Efficiency of Small Autonomous Wind/Diesel/Hydrogen Systems in Russia

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Abstract- The possibility of storing energy in the form of hydrogen in the small autonomous wind/diesel/hydrogen power systems that include wind turbines, diesel generator, electrolyzer, hydrogen tank and fuel cells is analyzed. The paper presents the zones of economic efficiency of the system (set of parameters that provide its competitiveness) depending on load, fuel price and long-term average annual wind speed. At low wind speed and low price of fuel it is reasonable to use only diesel generator to supply power to consumers. When the fuel price and wind speed increase, first it becomes more economical to use a wind-diesel system and then wind turbines with a hydrogen system. In the latter case, according to the optimization results, diesel generator is excluded from the system.

Keywords- Economic Efficiency, Renewable Energy Sources, Electricity Cost, Decentralized Power System, Wind Turbines, Hydrogen Production, Fuel Cells.

1. Introduction

Development and implementation of renewable energy sources (RES) are a very promising solution with excellent prospects to cover the energy needs of small autonomous systems in an efficient and sustainable way. In recent years the energy policy of many countries has been aimed at increasing the share of RES in the total energy production. In Russia the share of RES (without large hydro power plants) in the electricity production does not exceed 1%. However, the "Energy Strategy of Russia for the period up to 2030" (approved by the Russian Government) suggests that in 20 years this share may increase up to 4.5%.

Providing a substantial environmental effect (decrease in the emissions from energy sector), RES can often be economically efficient and competitive with the energy sources based on fossil fuel [1-7]. It is expected that in the nearest and, moreover, distant future the role of RES in Russian and world energy industry will essentially increase due to the improvement of characteristics and a projected rise in the fossil fuel price [8-12].

It is reasonable to use RES primarily in small autonomous (decentralized) power systems located in remote hard-to-reach areas, where the price of imported fossil fuel is very high. Russian zones of decentralized power supply that do not have any modern electrical networks and large energy sources occupy about 70% of the country and are situated mostly in the Far North.

Decentralized systems of power supply are characterized by the following features:

- settlements are spread throughout large scarcely populated territories;
- electric load of consumers in each settlement does not exceed 1-3 MW;
- transport infrastructure is underdeveloped;
- the main electricity source is diesel power plants;
- diesel power plants use expensive diesel fuel, which usually costs more than $800-$1000 /toe [4].

Therefore, the introduction of renewables to increase the cost effectiveness of power supply is an urgent problem for these systems. One of the most effective types of RES is wind turbines [1, 4].

The potential for the wind energy development in Russia is really great. Russia has the longest shoreline in the world, abundant treeless flatlands, and large water areas of inner rivers, lakes and seas, which represent the most favorable sites for wind turbines.

The main advantages of wind turbines are as follows:

- no harmful emissions in the process of electricity production;
- relative cheapness of generated electricity (3-5 cent/kWh for the best turbines under good wind conditions);
- possibility of significantly saving on fossil fuel in the course of operation in an autonomous power system.

At the same time wind turbines have a flaw. This is unsteady electricity generation (depending on changes in wind speed). Therefore, wind turbines are used in combination with energy sources that operate under the controlled conditions and supply power to the load when power generated by wind turbines is insufficient or during their downtime. Besides, power systems with wind turbines include energy storage devices.

The research aims to study the economic efficiency of harnessing wind energy in Russia for a wide range of parameters (fossil fuel price, climatic and meteorological conditions, power and load curve of consumers, current and prospective technical and economic indices of the power system components). First of all the authors consider the most promising wind/diesel systems, including the systems that produce, store and use hydrogen in fuel cells (wind/diesel/hydrogen systems).

2. Autonomous Power System

The considered autonomous power system (Fig. 1) includes diesel units, one or several wind turbines, electrolyzer, hydrogen tank, fuel cells and electricity consumers with their load curve.

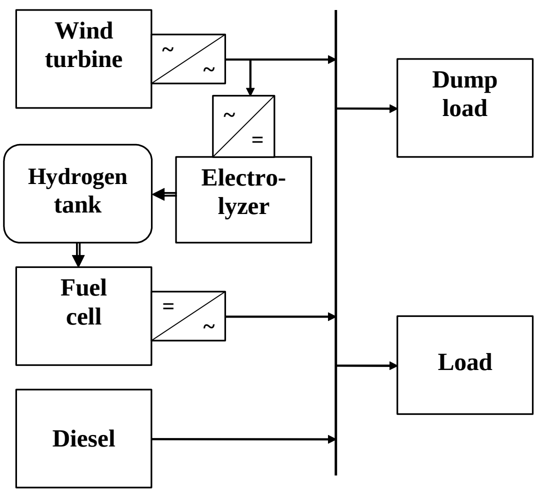


Fig. 1. Wind/diesel/hydrogen system.

It is assumed that the diesel power plant, wind turbines, electrolyzer and fuel cells are provided with all the devices required to control the network. Wind turbines supply electricity directly to the consumers with changing load. If this electricity is insufficient, diesel generator and fuel cells can operate simultaneously. The excess power from wind turbines is consumed by the electrolyzer (if the hydrogen tank is not fully filled with hydrogen) or absorbed by the dump load.

3. Calculation Method

Optimization of the autonomous power system (Fig. 1) structure and operation is reduced to solving the problem [1,3]: find the objective function (electricity cost) minimum

$$S=\frac{1}{Q}\left[\sum_i CRF_i\ K_i+Z_i\right]\to \min\ , \qquad (1)$$

subject to

$$P_{DG}(t)+P_{WT}(t)+P_{FC}(t)=L(t)+U(t)\ , \qquad (2)$$

$$0\le P_i(t)\le P_{i\,\max}\ , \qquad (3)$$

$$U(t)\ge 0\ , \qquad (4)$$

$$P_{WT}(t)=P_{WT\,\max}\,f(v)\ , \qquad (5)$$

$$P_{FC}(t)\le P^*_{HT}(t)\ \eta_{HT}\eta_{FC}\,/\,\Delta t\ , \qquad (6)$$

$$P_{EL}(t)=\min\ (U(t),(P^*_{HT\,\max}-P^*_{HT}(t))\,/\,(\eta_{EL}\Delta t))\ , \qquad (7)$$

$$P^*_{HT}(t)=P^*_{HT}(t-\Delta t)+\left[P_{EL}(t)\ \eta_{EL}-\frac{P_{FC}(t)}{\eta_{FC}\eta_{HT}}\right]\Delta t \qquad (8)$$

The following notation is used: Q is the annual electricity production, $CRF=\sigma/[1-\exp(-\sigma T)]$ is the capital recovery factor, $\sigma=ln(1+d)$, d is the annual discount rate, T is the time period considered, Z is the average annual costs, P is the power of energy source, P^* is the energy equivalent of hydrogen in hydrogen tank, t is the time, L is the load, U is the power surplus, $f(v)$ is the wind turbine power curve, Δt is the time step; indices: i is the type of energy source (DG is the diesel generator, WT is the wind turbine, EL is the electrolyzer, HT is the hydrogen tank, FC are the fuel cells), max and min are the maximum and minimum values.

Equation (2) is the power balance at the time point t, (3) is the power constraints, (4) is the condition of shortage-free power supply, (5) is the dependence of wind turbine power on wind speed (random value), (6) is the constraint on the power of fuel cells with respect to hydrogen reserve, (7) is the constraint on the power of electrolyzer with respect to power surplus and available capacity in the hydrogen tank, (8) is the hydrogen balance in the hydrogen tank.

To solve system (1)-(8), the following algorithm was used. Continuous time functions were replaced with sets of discrete values with the step of 1 hour. Wind speed was modeled in the form of random processes in terms of the alternating periods of low and high wind speeds. This is essential for the systems with energy storage systems, and in this case, for the determination of optimal capacity of the hydrogen tank.

At the first stage, when the installed capacities of energy sources and the hydrogen tank capacity are given, the operating conditions are optimized at each time point in accordance with the criterion of minimum fuel costs. The electric load (equation (2)) is first coved by energy from wind turbines, then by the energy stored in the hydrogen tank, and finally - by the energy from diesel generator. The excess energy from wind turbines is sent to electrolyzer for the production of hydrogen.

At the second stage after the calculation of operating conditions on the entire time interval from t=0 to t=T the installed capacities of energy sources and the hydrogen tank capacity are optimized according to criterion (1) subject to constraints (3) and (4).

4. Initial Data

The factors that determine the economic efficiency of using wind turbines and hydrogen system in addition to the diesel power plant (or instead of it) in the autonomous power systems are wind speed, diesel fuel price, maximum power and degree of load unevenness, technical and economic indices of power plants.

The most important energy characteristic of the wind is its long-term average annual speed V measured at a height of a weather vane (about 10 m). Fig. 2 presents the distribution of this characteristic across the territory of Russia.

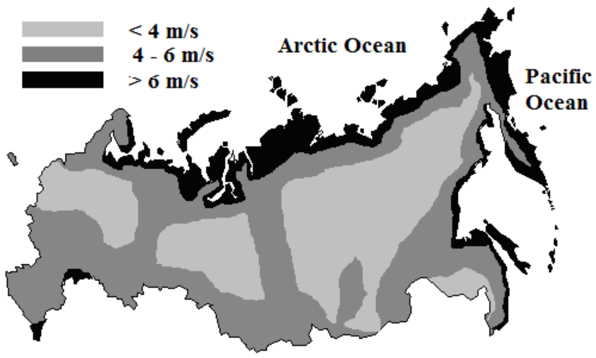


Fig. 2. Long-term average annual wind speed V (m/s) at a height of 10 m on the territory of Russia.

The zones of low (up to 4 m/s), medium (4-6 m/s) and high (more than 6 m/s) wind speeds are highlighted. Average wind speed reaches its maximum on the seacoasts and decreases in the continental areas.

In this study the calculations were made for average wind speeds equal to 4-8 m/s, which corresponds to a range of wind conditions from "bad" to "very good". Wind speed is distributed according to the Weibull distribution with a shape parameter 1.5, the relationship between wind speed and the height was described by a logarithmic dependence with a surface roughness degree 0.03 m [1]. The operating characteristic of wind turbines (power versus wind speed) is taken in accordance with the installation data of the company "Fuhrländer"; the height of a wind turbine tower for the load of 50 kW is 20 m, for the load of 1000 kW is 40 m.

A retrospective analysis shows that in the last 10-15 years the price of diesel fuel has increased 2-3 times. Today the minimum wholesale price of diesel fuel is in the North Caucasus ($780 /toe), and the maximum is in the Republic of Yakutia ($1600 /toe). For the southern and central regions of the European part of Russia the typical prices are $800-$1000 /toe, and for the northwest regions of the European Russia and northeast regions of the Far East they equal $1100-$1500 /toe.

In the calculations, the diesel fuel price in the range $800-$1500 /toe was considered, which corresponds to the conditions from "relatively cheap" to "moderately expensive" diesel fuel for the autonomous power systems.

The majority of decentralized electricity consumers live in rural and urban settlements with the population from 50 to 5000 people. We consider the following consumers: 1) small consumers with a variable electric load up to 50 kW and 2) larger consumers with a load up to 1000 kW.

The load power was assumed to be normally distributed. The parameters of the normal law were chosen by approximation of the annual load curve: for a load of 50 kW (maximum value) the average power is 20 kW, standard deviation is 5 kW, for the load of 1000 kW - 685 kW and 100 kW, respectively.

Table 1 shows the main technical and economic indices of the power system that will be available in the market in 2015-2020 years and for two power levels of consumers load (50 kW and 1000 kW). The indices are formed on the basis of the studies presented in [3, 4, 9-12].

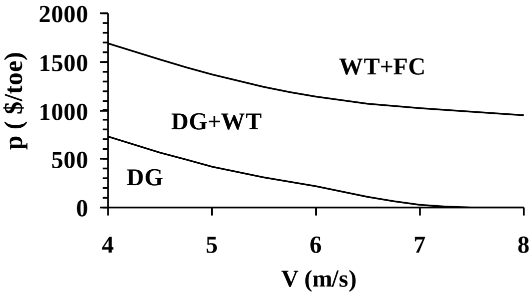
Table 1. Technical and economic characteristics of the power system components

Component	Specific investments ($/kW)		Specific fixed costs (% of investments)		Efficiency (%)		Lifetime (years)	
	50 kW	1000 kW	50 kW	1000 kW	50 kW	1000 kW	50 kW	1000 kW
Diesel	450	280	7	5	34	37	10	10
Wind turbine	1600	1100	3	2	35 **	35 **	20	20
Electrolyzer	2000	1000	3.5	2.5	77	77	20	20
Hydrogen tank	600 *	400 *	1	1	98	98	20	20
Fuel cells	2500	1500	3.5	2.5	70	70	10	10

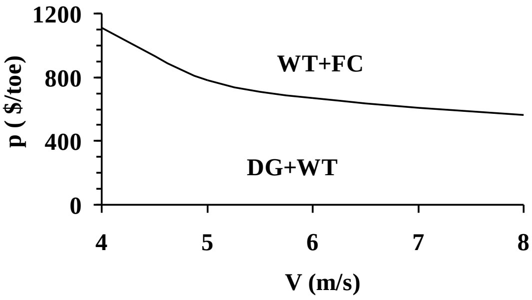
Footnotes: * - specific investments for the hydrogen tank are given in $/m3; ** - efficiency of wind turbines is given for information (the calculations use wind turbine characteristics (power curve)).

5. Calculation Results and Their Analysis

Fig. 3 presents the efficiency zones of energy technologies (optimal structure of the system depending on the diesel price and average wind speed). At low wind speed and low price of fuel it is reasonable to use only diesel generator to supply power to consumers.



(a)



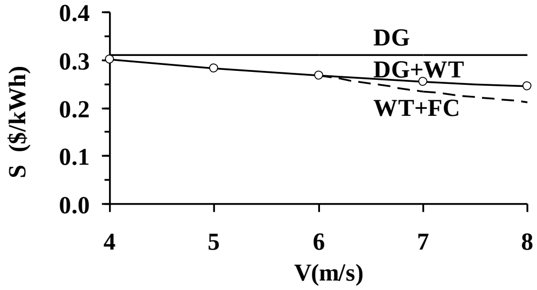
(b)

Fig. 3. The efficiency zones of energy technologies at the load power of 50 kW *(a)* and 1000 kW (*b*). *V* is the average wind speed at a height of 10 m, *p* is the diesel fuel price, *WT* are the wind turbines, *DG* is the diesel generator, *FC* are the fuel cells.

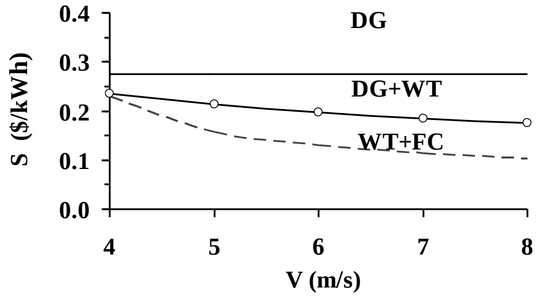
When the fuel price and wind speed increase, first it becomes more economical to use a wind-diesel system and then wind turbines with a hydrogen system. In the latter case, according to the optimization results, diesel generator is excluded from the system. Cost effectiveness of wind turbines and fuel cells at a load of 1000 kW is provided at lower wind speed and lower diesel price than for a load of 50 kW, since the specific indices of larger energy sources are better. When the load equals 1000 kW, the application of a diesel generator alone in the considered region of parameters turns out to be inefficient.

Zones of technological efficiency allow us to determine the best structure of the power supply system for the given conditions. Moreover, we should know what economic effect can be achieved by applying the optimal structure, because only if the effect is sufficient it makes sense to complicate the system by adding extra components. The corresponding data are presented in Fig. 4. As we can see, the size of the achieved effect is quite significant.

For example, with the load of 1000 kW and the average wind speed of 6 m/s the construction of wind turbines in addition to diesel generator makes it possible to decrease the electricity cost from 27 to 20 cent/kWh, and the replacement of the diesel generator by an electrochemical unit to 12 cent/kWh. Thus, the introduction of a wind-hydrogen system will allow us to halve the costs of electricity production as compared to power supply from diesel generator alone.



(a)



(b)

Fig. 4. Electricity cost for autonomous system at fuel price of $1100 /toe and with the load power of 50 kW *(a)* and 1000 kW (*b*). *V* is the average wind speed at a height of 10 m, *p* is the diesel fuel price, *DG* is the diesel generator, *WT* are the wind turbines, *FC* are the fuel cells.

6. Conclusion

The paper presents an analysis of the economic efficiency of harnessing wind energy in the autonomous power systems of Russia.

During the periods of strong wind some amount of power generated by wind turbines turns out to be redundant. Therefore, it becomes possible to use this power for hydrogen production by electrolysis and its subsequent electrochemical transformation into electricity. Under certain conditions the introduction of subsystem for hydrogen production, storage and use for energy purposes to the wind/diesel system can decrease diesel consumption (or even completely exclude diesel generators from the system) and reduce the costs of electricity production.

The study considered the possibility of storing energy in the form of hydrogen in the autonomous wind/diesel/hydrogen power systems that include a diesel generator, electrolyzer, hydrogen tank and fuel cells. The authors determined the zones of economic efficiency in the system depending on the load power, fuel price and long-term average annual wind speed.

Technical and economic characteristics of the equipment projected for the nearest future make the hydrogen system economically efficient at the fuel prices typical of the autonomous power systems ($800-$1400 /toe) and the average annual wind speed starting with 4.5-5 m/s. Application of the system for the hydrogen production and use for energy purposes will considerably reduce (more than by 50%) the costs of power supply to consumers.

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