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Energy management in hybrid complexes based on wind generation and hydrogen storage

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ABSTRACT

This work is devoted to the analysis of scientific articles in the field of hybrid energy complexes based on hydrogen technologies and renewable energy sources. A special attention is given to wind generation. The review of the topics of scientific publications indexed in the Scopus database in the field of research is carried out, the most frequently encountered topics and the rarest ones are highlighted. Brief statistics about publications selected for detailed analysis are given. The most interesting direction for studying is development of control systems for hybrid energy complexes. Several traditional approaches, which are commonly used in research on this topic and methods are highlighted. The existing shortcomings and inaccuracies in the overviewed works are identified. Conclusions are drawn about the need to transform existing methods and specific proposals are made to improve management systems to increase the efficiency of decision-making and achieve greater economic benefits. Promising areas of research that also require special attention are formulated.

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1. INTRODUCTION

Continuous development of the processes in the global economy require constant investments of tangible and intangible resources. For the normal functioning of any objects related to human activity, large energy amounts are required. In previous years electrical energy production was primarily associated with various types of fossil fuels, such as oil and gas [1]. Nowadays the intensification of production processes and arrearing concerns about the environmental situation have led to the development of unconventional methods of electrical energy production [2]. Among renewable energy sources, wind turbines and photovoltaic panels are the most common. They are widely integrated into the energy systems of many Western countries of the world (more than 20% of the generating facilities of the largest European countries are based on renewable energy), where it is effective due to the climatic characteristics. Hower producing renewable electrical energy does not always turn out to be economically profitable [3] comparing to fossil fuels, especially for Germany rich in coal. However, the global vector of decarbonization of human activity and adherence to sustainable development goals determines the need for "green energy" changes [4]. In addition to the ambiguity of the financial aspects, the use of renewable energy sources has a number of other fundamental features, in particular it is impossible to work at a speed of movement of air masses below

2.5-3.5 m/s for wind turbines, and there may be a lack of energy produced in cloudy weather and at night, speaking about photovoltaic installations [5], [6]. These aspects impose significant restrictions on the implementation of renewable energy facilities. In this regard, with the beginning of the development of "green energy", the beginning of the active development of energy storage technologies capable of solving the problem of the stochastic nature of electricity generation using renewable energy sources (RES) was launched. Widely spread energy storage technologies, which operating principle is based on the interaction of chemical elements and electrochemical processes, are not always fully able to meet the technological requirements imposed on them during creating energy complexes. They are characterized by high cost and great mass, require special care, and also have limitations on the speed of charge and discharge. Thus, as an alternative path to traditional methods of energy storing, it was proposed to use hydrogen fuel as a buffer carrier in hybrid energy complexes [7]. Despite the fact that these technologies are also characterized by a number of shortcomings, researchers are moving towards and work for the industrial implementation of pilot projects based on hydrogen electrolyzers and fuel cells [8]–[10]. In this regard, the topic of hydrogen energy is particularly important today, a large number of studies are devoted to various scientific problems in this area [11], [12].

This paper examines scientific articles on the functioning of hybrid wind-hydrogen energy complexes in order to identify promising areas for new scientific research works [13]–[15]. The list of the highlighted prospective scientific research topics is presented in the "results and discussion" part. Such overview articles lighten the most up-to-date and not cultivated topics for other scientists of different interests. Especially in this work a particular attention is paid to the management systems of hybrid energy complexes and the main methods that are used to form optimal operating modes for them. This problem is quite new for governal energy sector because most of the electrical energy generating plants (both governal and private) use only one type of energy source like coal or gas. Hower as the time goes by more and more private micro-grids using different types of fuels and sources appear to decrease the CO_2-footprint. That is why it is important to create modern management systems for modern electrical plants. In this research the main methods, often used criterions and basic optimization models are defined and presented as a table. This data and it’s every aspect is a kind of a field for new research works. The existing shortcomings and barriers for industrial implementation of energy-management systems need to be highlighted for future research works and this is the goal of this article.

A significant volume of publications is devoted to the feasibility study of the location of hybrid complexes in various conditions on specific examples of cities and industrial facilities. The articles provide an analysis of fuel sales markets and promising supply chains [16], compare the use of a hydrogen energy storage system with other technology options [17], [18], consider the prospects for the location of energy clusters in areas with a harsh northern climate [19], assess the competitiveness and forecast the potential of hydrogen complexes using various criteria such as, as LCOH and LCOE [20], [21]. These studies are mainly analytical and theoretical, they make general calculations, and the results of computer economic modeling are presented. However, there are also works with implemented projects for which the calculation of estimated indicators is carried out on a real industrial complexes [17]. The most important issue in the design of energy complexes is the determination of the parameters of individual objects and their mutual position. Determining the optimal composition of installations in terms of energy efficiency and financial benefits is a priority task [22]. Enough works by foreign researchers are devoted to this topic. In these researches the characteristics of existing power plants for which it is possible to connect hydrogen storage systems are considered in detail [23]–[29]. Researchers have developed various algorithms that allow to create a project of the optimal structure of an energy facility, depending on the target indicators [30]–[32]. Such algorithms, as a rule, are based on machine learning technologies, they also use the principles of fuzzy logic and predictive analytics [33]. In some studies, not only wind turbines, but also their mixture with photovoltaic panels is considered as energy source [34], and combinations of hydrogen technologies and lithium-ion batteries are considered as storage systems [18]. Due to the complexity of the operation of such systems in conjunction with integrated energy systems, they are often considered as objects of distributed generation and as part of microgrids [33]. Evaluation of the quality of computational decision-making algorithms is carried out by determining economic indicators (including LCOH) [35].

Technologies of floating (offshore) power plants are actively developing all over the world. In some regions, the conversion of wind energy is effective only in such conditions. In this regard, a large number of studies are devoted to analyzing the structures of floating hybrid complexes, considering options for the location of energy storage systems in the form of hydrogen installations and their comparative analysis [36], [37], assessing the impact of hybrid offshore complexes on tariff formation and the cost of electricity in the supply region [38], analyzing the efficiency of hydrogen fuel production using floating systems [39], changing the electricity generation schedules of existing offshore platforms using hydrogen technologies

[40]. Research on this topic is actively conducted by authors from China, as well as from Europe, and South America.

Hydrogen-fueled transport first appeared in Asian countries, such as China and Japan. Nowadays there is a number of models operating in hybrid mode including electric motors on the market of automobile and passenger transport. The issue of providing these vehicles with the necessary urban infrastructure becomes important at the stage of industrial implementation. Many publications on the topic are devoted to the development of the structure of fueling stations for hydrogen-fueled motor transport. They consider various options for fuel production plants [41], alternative ways of installing wind turbines for hydrogen production in the immediate vicinity of gas stations [42], as well as specific issues of joining such energy complexes to the unified energy system of the region [43].

The most important indicator of the development of any technology is its gradual cheapening. The reduction of cost demonstrates an increase in accessibility and the acquisition of mass properties. Appropriate research is being conducted to reduce the cost of technologies. In the structure of hybrid energy complexes, the most expensive equipment is an electrolyzer unit. As part of the review, the works devoted to improving the structure of electrolyzer plants, simplifying the components [44], [45], as well as the creation of "bidirectional" plants operating both in the mode of hydrogen fuel production and in the mode of reverse conversion–electricity generation [46] were highlighted.

A similar review of current research directions was conducted by a group of authors earlier, about a year ago, it is worth noting that a greater number of studies have appeared in the areas of modeling hybrid energy complexes in various software [47], there have been works devoted to algorithms for integrated intelligent control of wind-hydrogen systems [47], [48]. However, there is still an insufficient amount of work devoted to the safety of hybrid complexes [49], the development of predictive analytics algorithms for predicting electricity and hydrogen fuel consumption, as well as their production [42], [50], [51]. As a general problem, many scientists note the low degree of practical applicability of many studies that are exclusively theoretical and virtual. There is an acute shortage of competitive works supported by practical experience [52].

2. METHOD

The systematic development of renewable energy technologies and their widespread introduction into power systems, as well as the development of hydrogen energy technologies in the long term will lead to the creation of new hybrid energy complexes, so now it is necessary to conduct research to ensure the effective implementation of future projects. As part of the preparation of this review, about sixty articles were analyzed, their selection was carried out from scientific articles indexed in the Scopus database, according to the keywords "hydrogen", "energy", "wind", released not earlier than 2020 and to the present (Figure 1). About sixteen thousand articles were presented in the primary sample. The next step was a more detailed sorting, performed by adding a list of keywords (with such words as "management", "control system"), which allowed to narrow the field of view to one and a half thousand sources on the topic of a scientific article. Further, the selection of articles was carried out based on the method of expert assessment of compliance with the declared topic. The selection of current years for the analysis of sources was made based on the number of published articles (the years with the largest volume of published works were considered–more than 1000 publications).

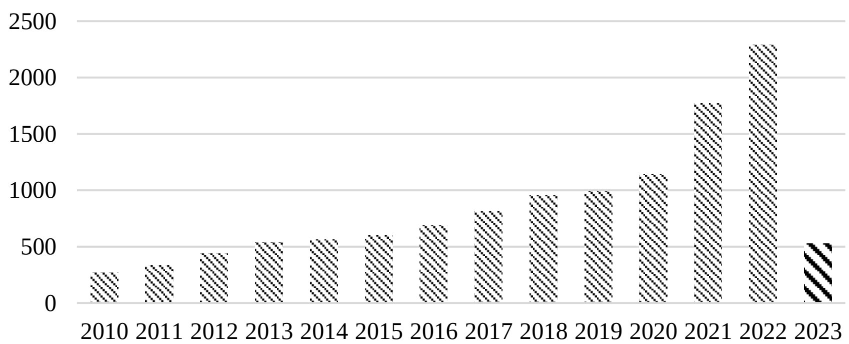

Figure 1. Statistics on the number of publications indexed in the Scopus database by year based on the search for the listed keywords

As part of the enlarged analysis of scientific articles, a list of thematic areas for all publications was defined. All articles generally devoted to the topic of hybrid wind-hydrogen energy complexes were further divided into narrower sections, the names of which are shown in Figure 2. As can be seen from the diagram (Figure 2), the largest number of selected sources are devoted to the feasibility study of hybrid complexes, technologies of hydrogen transport and fuel production, development of offshore complexes and management of power plants. It should be noted that "management" means both the development of algorithms for managing technological processes within complex systems, and the coordination of work in terms of interaction with the energy system of the region. In the next paragraphs, this direction is reviewed in more detail.

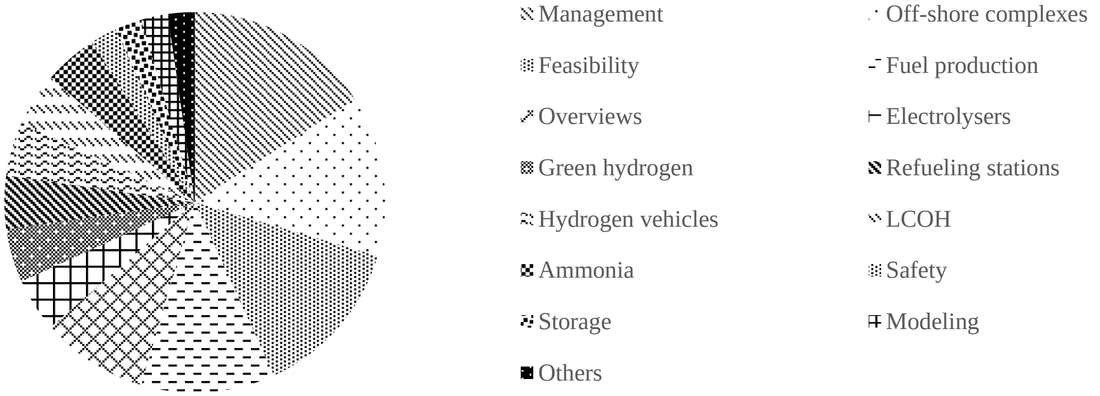

Figure 2. The structure of the analyzed articles

The basic articles outlined on the topic of energy-management systems were further analysed and compared following the list of important indicators, defined as the most often mentioned ones in the papers. The results of comparison are presented in the next section. Based on them the most prospective potentially improvable points for next research works were identified and presented in the end of the discussion-section.

3. RESULTS AND DISCUSSION

The normal functioning of complex systems, including generation facilities, energy storage and conversion systems, as well as consumers, is impossible without effective management [53]. The construction of algorithms for the operation of hybrid energy complexes generally comes to the definition of a "plan" or "schedule" for the sequential operation of installations, only approaches to determining this schedule differ, as well as mechanisms for developing an optimal solution from the point of view of a particular task. Significant difficulties in the construction of such algorithms appear when it comes to determining important variables and the degree of their influence on the development of a sequence of actions within the control system. Moreover, many variables at the time of design may be of an indefinite nature (as a rule, these are parameters related to legislative regulatory mechanisms), and there are also those variables that change dynamically.

In the work of hybrid complexes, the first step is to determine the basic task, which at the same time is a kind of "optimality criterion", under which the control system adjusts the developed schedule. Such a task may be formulated as maximum monetary benefit from the sale of produced hydrogen fuel during the hours of excess electricity or from the sale of electricity to the grid. In addition to economic tasks, technical tasks can be pursued, for example, increasing the stability of the power system and ensuring the reliability of its operation by leveling the risks of reducing electricity production during periods of windless weather. At the same time the tasks may also be of an environmental nature. In modern research works, technological solutions that allow working with only one "optimality criterion" are more common, other positive effects from the implementation of management system are understood as concomitant and are not initially considered as targeted. Although there are methods in modern mathematics that allow solving multi-criteria optimization problems, the concept of a multi-criteria objective function may be formulated in this way:

$$f(\vec{x})=\{f_1(\vec{x}), f_2(\vec{x}),\ldots, f_n(\vec{x})\} \rightarrow \max(\min), \vec{x} \in X \quad (1)$$

where:
$f(\vec{x})$: multi-criteria objective function;
$f_n(\vec{x})$: objective vector-function;
$\vec{x}$: a valid solution in the field of X.

An equally important point is the definition of the main restrictions imposed on the operation of the system, such may be the maximum possible amount of stored energy or, considering hydrogen fuel, the limiting rate of fuel conversion or discharge of the storage system. After determining the key tasks and basic constraints, the algorithm of the hybrid energy complex control system is developed and the main methods for this purpose are selected. Now methods of fuzzy logic, predictive modeling based on statistical data for various periods of the system's operation, heuristic, and metaheuristic methods, as well as methods based on a combination of the mentioned are used (Table 1).

Table 1. Basic one-to-one steps of creating energy-management system

Step no	Name of a step	Examples
1	Formulation of the optimization criterion (goal)	"Maximization of equipment lifetime", "Minimization of CO_2-footprint produced", "Maximization of savings benefit from optimisation", "Maximization of energy-efficiency level", "Maximization of commercial benefit from selling the additional electricity produced"
2	Best mathematical optimization-criterion equivalents selection	Loss of power supply probability (LPSP) Levelized cost of energy (LCOE) Levelized cost of storage (LCOS) Levelized cost of hydrogen (LCOH) Loss of load expectation (LOLE) Deficiency of power supply probability (DPSP)
3	Constraints determining	Nominal voltage level, Nominal system current, Nominal power of the generating system, Hydrogen tank sizes
4	System design restrictions determining	Maximal hydrogen electrolyser performance, Maximal storage system capacity, Maximal hydrogen tank fuel level
5	Choosing the type of optimisation	Multi-criteria Mono-criteria
6	Choosing the algorithmic method (s)	Heuristic Metaheuristic Deterministic Programmatic Stochastic Combined
7	Creating the program for energy management system	

The algorithms of the hybrid energy complex are formulated using the Markov method of optimal decision–making [54]. It is a complex mathematical instrument based on probability theory. The main technical means to produce mathematical calculations is dynamic programming. The novelty of this study lies in the deep integration of the market processes of sale and purchase of electricity and hydrogen fuel. The most important feature of such a technological solution is its focus on achieving maximum profit from the sale of electricity and hydrogen fuel. This does not mean that it is impossible to use such a method when formulating other tasks, but significant transformations of the computational model are necessary to achieve them. This method allows to cover many parameters related to both the environmental conditions and the internal characteristics of the system, but the high computational complexity affects the time required to obtain an optimal solution. Further research may be aimed at expanding the decision-making areas within a single system.

The work [55] is devoted to the complex development of an energy supply system for buildings that consume electricity for heating and household needs. The energy complex management system operates on the basis of a table of formulated rules and further the solutions produced are optimized using the gray wolf method. Neural nets are integrated into the control system, contributing to the adoption of the most appropriate decisions during the operation of the complex. The most important effect achieved through optimized management is a significant reduction in carbon dioxide emissions. The disadvantage of the work is the lack of algorithms for forecasting demand and electricity production, the same direction may be promising for continuing research on the topic.

The study [56] is devoted to the development of an algorithm for planning the operation of a complex hybrid complex, which includes, in addition to the main energy infrastructure, such consumers as hydrogen refueling station, heating system for an industrial facility, as well as a charging station for electric vehicles. In the work, a genetic algorithm is used to create a plan, the essence of which is to find the optimal solution from the probable by means of a combination of possible values of the output parameters of the system specified in the objective function. In (2) has a generalized form:

$$f\,(\text{control variables}) = P_e\left(D_{con} - D_{gen}\right) - D_{hp}P_h, \tag{2}$$

where:
P_e: electricity cost;
P_h: hydrogen fuel cost;
D_{con}: electricity consumption;
D_{gen}: the amount of electricity generated and sold on the market;
D_{hp}: the amount of hydrogen fuel produced and sold to the network.

However, this formula can be supplemented with a variable expressed in monetary terms that determines the operating costs of technological equipment:

$$f\,(\text{control variables}) = P_e\left(D_{con} - D_{gen}\right) - D_{hp}P_h + D_{exp} \tag{3}$$

where D_{exp} is operating costs.

To introduce these variables, it is previously required to develop complex models of the main components of power equipment (in particular, electric machines, as well as energy storage systems using ansys motor cad software), which allow using predictive analytics algorithms to form optimal modes of their operation to increase the service life and the repair interval. The introduction of this variable certainly increases the computational complexity of the operating system, but at the same time improves the efficiency of determining the economic effect and the depth of study of the proposed solutions. Moreover, the most labor-intensive stage in the process of modernization of the control system is the stage of model development. The further work is usually automated with sensors and devices that transmit signals directly from the working units, the control system only receives specific data on the estimated residual resource of the units. The choice of the most suitable working mode for integration into the schedule of the energy complex will be carried out based on determining the optimal value of operating costs in the process of solving the optimization problem for the objective function.

The computing part of the operating system proposed in this article begins its work in the last 10 minutes of the previous day, calculating the optimal functioning plan for the day ahead. Data collection algorithms are constantly working to quickly transfer data from the previous day to the computing part. The control system allows to reduce the cost of electricity for own needs, as well as to smooth out the stochastic schedule of electricity production. The key idea of the study is the possibility of applying such a planning scheme in systems with many different energy consumers. The research has been confirmed by practical tests at a laboratory test site. The solution requires significant computing power, while before technical application it is necessary to develop models of all industrial assets included in the power system and modeling the values of individual variables using predictive analytics mechanisms. Thus, the development of new control algorithms for hybrid energy complexes, as well as the improvement and expansion of the possibilities of using existing ones, remains an urgent area of research.

The number of publications devoted to control systems of hybrid energy complexes is not large. Existing works make a significant contribution to the development of this area [57]–[60]. However, they are characterized by certain shortcomings and represent a field for new research (Table 2).

When designing control systems and developing computational algorithms, the variables and factors considered play an important role. Most researchers in their works strive to cover as many aspects as possible to achieve the universality of the programs being developed. However, it should be mentioned that the unique structures of energy complexes, their geographical and geopolitical location, the situation on the fuel market significantly change not only the input data, but also should influence the implemented approaches to computing and decision-making processes. Moreover, none of the articles paid enough attention to justifying the averaging intervals for energy consumption and generation charts. Taking the too short may lead to the decrease of computational efficiency of the system and taking them too long may lead to missing peaks of consumption. These all may lead to uncertainties in the operation of energy-management system.

Still, many research works devoted to the development of control algorithms for hybrid energy complexes use the mathematical instruments of the optimization problem for one criterion. However, there are methods that allow solving a multi-purpose problem, looking for the most advantageous compromise solution from several points of view. In addition to monetary benefits, it is worth paying attention to reducing the impact on the environment and the reliability of the system and its parts.

Table 2. Energy management systems comparison through literature review

No	Name of strategy	Type of algorithm	Optimisation function	Prediction function	Performance	Type of consumer	Literature number
1	Dynamic programming (based on probability theory)	Marcov method of optimal decision-making	Maximum profit from the sale of electricity and hydrogen fuel	+	-	Industrial facility	[54]
2	Neural nets (using table of formulated rules)	Grey-wolves method	Reduction in carbon dioxide emissions, maximum energy efficiency (multi)	-	-	House-hold	[48], [55]
3	Heuristic algorithm	Genetic algorithm	Minimum operational costs	+	10 mins	Industrial facility	[56]
4	Model predictive control based on mixed-integer quadratic programming (MIQP)	Cutting plane, branch, bound algorithm	Maximum lifespan, cost efficiency and power sold (multi)	+	-	Industrial facility	[61]
5	Stochastic model predictive control	Scenario-based stochastic programming, gurobi optimizer	Minimum energy exchanged with the grid, minimum operation and maintenance costs, and minimum uncertainties of the forecast loads (multi)	+	Less then 1 min	Industrial facility	[62]
6	Fuzzy logic	Particle swarm optimization, rule-based optimization	Minimum operational and maintenance costs, minimum loss of power supply probability (LPSP) (multi)	-	-	Industrial facility	[63]
7	Rolling optimization-based strategy	Rolling optimization	Maximum hydrogen production	-	Works simultaneously with the process	Industrial facility	[64]
8	Multi-level model predictive control	Long-term sequential optimization, gurobi optimizer	Maximum benefit, minimum penalty and operational cost (multi)	+	-	Industrial facility	[65]
9	Model predictive controller	Mixed logic dynamics	Minimum operational cost, maximum benefit and satisfying system requirements (multi)	-	-	Industrial facility	[66]
10	Energy-management system	Biogeography-based optimization	Minimum equivalent hydrogen consumption, maximum equivalent hydrogen production (multi)	-	-	Micro-grid	[67]
11	RL-DQN energy management (neural net)	Deep Q network algorithm, reinforcement learning	Minimum operational cost	-	-	House-hold	[68]
12	Scenario-based modeling	Mixed-integer non-linear program	Maximum sustainability-weighted return-on-investment metric (SWROIM)	-	-	Micro-grid	[69]
13	Risk aware day-ahead planning	Risk neutral optimisation	Minimum operational cost	-	-	Zero-energy hub	[70]
14	Rule-based heuristic system	Digital twin optimizer	Minimum annual cost	+	-	Micro-grid	[71]
15	Multi-period stochastic decision system	Markov decision process, deep Q net algorithm	Minimum annual cost	-	-	Micro-grid	[72]

Only several works paid enough attention to the topic of the performance of the energy-management systems. However, this aspect and the computing power required for the normal operation of the presented algorithms are very significant for reproducing the control system physically. Most of the neural nets and optimization functions can not operate fast enough for nowadays industrial implementation.

A few studies in management models pay sufficient attention to the issues of reliable power supply from the point of view of the technical condition of the equipment, which changes significantly as the service lifetime increases. Safety issues and assessment of the probability of accidents and failures of power equipment included in the hybrid complex should not be neglected. It is possible to include elements of predictive analytics in the structure of control systems to monitor the condition of electric machines operating as part of hybrid complex generation plants to determine and maintain optimal operating modes to increase the repair interval and reduce operating costs.

With the development of hydrogen energy, there will be an increase in the infrastructure for organizing the supply of hydrogen fuel, respectively, there will be an increase in demand for this resource and an increase in its availability. This gas is used not only in the field of energy, but also in other industries. It is necessary to develop methods for managing demand for hydrogen fuel and other secondary products like ammonia like electricity demand management technologies. Implementation of predictive algorithms for forecasting of load demands may increase the effectiveness for all the existing control systems.

To implement individual approaches for optimizing solutions, significant computing power and time are required, as well as expert testing at the initial stages of industrial implementation. Not all studies are confirmed by experimental work. The directions listed in Table 3 are promising for the continuation of research on the selected topic.

Table 3. Prospective topics for future research on energy-management systems

No	General name of a topic
1	Creating a universal method for choosing the optimization algorithm
2	Enriching the existing, combining the existing and creating new optimization algorithms more accurate from the mathematical point of view
3	Implementation of constructive criterions into optimization parameters to prolong the lifetime of technological equipment
4	Setting the energy efficiency and electricity supply reliability as a goal for optimization algorithm
5	Implementation of methods of forecasting and predictive analytics into management systems
6	Development of multi-criteria optimization compromise energy management system
7	Shortening the time of optimization producing
8	Development of demand response systems considering hydrogen fuel as a source of energy

4. CONCLUSION

Within the framework of the review, studies related to the processes of development, creation and operation of hybrid energy complexes based on hydrogen technologies and renewable energy sources were considered. The main purpose of the study was to identify promising areas for conducting scientific work in the direction of managing hybrid energy complexes. An analysis of a large number of studies was carried out, based on it conclusions were produced about the main factors considered and basic approaches to the design of control and monitoring systems for energy complexes.

On the example of the considered works, specific shortcomings, and new points of growth for continuing research are identified. Finally, future directions are formulated: predictive analytics implementation, computational time decreasing and new variables considering equipment state including. The dynamics of the development of hydrogen energy technologies determines the relevance of these research areas. Conducting research on optimizing the operation of energy complexes is an investment into an energy efficient and high-tech future.

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