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Efficiency Assessment of Renewable Energy Sources

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Abstract A review of the methods and models used at the ESI SB RAS to assess the effectiveness of renewable energy sources (RES) was carried out. Criteria were formulated and calculation formulas were given for a preliminary assessment of the competitiveness of renewable energy sources as compared to alternative energy supply options. A mathematical model of the world energy system was considered, where renewable energy sources were described by averaged indicators. The model allows for different scenarios of external conditions to explore the prospects for the development of energy technologies, including renewable energy sources. For the analysis of autonomous energy systems with RES, a simulation model was developed so as to treat the processes of production, consumption, and energy storage in their dynamics. The optimization version of the mathematical model eliminates the need for a pre-assignment of the energy flow control algorithm. In this case, it is possible to study systems with the simultaneous presence of several units of energy storage of various types. For the study of renewable energy sources under market conditions, a model was developed so as to take into account the presence of various decision-making hubs, as well as the impact of governmental regulatory bodies in the market. It was shown that the most efficient mechanism for encouraging the development of renewable energy sources is the creation of a market for "green certificates", with the least efficient renewable energy sources to be subsidized.

1 Introduction

Nowadays, industrialized countries are paying increasingly more attention to the transition to environmentally friendly and resource-saving energy systems. This transition takes place through the development and implementation of new energy technologies such as renewable energy sources (hereinafter referred to as RES) [1].

When developing RES, along with the study of physical processes that take place in energy units, their design and control over scheduling them, it is required to evaluate and justify their efficiency against competing options of energy supply. Efficiency assessment of RES is based on mathematical modeling made up of the following stages:

- Assessment of the potential of renewable natural resources;
- Calculation of energy flows (production, consumption, storage) in energy systems that make use of RES;
- Selection of criteria to compare the performance of available energy supply options;
- Identification of optimal and rational options;
- Evaluation of the efficiency of the market with RES in terms of renewable energy sources optimizing measures to foster their development.

In addressing the above challenges, it is important to account for links of various types of energy sources, storage, and consumers between each other and the environment. Thus, the methods behind the research of energy systems that feature renewable energy sources should be based on the systems approach methodology [2]. At the Melentiev Energy Systems Institute SB RAS, to assess efficiency of renewable energy sources we make use of well-established methods and mathematical models and have developed new ones. This paper provides a brief overview of these methods and models and the findings obtained therefrom.

2 Economic performance of the RES investment project

Development and subsequent operation of renewable energy sources can be treated as an investment project so as to valuate it by applying conventional methods [3, 4]. The investment project evaluation criterion is its Net Present Value (NPV). The project is also described by such indicators as the payback period, the internal rate of return, profitability, etc. However, it is only the NPV that serves as the criterion, i.e. the performance indicator that should be used to rank projects. Relying on other indicators can lead to errors (inconsistent decisions) [3].

If the NPV is non-negative, then participating in the project is preferable to rejecting it; the project with the maximum NPV should be ranked highest among several competing projects. The formula for calculating the NPV is as follows:

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$$\hat{E} = \sum_t (R_t - Z_t)(1+d)^{-t} \quad (1)$$

where R_t and Z_t are the outcomes and costs of the project in year t as expressed in monetary terms, d is the annual discount rate. The project outcomes are equal to the proceeds from the sale of produced energy $R_t = p_t Q_t$ (p_t is the price, Q_t is the annual sales volume).

The Net Present Value (1) depends on the scale of the project and evaluates the latter in terms of the efficiency of the capital investment. In order to compare energy technologies, it is desirable to rule out the impact of economies of scale and to determine the quality of the energy supply project as based on per unit indicators. For this purpose, the cost of energy p, in particular, that of electric power, is used [5]. The cost of energy is by definition equal to such a fixed price ($p_t = p$ = const) that yields the NPV equal to zero. Then, it follows from (1) that

$$p = \frac{\sum_t Z_t (1+d)^{-t}}{\sum_t Q_t (1+d)^{-t}} . \quad (2)$$

The cost of energy (2) is the minimum price at which the energy supply project is still feasible ($\hat{E} = 0$); it is equal to per unit costs (the ratio of total discounted costs to total discounted energy output). The best energy source is the one that ensures the lowest cost of energy.

By assuming several reasonable approximations, the cost can be expressed as the sum of terms that allow for the following: a) the cost of constructing and running the plant; b) the cost of the fuel; and c) charges for emission of harmful substances, in this particular case, carbon dioxide, which is responsible for the greenhouse effect and climate change [6]:

$$S = \left[F \frac{e^{\sigma \Delta T} - 1}{\sigma \Delta T} + \mu \right] \frac{k}{CF \cdot H \cdot (1-\beta)} + \frac{p}{8{,}15 \cdot 10^3 \eta} + \frac{a p^*}{8{,}15 \cdot 10^3 \eta} \quad (3)$$

where $F = \sigma / (1 - e^{-\sigma T})$ is the capital recovery factor; $\sigma = \ln(1+d)$; d is the annual discount rate; T is the lifetime of the energy source, years; ΔT is the construction period, years; μ are annual fixed costs (as a share of total investment); k is specific investment, \$ per kW; CF is the capacity factor; H is the number of hours per year (8,760 hours per year); β is auxiliary energy consumption (as a share of the output); p is the fuel price, \$ per tce (t.c.e. - ton of coal equivalent); η is the efficiency; a is the emission factor, t CO_2 per tce; p^* is the carbon dioxide emission charge, \$ per ton of CO_2. Capacity factors of wind and solar power plants are determined by averaging over random variables, that is the wind speed and the solar radiation intensity.

Knowing the cost of energy (electric or thermal) allows making a preliminary assessment of the RES feasibility. The cost of energy when compared to the price accepted in the energy system or to the fuel component of the costs of an alternative option (in the case of wind and solar power units), indicates whether the introduction of RES can be feasible or this technology is obviously inefficient [7, 8]. By way of illustration, Table I provides a comparison of performances of RES and energy sources based on fossil fuels [9, 10].

Table 1 The costs of RES energy and fuel components of the cost of competing liquid fuel energy sources (diesel power plants and boiler houses) for the case of Russia, US cents per kWh

Energy source	Specific capital expenditures \$ per kW	Minor consumers			Major consumers		
		North	Central Russia	South	North	Central Russia	South
DPP	320–500	33	23	25	30	21	23
BGPP	1000–2200	12	13	11	7	7	6
Small HPPs	1800–4000	12	10	9	5	5	4
WPP	1300–2500	9	24	11	4	9	5
SPP	4000–4200	53	42	35	50	40	32
Boiler house	150–300	5	3	4	5	3	4
SHS	400–500	12	7	5	10	6	4

Notes 1. DPP - diesel power plant, BGPP - biomass gasification power plant, HPP - hydroelectric power plant, WPP - wind power plant, SPP - solar power plant, SHS - solar heating system. 2. The zones within which RES prove competitive are highlighted in grey; a lower value of specific capital expenditures corresponds to the units of higher capacity (those that serve large consumers).

3 RES in the energy balances model

A comparison of energy sources based on the cost of energy presupposes that each of them works independently, while all of the energy produced is used up by the consumer. This is a pretty rough approximation, which is suitable only for preliminary estimations. In fact, RES usually operate within an energy system that includes various types of energy sources that work together to provide energy to consumers. The Global Energy Model (GEM) developed at the Melentiev Energy Systems Institute SB RAS is used to determine the scale of RES development in the long run while addressing the system effects [11-13].

The model minimizes the objective function being the total discounted costs over all regions of the world and all energy technologies while respecting the constraints set on resources, energy consumption, the scale of development of individual technologies, as well as financial and environmental constraints. As a result, one arrives at the scale of development of different types of renewable energy sources and the corresponding system effects, that is changes in the scale of production and consumption of fossil fuels, emissions of harmful substances into the environment, and energy costs.

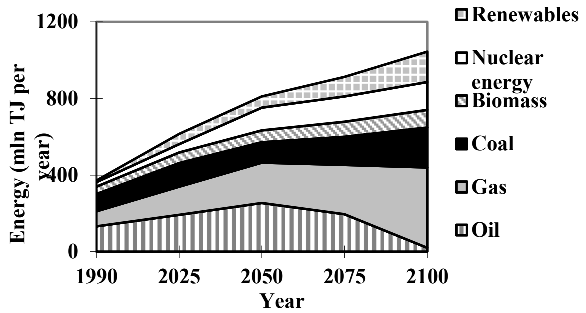


Fig. 1. World production of primary energy.

When incorporating RES performance indicators in the optimization model, these system effects are accounted for automatically. In the GEM mathematical model, all energy technologies, including RES, are represented in a unified way and described by such technical and economic performance indicators as specific capital expenditures, fixed costs, efficiency, capacity factor, etc.

The regional features of RES operation are addressed by breaking down the renewable energy sources potential into cost-based categories. The variability and the random nature of wind and solar power generation are addressed as follows: a) by averaging out the output while accounting for the probability of the wind speed distribution and the solar radiation intensity, and b) by incorporating these energy sources in the power balance equations with coefficients set to lower than unity.

With the help of the GEM model, several dozens of scenarios and the role of RES in the development of the world energy sector have been investigated [11-13]. By way of illustration, Fig. 1 shows the possible scale of application of RES in the long run under one of the intermediate scenarios that satisfies the conditions of sustainable development to the greatest extent [11].

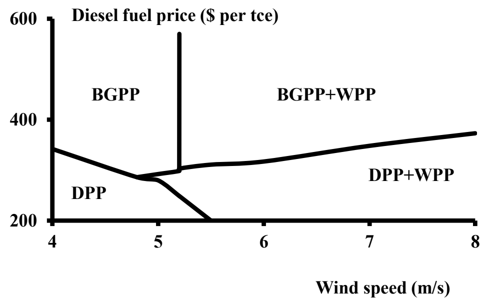
4The RES simulation model

The GEM model describes large-scale technologies of using renewable energy resources over a long period of time. In this case, it is sufficient to use the averaged data on RES energy production, which is assumed to be fully used up by consumers (with the share of RES being relatively minor). In small autonomous energy supply systems with a significant share of RES, averaging does not allow an adequate description of energy production and consumption processes. Both the load and output of RES that operate in a stochastic mode (WPP and SPP) are permanently changing. Sometimes, the amount of energy produced by RES is not sufficient, then the back-up energy sources are put into operation. Sometimes, the amount of energy produced by RES is excessive, in which case the energy is directed to storage, production of a secondary energy carrier, e.g. hydrogen, to supply heat or is otherwise dissipated by the dump load.

The REM (Renewable Energy Model) simulation model was developed to capture autonomous energy supply systems [14, 15]. The energy system includes renewable and non-renewable sources of electricity and heat, as well as an electric accumulator or a tank for storing secondary energy carriers, e.g. the syngas produced from biomass or hydrogen produced by electrolysis from excessive (at certain moments of time) power of renewable energy sources. The sequence of wind speeds is modeled with the 1 hour time step in the form of the first order autoregression, the intensity of solar radiation is modeled as a superposition of the deterministic radiation input and the random process imitating the effect of the cloud cover.

The system of equations is solved as follows. In the first stage, the operating mode at any given time is optimized (as per the criterion of minimum variable costs) at the specified installed capacity of energy sources and the battery capacity. For this purpose, energy sources are ranked sequentially in terms of their performance (sorted in ascending order by variable costs) and their capacity is increased until balance equations are fulfilled. To satisfy electrical loads, first the RES energy with zero variable costs is used, then the energy stored in the battery, and then the energy of power plants that run on the fossil fuel. Excess RES energy with zero variable costs is either accumulated or used to produce heat. In the second stage, after calculating the operating modes for the entire period of time under consideration, the installed capacity of energy sources and the battery capacity are optimized.

The model makes it possible to study energy systems of various configurations, to determine optimal capacity and operating modes, to estimate reliability, and to arrive at conditions under which RES are economically efficient. By way of illustration, Fig. 2 shows the efficiency zones of energy sources as a function of external factors, i.e. the average annual wind speed and diesel fuel price [16, 17].



a)

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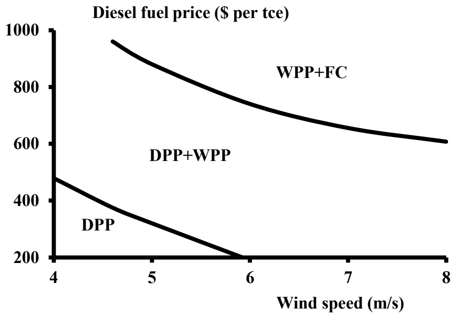


b)

Fig. 2. Efficiency zones of technologies: the DPP-WPP-BGPP system (*a*); the DPP-WPP-FC system (*b*); FC - fuel cells.

Within the DPP-WPP-BGPP system with a tank for storing syngas, given the availability of the cheap fuel and low wind speeds, the most preferable option would be to use the DPP only, while at higher wind speeds that would be the DPP working together with the WPP. In the case of a more expensive diesel fuel, it is advisable to use the BGPP working together with the WPP (see Fig. 2a).

Within the DPP-WPP-FC (hydrogen fuel cells) system with a tank for storage of hydrogen, given the availability of a cheap fuel and low wind speeds, just like in the previous case, the optimal solution includes the DPP only. If the price of the fuel and the wind speed increase, first the wind-diesel system becomes economically feasible, then the same becomes true of the WPP and hydrogen-based system working together (the electrolyser, the hydrogen storage tank, and fuel cells). Thus, we have an environmentally friendly energy supply system, since there is not a single fossil fuel powered energy source in the system (see Fig. 2b).

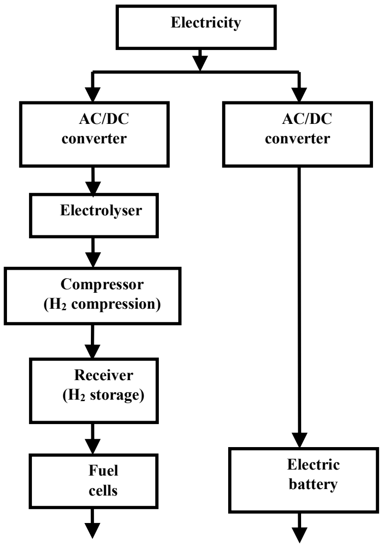
5The RES optimization model

Calculations using the simulation model show that the unevenness of wind power generation can be offset not only by the inclusion of back-up energy sources in the energy system, but also by energy storage (with a significant increase in economic performance at the same time). With a single battery, it is easy to model energy flows in the energy system: if there is an overproduction of RES, the battery is charged, if there is a shortage of RES, it is discharged. However, for several different types of batteries, simulation becomes difficult due to the impossibility of developing predefined strategies for the energy flow control. It is not clear which battery to charge first, whether it is necessary to accumulate energy in advance to compensate for the lack of output by the WPP in the period of no wind or that by the SPP on a cloudy day, etc.

To solve this problem, the REM-2 optimization model was developed using the GAMS (General Algebraic Modeling System) framework [18-20]. The energy system under consideration is treated as a set of energy sources, consumers and storage of various types. The objective function is the total cost of all components of the system. As a result of the optimization, the installed capacity of energy sources and battery capacity are determined, as well as the energy flows between the components of the system at any given time.

The model allows comparing the efficiency of various energy storage methods. Fig. 3 compares two systems of converting the stochastic output of RES into constant flows of final electric energy. The first system is the electric power battery, the second one is the system of production and storage of hydrogen that is subsequently used in fuel cells. It is obvious that energy-wise electric power storage is more efficient due to the absence of intermediate stages of energy conversion with low efficiency. However, the economic costs show that the electrical system is more efficient only in the case of the short-term energy storage (less than 100 hours), whereas in the long term, it is the hydrogen system that proves more efficient [21].

Fig. 4 shows the energy system with renewable energy sources (photovoltaic converters and wind turbines) and electric energy and hydrogen storage. The results of calculations show that due to significant fluctuations of the wind speed and solar radiation intensity over time, both short-term (electric energy storage) and long-term (hydrogen system) energy storage prove efficient at the same time [20].



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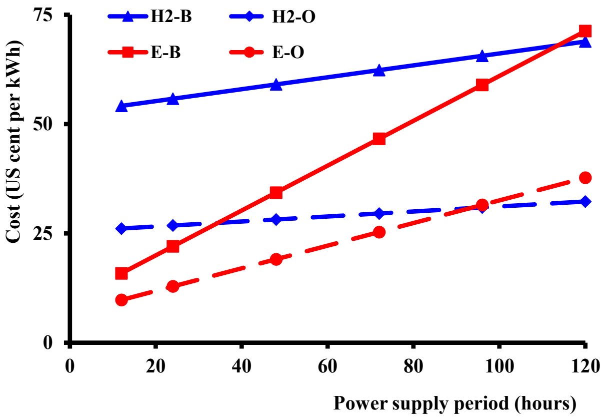


b)

Fig. 3. The compared systems of final energy production (*a*) and the cost of final energy (*b*) as a function of the power supply period (the period of sustaining the power by means energy storage). H2 - hydrogen, E - electricity, B - the baseline scenario, O - the optimal scenario.

Fig. 5 shows the energy flows on a winter's day and a summer's day. On the winter days (Fig. 5a), when the WT output is excessive, this energy is used to charge the battery and produce hydrogen. On the summer days (Fig. 5b), fuel cells generate electricity at certain time by means of previously stored hydrogen.

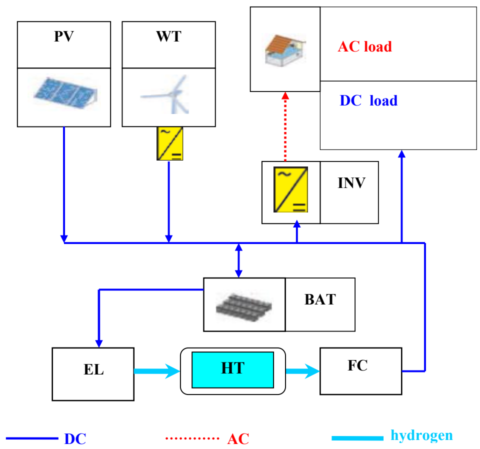
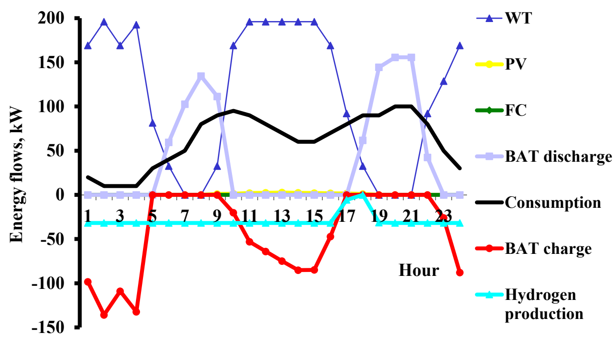


Fig. 4. Power supply system. Legend: PV - photovoltaic converters, WT - wind turbines, BAT - storage batteries, EL - electrolyser, HT - hydrogen tank, FC - fuel cells, INV - inverter.



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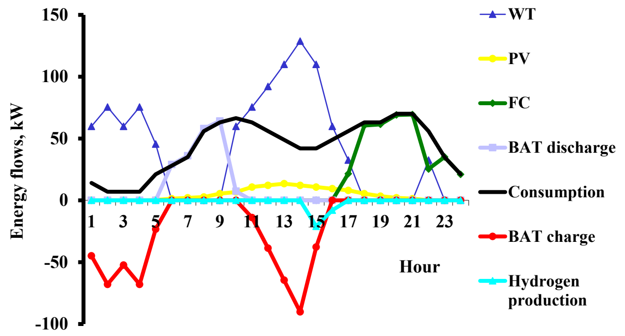


b)

Fig. 5. Energy production, consumption and storage (*a* - winter day, *b* - summer day).

6The RES market model

In order to study RES in the market environment where there are various decision-making hubs, optimization based on a single criterion is not sufficient. It is necessary to consider individual agents optimizing objective functions of their own. In addition, there is the presence of the state in the market which influences the market in such a way as to shift the market equilibrium in the desired direction, e.g. towards reducing harmful emissions from energy facilities by increasing the share of renewable energy sources.

For this purpose, a mathematical model of the renewable energy market has been developed [22, 23]. The model takes into account both the stochastic nature of renewable energy generation and the impact of regulatory authorities on the market equilibrium (subsidies, penalties, etc.).

In accordance with the unique features of the electric power industry, the model considers the long-, medium- and short-term periods. In the first case, investors evaluate the efficiency of promising energy sources, in the second one, consumers optimize their electricity consumption, while in the third one, the equilibrium price is set in the market depending on the supply/demand ratio.

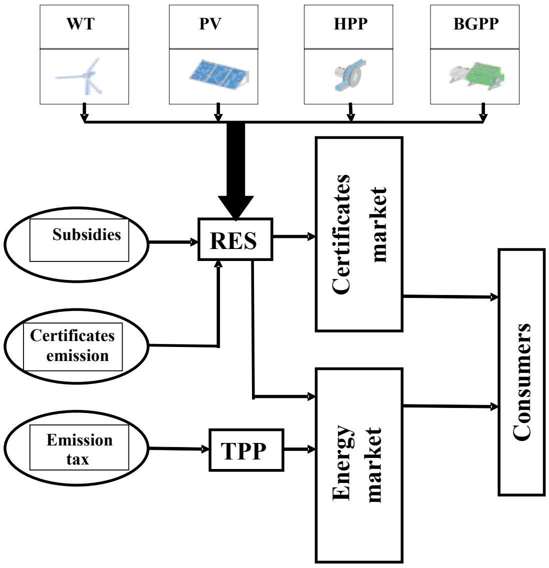
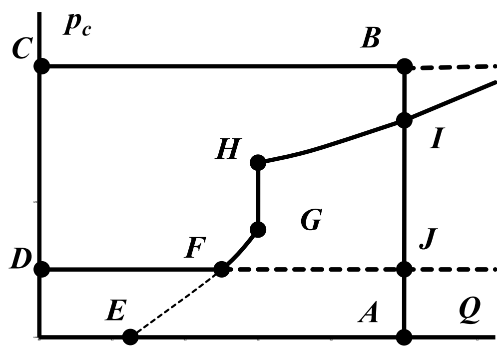


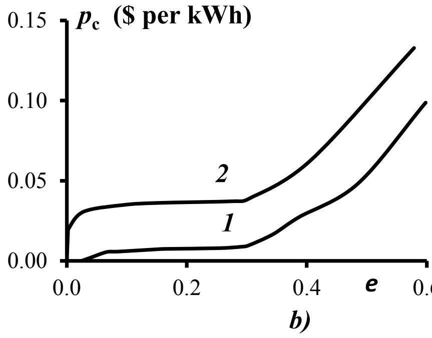
Fig. 6. Factors that influence the decisions made by the agents in the electricity and green certificates markets: WT - wind turbines, PV - photovoltaic converters, HPP - hydroelectric power plants, BGPP - biomass gasification power plants, TPP - thermal power plants.

The agents include investors that make decisions to build (or not to build) different types of power plants; energy systems that produce electricity and choose electricity output optimal for them depending on market prices; and, consumers that choose the amount of electricity they consume based on its price so as to maximize their utility.

Renewable energy subsidies, fees for emissions from fossil fuel power plants, and standards set for the minimum share of renewable energy produced through "green certificates" and subsequent trade thereof have been considered as factors that enable one to control the market (see Fig. 6).



a)



b)

Fig. 7. Demand (ABC) and supply (DFGHI) curves in the green certificates market (*a*); the price of certificates p_c as a function of a given share of RES *e* (*b*); (1 and 2 stand for less and more capital-intensive options respectively).

With the introduction of the green certificates market, the owners of renewable energy sources receive income from the sale of energy and the sale of certificates at the same time. For each unit of green energy, the producer receives a certificate. The consumer is obliged to buy part of the green energy in the form of certificates.

The results of the calculations show that the most efficient of the above three mechanisms is the tax on electricity consumers that comes as an obligation to purchase green certificates, while the least efficient one is subsidies for RES.

Fig. 7a shows the curves of supply and demand in the certificate market. The green certificates mechanism assumes that the regulators set not fixed prices for RES or subsidies, but rather the desired amount of renewable energy. This corresponds to the vertical straight line of demand in Fig. 7a. Fig. 7b shows the results of the calculations of the certificate price as a function of a given share of renewable energy. In the first variant (with lower capital expenditures) production of about 3% of electricity RES turns out to be economically efficient even without additional support of the green certificate market.

7Conclusion

The methods and models used at the Melentiev Energy Systems Institute SB RAS for efficiency assessment of renewable energy sources were considered.

The Net Present Value and the cost of energy enable a preliminary assessment of renewable energy sources and comparison to alternative options. The cost of energy when compared to the price accepted in the energy system or to the fuel component of the costs of an alternative option (in the case of wind and solar power units), indicates whether the introduction of RES can be feasible or this technology is obviously inefficient.

In order to allow for the system effects of RES, the latter are incorporated in the mathematical model along with other types of energy sources. The variability and the intermittent nature of wind and solar power generation are addressed as follows: a) by averaging out the output given the probability of the wind speed distribution and the solar radiation intensity, and b) by incorporating these energy sources in the power balance equations with coefficients less than unity.

Average values of RES parameters are not sufficient for the analysis of autonomous energy systems of small capacity. For such systems, it is practical to use simulation modeling of energy system dynamics. To this end, in the first stage, the modes of operation of energy sources are optimized by the method of their ranking as per the criterion of the minimum variable costs, and, in the second stage, their installed capacity is optimized as per the criterion of the minimum total costs. The model makes it possible to study energy systems of various configurations, to determine optimal capacity and modes of operation, to estimate reliability, and to arrive at conditions under which RES are economically efficient.

An optimization mathematical model is used to analyze of an autonomous system with energy sources and storage of various types. The objective function is the total cost of all components of the system. The model determines the optimal structure and modes of operation of the energy system, and compares the efficiency of various methods of energy storage.

A mathematical model of the renewable energy market has been developed for the study of RES under market conditions where there are various decision-making hubs. The model takes into account both the stochastic nature of renewable energy generation and the impact of regulatory authorities on the market equilibrium (subsidies, penalties, etc.). It is shown that the most efficient mechanism to encourage the development of RES is the tax on electricity consumers in the form of an obligation to purchase green certificates, while the least efficient one is the RES subsidies.

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