, etc. Subsequently, the search was refined with keywords, according to the selected research directions. The statistics obtained from the general and refined search are illustrated in Figure 4.

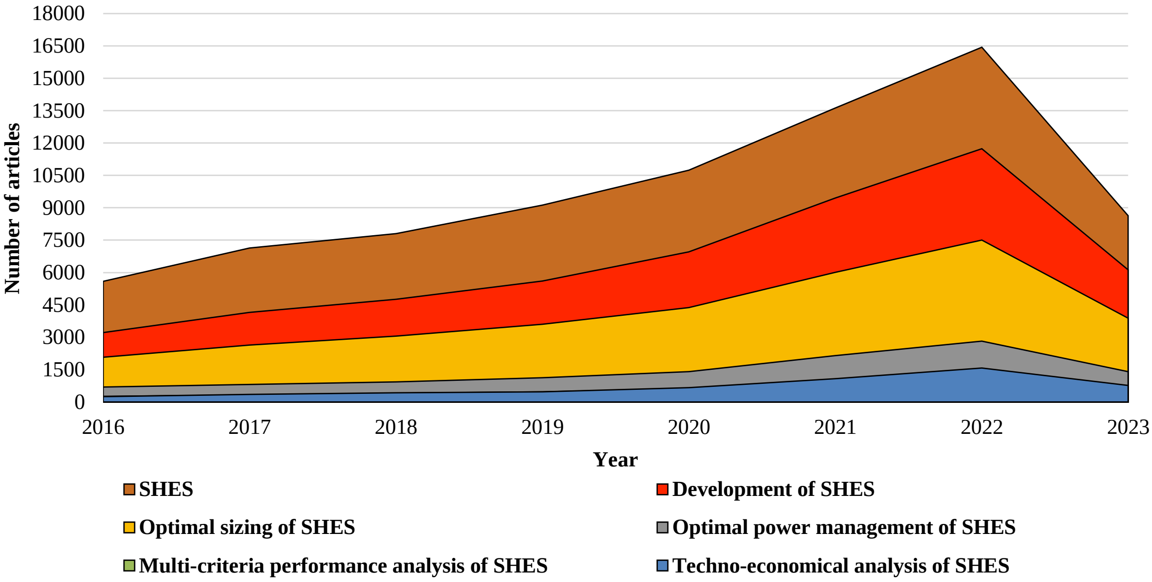

Figure 4. Statistics on the number of articles related to the subject under study and published in leading Scopus journals [compiled by the authors]

The number of publications in the field of hybrid energy systems, encompassing renewable energy and hydrogen storage systems, their management, operational analysis, optimal sizing and capacity calculation, and energy efficiency improvement, has been consistently increasing every year. Since 2016, there has been a significant surge in the number of publications. Notably, in the first quarter of 2023, more articles were published in these areas than throughout the entirety of 2019. This upward trend signifies the ongoing active research and experimental implementation of these power supply systems as alternatives to traditional fuel-based complexes. This active engagement can be observed both in practical research and within scientific circles.

The main volume of scientific works is devoted to the technical and economic analysis of autonomous hybrid photovoltaic systems with hydrogen fuel cells. The main purpose of these works is to optimize the design and further development of dispatching control to provide electricity, as for example in [37], a settlement located in a desert region. To assess the technical and economic implementation of the multigeneration system under consideration [38], [39], consisting of a fuel cell system with a proton exchange membrane, an electrolyzer powered by solar energy, a parabolic grooved photovoltaic collector, a solid oxide fuel cell and a thermal energy storage, the characteristics are calculated under various operating conditions and a multi-criteria analysis of thermodynamic and economic parameters is applied.

The research [40], employs HOMER Pro (Hybrid Optimization of Multiple Energy Resources) software to ascertain the energy complex's parameters, economic viability, and energy characteristics. This software facilitates comprehensive system simulation, parameter optimization based on specific criteria, and sensitivity analysis. Such approaches as Monte Carlo [41], [42] are used as a tool for evaluating a wide range of initial assumptions to determine the key cost factors, key indicators and environmental conditions required for the economic conclusion of the payback of autonomous hydrogen electrolysis using solar panels. The initial assignment of the normalized cost of hydrogen (LCOH), taking into account the insolation of the terrain, allows you to set such an optimality criterion, according to which a photovoltaic system and an electrolyzer are built in the future. There are also scientific works [43] developing the joint production of hydrogen and electricity based on solar energy to provide small settlements. In addition, a combined configuration with RES has been created to provide a continuous supply of the required direct current to a solid oxide electrolyzer. This system is analyzed using exergetic, economic, and exergoeconomical methods to assess its performance and identify areas of increased sensitivity.

The next important direction in the study of hybrid complexes with RES is the management of these systems, including when they are not connected to a centralized power supply and operate autonomously [44]. In this regard, the question arises of finding an effective approach to providing electricity to an autonomous consumer. The stochastic nature of energy generation by photovoltaic panels requires precise determination of the optimal operating point of a hybrid energy system [45], [46]. To solve these problems, the work of [47] describes a dynamic programming strategy for dual-purpose optimization of a hybrid complex consisting of fuel cells, photovoltaic panels, an electrolyzer and energy storage systems in the form of hydrogen fuel and in batteries. The input data in the control system is the output power of photovoltaic cells and the power consumption of the load. Simultaneously, the battery charge status and hydrogen storage levels are monitored, using them as reference parameters for decision-making to prevent excessive discharge or overcharging of both the batteries and hydrogen capacity. Also, taking into account the dynamic characteristics of fuel cells, the instantaneous power change is limited by calculating the output power at the previous time. Then, having received the input signals, the decision-making unit determines the energy distribution strategy within the system.

As mechanisms to ensure efficient operation and prolong the service life of the components included in the complex, especially fuel cells, a reasonable energy management strategy is being developed, which is divided into two types: a strategy of strict rules and based on optimization [48], [49]. The strategy of strict rules determines the specific values of the observed parameters, the change of which near the threshold point leads to frequent switching of modes and disruption of stable operation. Rigid switching of operating modes leads to abrupt changes in operating points and can provoke disruptions in the operation of elements of the hybrid complex. In order to achieve a flexible change in the trigger point of the component, a fuzzy control strategy with an array of undefined rules is being implemented into the energy management system [50]–[52]. Applying the strategies of rules, rigid or even more advanced, flexible, you can count on simplicity and convenience in implementation, but it is important to understand that these methods do not allow you to achieve the optimal order of the system.

Management strategies based on optimization use methods based on metaheuristics, artificial intelligence or forecasting elements in their calculations [53]–[55]. The paper [56] describes an increase in the efficiency of energy system modeling using the TRNSYS (Transient System Simulation Tool) software package by adding optimization solutions in the form of a neural network-genetic algorithm that allows calculating the optimal number of solar panels and wind turbines. The resulting model provides a reduction in the capital costs of installation, the amount of carbon dioxide emissions and the probability of loss of power supply (LPSP).

The advancement of hybrid solar-hydrogen systems aligns with contemporary approaches to constructing, calculating, and optimizing complex structures. Employing state-of-the-art mathematical algorithms for technical and economic analysis, as well as enhancing control systems, holds a crucial role in enhancing energy efficiency and minimizing operational costs. Ultimately, these efforts foster the widespread adoption of renewable energy and hydrogen fuel as sustainable alternatives to conventional resources.

2. RESEARCH METHOD

According to current global trends in the development of renewable energy sources, the use of wind and solar generation is growing, which means that research in the field of building an efficient architecture of energy complexes is relevant today. To do this, a method is used that affects the final value of the total net present value (TNPV), based on the selection of the optimal number of photovoltaic modules and fuel cell batteries, hydrogen fuel storage and electrolyzers. At the same time, the reliability of the system is also important, achieved by reducing such an indicator as the probability of power loss (LPSP).

Thus, the desired objective function looks like this:

$$F = minTNPV(N_{PV}, N_{FC}, N_T, N_{EL}), \quad (1)$$

Where N_{PV} is the number of photovoltaic modules; N_{FC} is the number of fuel cell batteries; N_T is the number of hydrogen fuel tanks; N_{EL} is the number of electrolyzers. The LPSP value is limited to the range [0,1], while if LPSP = 0, then the consumer is fully provided with electricity, and if LPSP = 1, then in this case there is a loss of power supply to the consumer on the side of the combined power system. Figure 5 shows a generalized structure for the construction of hybrid renewable energy systems.

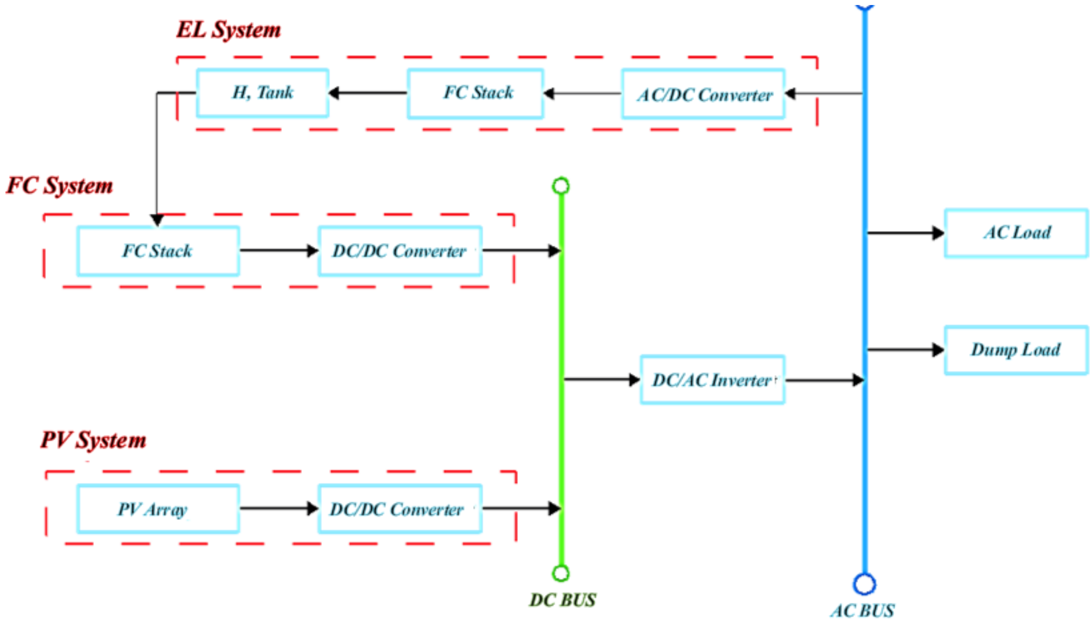

Figure 5. Typical structure of a hybrid renewable energy complex with solar-hydrogen generation [57]

The installation of an AC/DC converter in this system is necessary to ensure the matching of currents received from fuel cells and photovoltaic panels and those required at the load. If the power generated by the photovoltaic installation exceeds the power required on the consumer's side, then electricity begins to flow to the electrolyzer generating hydrogen fuel, in order to then accumulate it in special storage facilities. In the operation scenario, when the power generated by solar panels is not enough to provide the required power on the load, a backup power source is connected. In this case, it is a fuel cell system that uses stored hydrogen to generate electricity.

After defining the main goals and formulating the basic formulas and dependencies, the algorithm for optimizing the construction of a hybrid system is selected. In problems of this type, the result obtained will be the optimal solution from a certain calculated sample of solutions, which either minimizes or, conversely, maximizes the cost function F. The problems encountered in solving optimization problems are complex and confusing. It often takes longer than expected to find the necessary solution or solutions.

A metaheuristic algorithm is used, which is also known as a fractional order algorithm as shown in [58]. A clear advantage of such algorithms is the use of limited space when searching for a solution, which significantly affects the speed of its operation. Metaheuristics is a well-known and powerful class of optimization methods that is capable of solving a wide range of problems from various applications. These algorithms implement a direct random search for possible solutions to problems that are optimal or close to them. To date, there are many varieties of metaheuristic algorithms, among which are the chimpanzee optimization algorithm, the ant lion optimizer, the World Cup algorithm, and neural network optimization.

The peculiarity of the latter is that its operation concept was derived from the workings of the human brain, where a vast number of neurons exchange information through electrical impulses. To implement an artificial neuron, program code is used. The analogue of the main part of the cell is a memory cell, in which a limited range of values is placed. The information coming into the cell contains numbers and formulas. A data transfer model from one neuron to another is also implemented programmatically, while at each iterative step the received information is processed and calculated. In this way, the network is trained- the coefficients inside the cells are adjusted, information is distributed, neurons are exchanged [59].

The work of training can be divided into 4 stages: providing information, transformations, processing and conclusions, results. At the first stage, initial data is entered into the neural network, according to which calculations and reference correct solutions will be carried out. At the second stage, the input neurons receive the initial data, process it and pass it on. The composition of the information is translated into the language of numbers and formulas. At the third stage, the weight coefficients of neurons are adjusted numbers calculated using special algorithms. The "weight" of a neuron determines the importance of its output readings for the system as a whole. It is important to understand that setting the values of the weighting coefficients lies with the neural network itself, as it is part of its training process. At the final stage, the final calculations are converted into a response. Due to the peculiarities of the neural network structure (closeness and instability of neurons) she cannot give an absolutely accurate answer, only to get as close to it as possible.

In order to solve the problems with the approximation of the neural network algorithm responses, the fractional operator (FO) is used in the described work, which is used as an addition to metaheuristic algorithms [60]. The work uses about 100 neurons in the network, and the number of iterations is 200. Ensuring such characteristics of the program gives proper and consistent results. The simulation was run 40 times, after which the average values of the output values were found, which were already taken as reliable.

Other metaheuristic algorithms were also used in the simulation. The use of the modified algorithm of the fractional-order neural network algorithm (FONNA) neural network demonstrates the best results according to the four criteria of the desired objective function, unlike other tested algorithms. Comparisons were made with the arithmetic optimization algorithm (AOA), the World Cup optimization (WCO), the coati optimization algorithm (COA) and the basic neural network algorithm (NNA). The LPSP value was 2.49%. The percentage of electricity generation by photovoltaic panels for the year amounted to 56.3% of the total amount of electricity generated, which indicates its priority in the resulting system. FONNA also demonstrates the best TNPV convergence profile compared to other optimizers.

This article describes a way to find the optimal size of a hybrid renewable energy system based on solar and hydrogen energy. The authors justified using the improved metaheuristic algorithm of the FONNA neural network because they aimed to achieve the best optimization results without resorting to complex mathematical operations and to calculate the model in a relatively short period of time.

Having undeniable advantages, the neural network algorithm has a number of disadvantages, which in some tasks can still limit the use of neural network technologies. In their work, the authors did not compare FONNA with various algorithms such as random search or simulated annealing. This comparison would have revealed the extent to which the metaheuristic algorithm's suboptimal solution deviates from more accurate numerical methods with higher precision. Due to the functioning of the black box principle, the neural network does not allow you to follow the process of solving the optimization problem, which means that there is no way to explain the reason for accepting such an outcome when it is necessary. This imposes restrictions on the developer of the energy system, because otherwise, it would be possible to look into the process of the optimization algorithm and make adjustments. Subsequent developments can be aimed at comparing several types of optimization algorithms for building a solar-hydrogen hybrid renewable energy complex.

Lu *et al.* [61] describes the calculation of the optimal size of a grid-independent hybrid renewable solar-hydrogen energy system to provide electricity to a "green" residential complex. This generation structure is equipped with photovoltaic panels, fuel cell batteries, an electrolyzer and a hydrogen fuel storage system.

The optimization algorithm used — the Improved Particle swarm (IPSO) — designs the final version of the complex in such a way as to reduce the life cycle costs (LCC), while taking into account the limitation on the reliability of the system (RS), implemented in the form of LPSP, as well as other types of technical and economic obstacles. The area of solar panels (A_{pv}) and the storage capacity of hydrogen energy (CHST) were chosen as the target functions in this work.

$$LCC(A_{PV}, C_{HST}) = \sum_{k \in PV,HST,FC,EL,INV} IV_k + OM_k + RP_k, \quad (2)$$

Where IV_k is annual investment costs; $O\&M_k$ is annual operating and maintenance costs; RP_k is annual component replacement costs.

The metaheuristic method used the IPSO algorithm solves the optimization problem by iteratively iterating through a set of probable values. There were 1000 such iterations in this case. This algorithm allows you to get a significant number of possible answers at the output. An improved version of the particle swarm is used to increase the speed of each particle involved in the process and improves the search at the local and global level in each iteration. When modeling a scenario in which RS = 3%, IPSO proposed an LCC value lower than that obtained with the same reliability value, but using PSO. The scenarios were divided into two parts. Half of them implied the implementation of the complex in terms of high reliability (0% ≤ RS ≤ 3%), while the second half contained scenarios with reduced reliability (5% ≤ RS ≤ 15%). According to the obtained optimization results, by reducing the specified reliability of the system, the algorithm reduces the total number of photovoltaic panels and the storage capacity of hydrogen fuel. Thus, the number of system components will be adjusted in order to reduce the overall LCC, but the LPSP will increase at the same time. The authors of the article selected optimal scenarios for the construction of this complex, in which RS takes the value of 1 and 3%, respectively. It is important to note that in scenarios in which reduced reliability was considered, the total power of the solar-hydrogen energy system was less than that of the same, but taking into account RS in a high reliability range. By reducing the number of solar panels and storage capacity, the amount of energy generated will also decrease.

Thus, the authors use a metavehuristic method in the form of an improved particle swarm algorithm to model the optimal size of a grid-independent hybrid solar-hydrogen renewable energy system. This algorithm allows you to identify several ready-made scenarios, according to which the analysis will be carried out further. The disadvantage of this work is the lack of comparison of the results with other modern optimization methods for qualitative analysis and search for the optimal solution among disparate algorithms. As a continuation of the research, the same system can be considered, but with the addition of other energy storage devices, such as a battery and a supercapacitor.

3. RESULTS AND DISCUSSION

As can be seen from the review, there are not so many scientific papers devoted to the optimal construction of hybrid renewable energy complexes; compared with other topics in this area. Published works allow us to determine what successes have already been achieved in this area, what shortcomings still exist and in which direction to develop technologies further [62].

Recently, serious steps have been taken in the field of research and development concerning methods for determining the size of hybrid power complexes. First of all, scientists focus on improving productivity, then on obtaining accurate forecasts and finally ensuring the reliability of power supply and reducing capital investment. Basically, the target optimization functions of such solutions are either economic indicators (LCC, TNPV), or indicators of the reliability of power supply to consumers (LPSP, RS), or the parameters of generating facilities (the area of photovoltaic panels, the storage capacity of hydrogen fuel). However, in the algorithm for optimizing the size of the complex, it is important to take into account the optimal geographical location of the future complex, since the renewable energy sources used in it are extremely sensitive to external conditions. Also, due to the consideration in the optimization algorithm of the size of the complex of load consumption schedules, it becomes possible to optimally dispose of the capacity of storage devices, due to the use of dynamic energy planning.

Most of the studies devoted to size optimization by hybrid energy complexes use metaheuristic methods for calculations, for example, algorithms for optimizing a swarm of particles, finding harmony, simulated annealing, ant colonies, finding food for bacteria, creating an artificial bee family, searching for a cuckoo. These solutions are popular with researchers and are often the only option for optimizing the size of a hybrid complex. In rare cases, in the process of developing a device for a specific object, the results obtained from different algorithms are compared. As a rule, if compared, then the basic version of the current algorithm is taken as an alternative.

It is also worth mentioning the software tools used to optimize the dimensions. Often, software complexes are used not only to find optimal sizes, but also to develop an optimal strategy for managing a hybrid system, since these two directions are interrelated. However, then the research vector will be directed towards the technical and economic analysis of the hybrid energy complex.

Deterministic and stochastic approaches for determining optimal sizes are much less common than those described earlier. Usually, these categories include optimization methods such as the average annual monthly method that determines the size of photovoltaic panels according to the average annual monthly load values or the worst-case month method, in which the calculation is made according to the most unfavorable month for renewable energy sources that are part of the complex. It is noticeable that in these works little attention is paid to the comparison of different approaches to size optimization, which have radically different mechanisms of operation, which is a disadvantage and a ground for subsequent research.

In modern methods of size optimization, one should not neglect safety issues and the assessment of the probability of malfunctions and accidents of equipment included in the projected hybrid complex. To enhance their structure, incorporating predictive analytics elements for forecasting the conditions of electrical machines and semiconductor devices is necessary. This will enable the determination and maintenance of optimal operating modes under specific climatic conditions and loads, ultimately optimizing the life cycle cost (LCC) and extending the repair interval. In addition, a promising area of research is the variation of criteria responsible for the reliability of power supply and the cost of the system. In the quest for the optimal balance between economic benefits and uninterrupted power supply, it is necessary to utilize various reliability criteria and their combinations, including expected load loss (LOLE), expected energy loss (LOEE), probability of power supply loss (LPSP), probability of power failure (DPSP), and probability of load loss (LLP). In the context of economic criteria, one of the few suitable is the life cycle cost (LCC). The LCC analysis consists in calculating the net present value of all expenses that will occur during the entire service life of the system. This usually includes capital costs, operating and maintenance costs, replacement costs, and disposal costs. The interweaving of the described criteria can become a new stage in the development of optimization methods, the compilation of target functions and the improvement of energy efficiency in determining the size of a hybrid solar-hydrogen renewable energy complex.

4. CONCLUSION

In the context of the analysis, scientific works devoted to the processes of development, creation, management and functioning of hybrid renewable energy complexes based on renewable energy sources and hydrogen technologies were studied. The key task of the work was to determine further directions of research in the field of optimizing the size of the hybrid complex. The article describes a number of foreign publications devoted both to hydrogen energy in general and specifically to the optimization of the configuration and structure of the hybrid energy complex. Based on the analysis of existing studies, conclusions were drawn about the main factors taken into account and standard solutions in the field of optimization approaches to the calculation of the components of the complex. During a detailed review of two papers devoted to this topic, specific shortcomings were identified and suggestions were made about further promising areas of research. It is revealed that none of the separately used methods can provide the best work of determining the size of a solar-hydrogen hybrid system, while simultaneously taking into account all the key parameters. However, optimization approaches that use various modern methods of metaheuristic algorithms, artificial intelligence, software, and hardware complexes prove to be more effective than traditionally used solutions due to their ability to search for optima at the local and global levels, achieve acceptable calculation accuracy, and exhibit a higher convergence rate of objective functions. Further development in the field of methods based on natural phenomena, as well as their combination, will be the most important direction in future research aimed at solving complex problems of determining the optimal size of hybrid renewable energy systems.

The development of renewable energy sources and technologies related to them can provide profitable and environmentally friendly solutions to meet electricity needs. Moreover, the intensive pace of development of hydrogen technologies determines the relevance of research in terms of the integrated use of solar, wind and hydrogen generation, as well as the optimization of their construction and collaboration.

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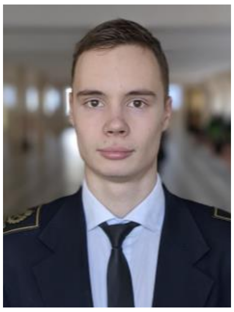

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