Modeling and research of power supply systems with renewable energy sources and hydrogen fuel cells

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Abstract. Currently, the creation of environmentally friendly energy systems, including only renewable energy sources, is an urgent task. In this paper, such an autonomous power supply system (microgrid) for isolated consumers is investigated. It includes photovoltaic converters, wind turbines, an electrolyzer, fuel cells, electrical energy and hydrogen storage. For its study, an original optimization mathematical model was used. The optimal structure of the system and its operation modes are determined according to the criterion of minimum total discounted costs, taking into account energy balances and a number of additional conditions and constraints. It is shown that the use of energy sources of various types and energy storage devices makes it possible to smooth out the uneven generation of solar and wind power plants. It has been established that it is expedient to use electric batteries for short-term, and hydrogen accumulators – for long-term energy storage.

1. Introduction

In recent years, global climate change has become a critical and urgent problem. A number of publications state that measures to prevent climate change are currently urgent, since the consequences of such a change may turn out to be worse than previously expected [1]. It has been found that even a stabilization of the concentration of greenhouse gases will lead to continued warming, and therefore it is necessary to drastically reduce CO₂ emissions associated with the combustion of fossil fuels. One of the most effective ways to solve this problem is the large-scale use of renewable energy sources (RES) and environmentally friendly energy carriers such as hydrogen [2-6]. The technologies developed to date make it possible to create power systems with a 100% share of RES [4-8].

In 2020, the installed capacity of photovoltaic converters (PV) in the world reached 760 GW, wind turbines (WT) – 743 GW [9] (figure 1). Over the second decade of the 21st century, the installed capacity of wind power plants (WPP) increased by almost 3.7 times (an average growth rate of 14%), and solar power plants (SPP) by 19 times (34% per year). In total, renewable energy sources generate about 29% of the world's electricity [10].

The world leaders in the use of RES are the countries of Northeast Asia, especially China (more than a third of the installed capacity of solar and wind power plants) (table 1) [9-10].
Some types of renewable energy sources (hydropower, geothermal power and bioenergy) can provide a reliable supply of electricity seasonally or all year round, but their use is limited and depends on the location. Solar and wind energy have huge resources but lack reliability due to their volatile nature. In this regard, it is advisable to create hybrid energy systems that combine energy sources of different types, as well as energy accumulation and storage systems [4;7;11–14].

2. Materials and methods
In this paper, we study an autonomous power supply system, including photovoltaic converters, wind turbines, an electrolyzer, fuel cells, electric energy and hydrogen storage devices (figure 2).

![Figure 2. Power supply system: PV – photovoltaic modules, WT – wind turbines (with AC/DC converters), INV – inverter, BAT – batteries (with charge controllers), EL – electrolyzer, HT – hydrogen tank, FC – fuel cells.](image)
The REM-2 mathematical model [15] based on the GAMS (General Algebraic Modeling System) [16] optimization algorithms was used for calculations. The model determines the system structure (installed capacities) and operating modes (energy flows between system elements depending on time). To model the system, the problem of mathematical programming is solved - the search for a minimum cost, taking into account energy balances and a number of constraints. The production of PV and WT varies depending on the intensity of solar radiation and wind speed set for each hour of the day and four seasons of the year.

3. Results and Discussion
Input data. The technical and economic indicators of the system elements correspond to the data published in [17–20]. Specific investments ($/kW): PV – 1200, WT – 1800, electrolyzer – 1000, FC – 1200, inverter – 220, battery – 150; hydrogen tank – 25 $/kWh.

The area with the arrival of solar radiation of 1300 kWh/m² and the average long-term wind speed of 5 m/s is considered. These conditions approximately correspond to some areas of Southern Siberia, for example, the coast of Lake Baikal. The maximum electrical load is 1 MW.

As a result of solving the problem, the optimal structure of the power system was found, which includes all the shown in figure 2 elements. This means that the most effective is the simultaneous use of renewable energy sources of different types that complement each other, as well as energy storages. Figures 3a and 3b show the dynamics of energy production, consumption, and storage for winter and summer days.

![Figure 3. Energy flows on winter day (a) and on summer day (b).](image-url)
On winter day, the production of electricity by PV is minimal, and the generation of WT varies significantly with time (figure 3a). At some moments in time, the generation of WT is excessive to supply the load, at others it is insufficient. With a lack of energy production, the batteries are discharged, and the discharge power may exceed the load consumption. In this case, electricity is supplied simultaneously to the load and to the electrolyzer to produce hydrogen and fill the hydrogen tank. Excess electricity from WT is partly used to charge the batteries and partly to produce hydrogen. Most of the day, hydrogen accumulates in the hydrogen tank, except for a short period of time when the combined production of PV and WT is insufficient to supply the load. Thus, the batteries are used for short-term, and the hydrogen tank for long-term energy storage.

In summer, the PV production increases during the daytime (figure 3b). The production of WT is less than on a winter day, and therefore the electrolyzer produces hydrogen for only one hour. Batteries charge and discharge over the course of a day. During a period of simultaneous decrease in solar and wind activity and when the batteries are discharged, fuel cells are switched on, consuming previously accumulated hydrogen.

According to the calculation results, WT are the most efficient energy source, they produce the largest amount of energy. PV successfully complement them (especially in summer). The batteries compensate for the uneven generation of renewable energy, it are charged and discharged for several hours within one day. The accumulation of hydrogen in a hydrogen tank proves to be beneficial over a longer period.

4. Conclusion
In the present work, an autonomous power supply system (microgrid) based on wind and solar energy is investigated. The system includes photovoltaic converters, wind turbines, an electrolyzer, fuel cells, as well as electric energy storage and a hydrogen production and storage subsystem.

To model the system, an optimization mathematical model based on GAMS (General Algebraic Modeling System) was used. The model determines the optimal installed capacity of energy sources, the capacity of electric energy and hydrogen accumulators and their operating modes.

It is shown that the simultaneous use of renewable energy sources of different types that complement each other, as well as storage of electricity and hydrogen, is cost-effective. The dynamics of production, consumption and accumulation of energy has been studied. According to the calculations results, in the optimal mode of operation, electric batteries are used for short-term, and hydrogen tank – for long-term accumulation of energy.

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