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Efficiency Estimation of Constructing of Wind Power Plant for the Heat Supply Needs

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Abstract. As in the whole world, there are regions in Russia that experience heat supply difficulties, mainly due to the high cost of fossil fuel as well as to growth of energy resources cost and polluting emissions. In this regard, search for solutions which would provide energy saving with an increase of energy, commercial and ecological efficiency of modern heat supply systems is becoming vitally important today. One of them is the development and use of special types of energy including renewable energy sources, wind energy in particular. Accordingly, the paper presents one of the possible solutions to the heat supply problem which are directed at meeting the whole region's heat demand through the joint use of wind power plants with a boiler room operating on fuel oil. The study assessed the efficiency of constructing of wind power plants with a total capacity of 1.7 MW for the heat supply needs of a settlement, which is located on the Barents Sea coast in Russia. The selected area is characterized by an average annual wind speed of 7.0 m/s and a long heating period (9–10 months a year). The assessment showed that the wind power plant construction is financially reasonable, as additional profit can be generated by the end of the wind power plants scheduled service life that make up the half of primary investments. The results obtained in the paper are expected to make up for the lack of information on the feasibility of wind power plants construction for the heat supply needs, which is very useful for other countries that have similar areas experiencing various heat supply difficulties.

Keywords: wind energy, heat supply, feasibility study, net present value, Arctic zone of Russia, wind power plant

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Оценка эффективности сооружения ветроэнергетических установок на нужды теплоснабжения

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Реферат. В России, как и во всем мире, имеются районы, испытывающие различные проблемы с теплоснабжением, главным образом обусловленные высокой стоимостью органического

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топлива, ростом тарифов и загрязнением окружающей среды. В связи с этим поиск путей, способствующих энергосбережению и повышению энергетической, экономической и экологической эффективности работы современных систем теплоснабжения, становится жизненно важным. Один из них заключается в освоении и вовлечении в топливно-энергетический баланс особых видов энергии, к числу которых относятся возобновляемые источники энергии, в частности энергия ветра. В статье рассмотрен способ решения проблемы теплоснабжения, направленный на удовлетворение потребности в тепловой энергии целого поселка, путем использования ветроэнергетических установок совместно с котельной, работающей на мазуте. Выполнена оценка эффективности сооружения ветроэнергетических установок общей мощностью 1,7 МВт на нужды теплоснабжения поселка Териберка, расположенного на побережье Баренцева моря в России. Выбранный район характеризуется среднегодовой скоростью ветра 7,0 м/с и длительным отопительным периодом (9–10 месяцев в году). Как показали исследования, с финансовой точки зрения сооружение ветроэнергетических установок является оправданным: к завершению их планового срока службы может быть сформирована дополнительная прибыль, достигающая половины суммы первоначальных инвестиций. Ожидается, что полученные результаты восполнят недостаток информации о целесообразности сооружения ветроэнергетических установок на нужды теплоснабжения, что весьма полезно для других стран, в которых имеются похожие районы, испытывающие различные проблемы с теплоснабжением.

Ключевые слова: ветроэнергетика, теплоснабжение, технико-экономическая оценка, чистый дисконтированный доход, Арктическая зона Российской Федерации, ветроэнергетическая установка

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Introduction

Due to the high cost of fossil fuel, growth of energy resources cost and polluting emissions, the researches aimed at inquiries of the solutions, which would provide energy saving with an increase of energy, commercial and ecological efficiency of modern heat supply systems, are becoming more relevant today. One of such solutions is the promotion and involvement in the fuel and energy balance of particular kinds of energy, including renewable energy sources (RES), and, specifically, wind energy [1–4]. It enables using wind power plants (WPP) in the areas with enhanced wind potential and extended heating season for generating thermal energy for the heat supply needs. Joint operation of them with conventional heat supply facilities is able to reduce expensive fossil fuel utilization and hence to reduce cash costs for its purchase and make environmental improvements close to heat consumers [5–7].

WPP are primarily used throughout the world to produce electrical power for power supply to consumers [8–12]. The electricity is either directly transferred to a consumer, or first transferred to the Unified Energy System of Russia, where it is further distributed to consumers. In these cases, power produced can be partially used by consumers for heating needs through the use of electric heaters (such as convectors, floor heating systems or oil heaters). It concerns group of consumers who have been initially provided with the heaters installed inside heated buildings and which accommodations are heated by them. It should be noted that additional equipment (for example, an inverter) is required to be installed to maintain power supply systems using WPP in good working order, along with carrying out extra measures providing the required quality of WPP power output. This quality is determined by the external electrical network [13–15].

This paper is related to such an operational technique of a WPP, which allows one to abandon additional equipment and additional measures to ensure the quality of the power output. The principle of this technique is to use all WPP power output for the heat supply needs only. Thus, the power produced by WPP comes straight to the heater, which heats the water (coolant) circulating through the heat supply system. The heater here could be powered by electricity of any quality, thereby possible fluctuations of WPP power become unimportant. Short-term (second and minute) fluctuations will be smoothed out by the coolant itself, together with the slow response of heat supply systems. Longer (hour) fluctuations are flattened by the heat-retaining capacity of the heated buildings and structures. Furthermore, that WPP operating technique enables saving money on extra equipment purchase and reducing the operating costs associated with the equipment maintenance.

The feasibility of constructing and using WPP for the heat supply needs within particular zones and conditions should be confirmed by modern feasibility studies and analysis of WPP performance indicators. A number of international researches have dealt with these issues, but all of them are basically concerned with the analysis of hybrid systems, normally composed of photovoltaic cells and WPP, operating for the electric power supply needs [16–18]. In so doing, some researches however deal the issues of heat supply from WPP, but heat and electrical loads are considered together [19–22].

Thus, the analysis of these and other similar researches showed poor data on technical and economic performances of WPP construction for the needs of heat supply, which completeness could have indicated the possible WPP construction feasibility for some regions. The paper accordingly presents one of the possible solutions to the heat supply problem, directed at meeting the whole region’s heat demand through the joint use of a WPP with a boiler room. The construction and further use of WPP for the heat supply needs may not only be productive for some regions, but also help to attract additional investment to them. The results obtained in the paper are expected to make up for the lack of information on the feasibility of WPP construction for the heat supply needs, which is very useful for other countries, having similar areas with various heat supply difficulties.

Materials and methods

There are regions in Russia, as in the world, experiencing heat supply difficulties (problems with the delivery and storage of fossil fuels, the state subsidy need, obsolescence and worn-out state of heat supply systems, etc.) [23–26].

One of these areas is the Teriberka settlement, which is located in Russia within the Arctic Circle, 120 km east of Murmansk (Fig. 1).

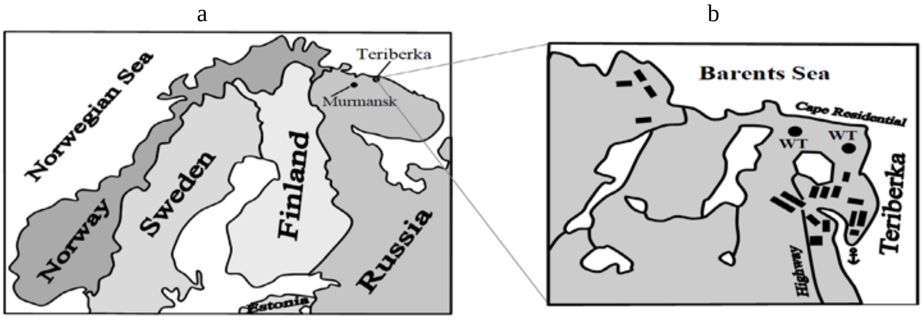

Fig. 1. The situation of Teriberka (a) and the site for the wind power plants construction on the settlement's territory (b)

Teriberka has been supplied with district heating. The heating period stretches about 9–10 months a year. The basic heat source in Teriberka is a boiler room, with the installed capacity of 10001.8 kW, of which only 2095.73 kW is used for heating load. The basic fuel type is fuel oil, with constantly growing cost on the market, leading to heat power tariff increase, which keeps up in years to come (Fig. 2). At the same time, fuel oil combustion at the boiler room is accompanied by environmental discharge of harmful substances.

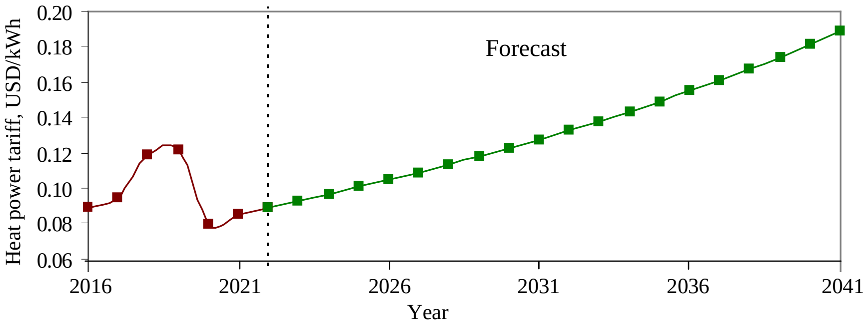

Fig. 2. Heat power tariff increasing in Teriberka

To increase the efficiency of the heat supply system under consideration, WPP are proposed to be used, jointly operating with a boiler room. In this case, the WPP use will make it possible to reduce the boiler room participation in the heat supply and thereby to reduce fuel oil consumption.

Seed funding will be required to carry out and implement the WPP construction project into the heat supply system. The sooner the investments pay off, the more economically attractive project is seen, where investors more likely investing their money in.

The net present value (NPV) could be taken as a criterion for the construction profitability of the WPP in question, which expresses the total economic benefit or diseconomy of the object realization for the entire duration of its operation, adjusting for changes in the inflation and the heat power tariff [27, 28].

In our case, the equation for calculating the NPV can be written as follows

$$\text{NPV} = \sum_{i=1}^{n} \frac{B_i}{(1+r)^i} - I_0, \quad (1)$$

where i = 1, 2, …, n – the number of the WPP operational year; n – the WPP service life, years; B_i – current income from the WPP operation for the relevant i-th year, USD; r – real discount rate, per unit; I_0 – total investment in the WPP construction, USD.

When using WPP for heat supply, the current income from their operation for the relevant i-th year can be determined from the expression

$$B_i = W f_i - C_{0i}, \quad (2)$$

where W – the total annual output of two wind turbines, kWh; f_i – heat power tariff in the i-th year, USD/kWh; C_{0i} – total operating costs of the WPP for the relevant i-th year, USD.

Annual operating costs C_{0i} generally include the expenses on overhaul and repair, wages and others.

The major effect of the WPP implementation is to save fuel oil used in the boiler room. Therefore, the boiler room's owner, whose balance sheet it is on, as well as regional and local authorities, having had to subsidize the fuel oil purchase and delivery, are primarily interested in the WPP construction. If the boiler room's owner happens to have the seed funding for the WPP construction, then he can make maximum or partially use of his own funds. The deficit can accordingly be allocated from the national budget, for example, in the form of subsidies.

In this case, when calculating NPV to determine the nominal discount rate r_{CAPM} (the rate of return on equity), we can apply the capital assets pricing model (CAPM)

$$r_{CAPM} = r_f + \beta(r_m - r_f), \quad (3)$$

where r_f – the risk-free rate of return, per unit; β – the coefficient corresponding to the change in the company's share price from the change in the share price for all companies in this market segment; ($r_m - r_f$) – market risk premium, per unit; r_m – the average market rate of return in the stock market, per unit.

The refinancing rate offered by the Central Bank of Russia (CBR) can be used as r_f, when placing the project under the Russian market conditions. At the time that calculations being performed, the refinancing rate has been set at 6.75 % per annum. In the Russian market, the calculating procedure for the β coefficient is also determined by the CBR. Companies that do not trade their shares on the stock markets do not have sufficient statistics to calculate their β coefficient. In this case, the average β coefficient of the closest equivalent companies is used for calculations (Tab. 1).

Table 1

β coefficient of some closest equivalent companies

Company name	β coefficient
Enel Russia	0.86
TGC-1	1.63
TGC-2	0.66
RusHydro	0.69
Yakutskenergo	0.28
Mean	**0.82**

The average market rate of return in the stock market r_m for Russia can be taken as either the average return on the Moscow Interbank Currency Exchange (MICEX) index or the RTS index. The indices of MICEX and RTS are the main indicators of the Russian stock market. The average annual return of these indices is at the level of 12.5 % per annum [29]. We use this value in further calculations.

In the following NPV calculation to determine the real discount rate, the expression can be used [30]

$$r = \frac{r_{CAPM} - J}{1 + J}, \tag{4}$$

where J – inflation rate in the current and expected time period, per unit.

If the boiler room's owner and public authorities do not have funds for the WPP construction, the funding can be obtained in terms of a bank loan. When this occurs, the discount rate depends not only on inflationary development, but also on loan conditions for the WPP construction. When calculating the NPV, the nominal discount rate can be defined as the weighted average cost of capital (WACC):

$$r_{WACC} = r_{CAPM}\left(E/V\right) + r_{nd}\left(D/V\right)\left(1 - t\right), \tag{5}$$

where r_{CAPM} – the rate of return on equity, resulted using the CAPM model, per unit; E – market value of equity, per unit; D – market cost of debt, per unit; $V = E + D$ – total market cost of debt and equity, per unit; t – profit tax rate (makes up 20 % in Russia), per unit; r_{nd} – the rate of return on debt (cost of borrowing of the loan), per unit.

In this case, such costs are the nominal interest rate, set by the bank on the loan.

The real interest rate r_d imposed by the bank on the loan, can be found similarly with formula (4) from the expression

$$r_d = \frac{r_{nd} - J}{1 + J}. \tag{6}$$

When calculating the NPV accordingly to the formula (5), the following expression can be used to determine the real discount rate

$$r = \left(\frac{r_{CAPM} - J}{1 + J}\right)\left(E/V\right) + \left(\frac{r_{nd} - J}{1 + J}\right)\left(D/V\right)\left(1 - t\right). \tag{7}$$

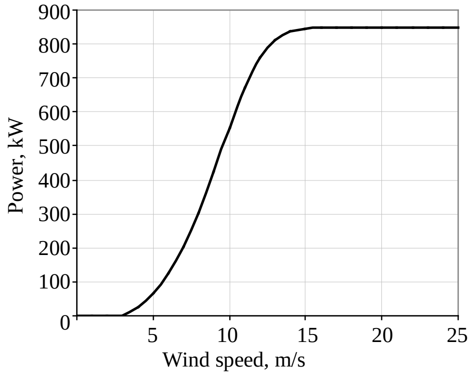

Fig. 3. Vestas V52-850 kW wind turbine power curve

The present area is proposed to place two Vestas V52-850 kW wind turbines (80 % of the boiler room supplied load), with a wind wheel diameter of 52 m and a tower height of 65 m. Its power curve is shown in Fig. 3. The WPP site location should have high wind potential and ensure the lowest costs for the creating the access roads, wind turbines transportation, laying of a foundation, etc. Considering the requirements mentioned, the site was selected on the Barents Sea coast, at a distance of 1.5 km from Teriberka, where an average annual wind speed is of 7.0 m/s (Fig. 1b).

The annual power output of each wind turbine depends on the average annual wind speed and to a large extent on the wind distribution at the hub height. The average annual wind speed at the height of 10 m aboveground level for Teriberka is mentioned earlier to be 7 m/s. Wind speed increases with height. The issue concerning wind profile particularized in [31, 32], where a formula was resulted from researches, determining the transition from one high level, for example, 10 m, to the height H

$$V_H = V_{10}\left(\frac{H}{10}\right)^m, \tag{8}$$

where V_{10} – the average annual wind speed at the height of 10 m above ground level, m/s; H – hub height, m; m – coefficient that depends on the surface roughness of a particular area and is usually in the range of 0.05–0.50 [33].

The value of m can be determined by the logarithmic equation solution (8), as shown in [34]

$$m = \frac{\log\left(\frac{\bar{V}_H}{\bar{V}_{10}}\right)}{\log\left(\frac{H}{10}\right)}. \tag{9}$$

Using the formula (8) and taking into account that for Teriberka m takes on the value of 0.134, the average annual wind speed at the height of 65 m appeared to be 9 m/s.

Fig. 4 shows the wind distribution view when the average annual wind speed is of 9 m/s at the height of 65 m above ground level. If we now take into account Vestas V52-850 kW wind turbine power curve shown in Fig. 3, then the possible annual power output of the two wind turbines will be about 6.78 million kWh, and the installed capacity utilization hours for each wind turbine per year is 3985.

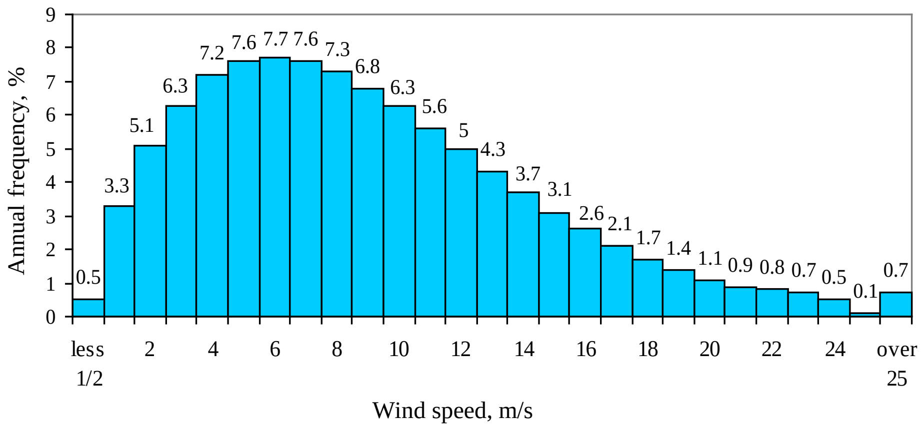

Fig. 4. Wind distribution at an average annual wind speed of 9 m/s

For the correctness of the calculations, we can take into account the particular heating-load curve, provided with the operation of the WPP and the boiler room. Previously, the study [35] has considered such a curve. The curve given by Fig. 5 shows which part of it is covered by the WPP, and which part is covered by the boiler room. A part of the wind energy appears to be apparently non-demanded (excessive). The share of this energy in the WPP total annual output is about 25 %. Given this, the share of useful power annual output generated by the two wind turbines is reduced to 5.09 million kWh and the WPP installed capacity utilization hours per year – to 2989.

Having data presented, we can proceed to efficiency estimation of constructing WPP for heat supply needs.

WPP construction and their further operation imply income. The income from the WPP operation depends on the heat power tariff. As of the end of 2022, the average heat power tariff in Teriberka is approximately 0.089 USD/kWh.

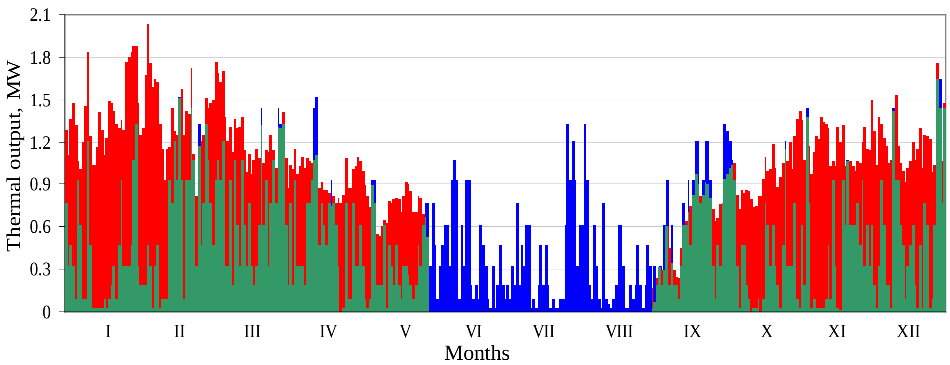

Fig. 5. Heating-load curve for the Teriberka's settlement, provided with the operation of wind power plants (green area) and boiler room (red area); WPP's surplus power – blue area

According to the Ministry of Economic Development of Russia, in 2014–2021 inflation rate ranged from 2.5 to 12.9 % per annum. As far as inflation in 2022 and beyond is concerned, that very Ministry gave the following data: 7.0 % in 2022 and then about 4 % in subsequent years (Fig. 6).

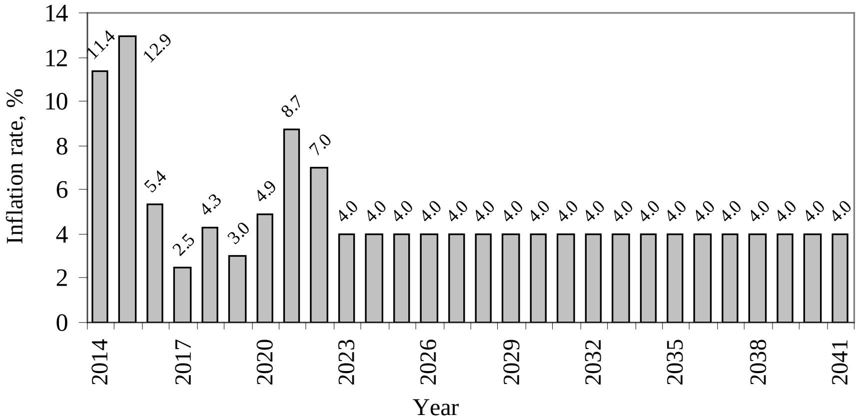

Fig. 6. Inflation rate change in Russia

If we assume that the further annual increase in the heat power tariff is not to be lower than the inflation rate, eventually throughout the wind turbine service life (20 years), the tariff will on average increase from 0.089 USD/kWh in 2022 to 0.1928 USD/kWh in 2041, according to Fig. 2.

To carry out the WPP construction project, the seed funding I_{WPP} will be required. Such funding is determined by the specific capital investments in the wind turbine purchase k_{WPP} and its capacity N_{WPP}, USD:

$$I_{WPP} = k_{WPP} N_{WPP}. \quad (10)$$

The specific capital investment in modern wind turbines is about 1.150 USD/kW, the subsequent costs associated with the WPP construction and commissioning (transportation, customs duties, creating the access roads, installation and assembling of wind turbines, constructing the power transmission line and the transforming substation followed by its connection to WPP, etc.), will lead to cost increase of WPP by about 50 %. Specific capital investments in wind turbines will result an increase approximately up to $k_{WPP} =$ $= 1.715$ USD/kW, which meets the world level [27, 36]. Then construction investments in the wind turbines will be $I_{WPP} = 1.715 \cdot 1.700 = 2.915$ million USD.

In order to convert the electrical energy generated by WPP into heat, it is necessary to provide for the installation of an electric boiler room, for the purpose of heat water to supply it to the heating network. At the time of weak or no wind, when the water has no time or cannot be heated to the proper temperature, it first enters the boiler room, running on fuel oil, where it is heated up, and after that it is supplied to the heating network.

Modern electrical boiler rooms can be made as ready-made heat-insulated block-modular prefabricated containers, which include a full range of equipment for generating and supplying heat. This significantly reduces the installation time of such a boiler room, as well as simplifies assembling and connection to external systems.

When selecting an electric boiler room, first things first, its optimal power is determined. In our particular instance, the optimal power of the electric boiler room should be taken so as to all the WPP power can be used in the required amount. Assuming that the total power of the WPP considered is 1.7 MW, the power of the electric boiler room should not be less than this value.

Supply analysis of some companies engaged in the manufacturing and sailing block-modular electric boiler rooms showed that the cost of constructing 1.7 MW electric boiler room is about 143000–285000 USD, which includes the purchase, transportation and connection of an electric boiler room on-site. Thus, to the investments for the wind turbine construction (2.915 million USD), one also need to add the electric boiler room construction costs (on average, this is 215000 USD). The total investment will appropriately be I_0 = 3.130 million USD. This value is used in the calculations further.

To service the WPP, one technician working at half pay with a salary of 430 USD a month is required. Then, salary presumably changes likewise the inflation rate assumption (Fig. 7, curve 4). The calculation results of other annual operating costs of the WPP considered are also presented in Fig. 7.

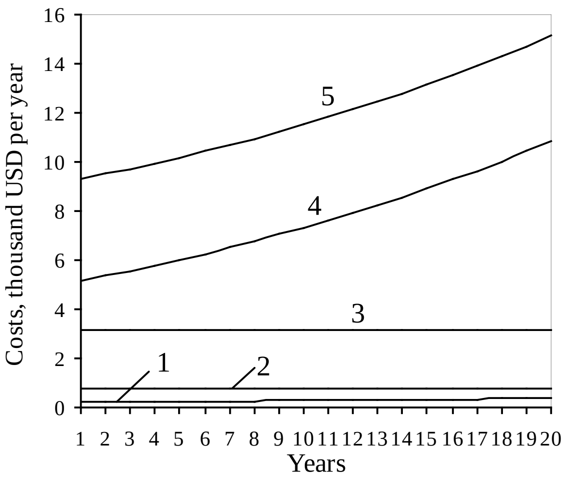

Fig. 7. The annual operating costs structure of the wind turbines considered: 1 – miscellaneous costs; 2, 3 – costs for repairs and overhauls respectively; 4 – salary; 5 – total operating costs

Results and discussion

The feasibility of the construction and the use of the given wind turbines for the heat supply needs, feasibility studies of the WPP efficiency with the following analysis were carried out for different possible scenarios.

Scenario 1. Unleveraged WPP construction. In this scenario, WPP can be purchased and constructed using the funds of a future owner, state subsidies and project co-founders investments. Then, in accordance with formulas (3), (4), the discount rate is r = 0.04 (4 % per annum). The NPV calculating results for this the WPP construction scenario are shown in Fig. 8, curve 1. There only investments I_0 are apparent that at the beginning, right after the WPP construction (zero year in the Fig. 8). The investments equal to 3.130 million USD are on the lower part of the *Y*-axis. As the WPP operates, income is generated, determined by the heat power tariff and the amount of energy generated by the WPP. Due to the income, investments are progressively amortized, and the discounted payback period (DPP) of the project is about 7 years. After that, the NPV curve goes up, 5.66 million USD profit can be consequently generated by the end of the scheduled service life of the wind turbines (20 years), which corresponds to 180 % of the seed funding. This means that for each US dollar invested, the WPP owner can make 180 US cents profit, taking into account the repayment of a US dollar invested.

Scenario 2. WPP construction funded by bank loan. The scenario under consideration of wind turbines construction and their further use is a business project that can be classified as small and medium-sized businesses. The state variously supports such businesses, providing favorable conditions for existence and facilitating the subsidy and exemptions, for example, a preferential tax treatment and lending can be offered. For their part, commercial banks offer more and more favorable credit facilities for the small and medium-sized businesses development, trying to make them more attractive to potential entrepreneurs. Regarding that business funding amount is several times higher than, for example, ordinary commercial loan, it is a low interest rate and a long-term repayment period which becoming pivotal here. In view of this, banks develop new business lending programs. Tab. 2 presents a review of the principal lending conditions for small and medium-sized businesses, which are imposed by some of the leading banks in Russia at the time of calculating. As it is shown in the table, the repayment period established by banks for business is quite long and it basically ranges up to 10–15 years with an interest rate from 6–13 % per annum.

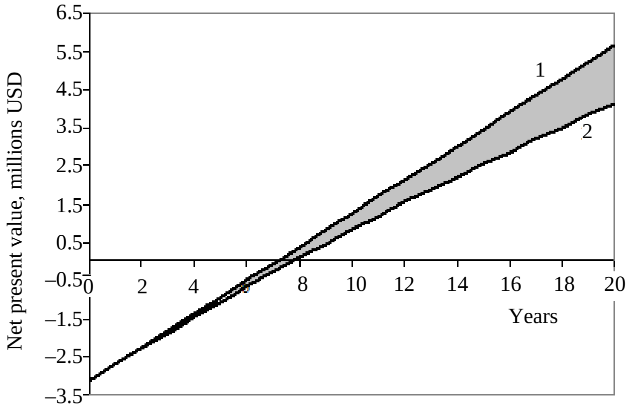

Fig. 8. The net present value formation over the years of wind power plants operation

In that regard, based on the credit drawing facility at a nominal interest rate r_{nd} = 0.15 (15 % per annum) and an inflation rate J = 0.07 (7.0 % per annum), in accordance with formula (6) the real interest rate imposed by a bank on the loan is r_d = 0.07 (7.0 % per annum). If only a bank loan is used for the WPP construction, formula (7) for determining the discount rate is as follows $r = r_d(1-t)$. As a result, the discount rate is r = 0.06 (6.0 % per annum).

Let's address to curve 2 at Fig. 8, which shows the result of calculating the NPV for this WPP construction scenario. The curve shows that the DPP of the WPP construction project is about 8 years, the NPV is about 4.1 million USD (130 % of the seed funding) for the calculation period of 20 years. It follows that for each US dollar invested, the WPP owner can make 130 US cents profit, taking into account the repayment of a US dollar invested.

Table 2

Principal lending conditions for small and medium-sized businesses imposed by some Russian banks

Bank name	Lending conditions		
	Amount of the loan, million USD	Interest rate, % per annum	Repayment period
Sberbank	from 0.002	from 11	to 10 years
VTB Bank	to 2.15	from 6–10	to 10–12 years
Otkritie FC Bank	from 0.004 to 14.3	from 9	to 10–15 years
Russian Agricultural Bank	from 0.007 to 14.3	from 10	to 10 years
Credit Bank of Moscow	determined by an agreement	from 10	to 10 years
Promsvyazbank	to 1.45	from 9	to 5 years
Raiffeisenbank	from 0.06 to 2.2	from 10	to 10 years
Uralsib Bank	to 1.45	from 10	to 10 years
Russian National Commercial Bank	to 2.9	from 13	to 10 years

Scenario 3. WPP construction financed by an owner and a bank loan. World experience [37–39] shows that one loan is not enough to implement projects based on RES, since when granting a loan, a bank takes into account not only the total investment into the project, but also the funds invested by project participants (owner, investors and the state). Therefore, the project implementation scenario is more realistic when the WPP construction is financed by an owner and a bank loan. When implementing this scenario for the WPP constructing, the project's DPP is between 7 and 8 years, and the NPV is in the range from 4.1 to 5.66 million USD, which is illustrated in Fig. 8 (fill area).

The analysis of the financial indicators of the project generally shows that the project is financially reasonable, since for any WPP constructing scenario, the repayment period is quite acceptable, and the funds accumulated is in the positive quantity area, the project can therefore be recommended for practical implementation.

CONCLUSIONS

1. There can be implemented the project for the construction of wind turbines with a total capacity of 1.7 MW on the Barents Sea coast, in the area with the

average annual wind speed of 7.0 m/s, which are intended to be jointly used with a boiler room for heating needs. In this context, the use of wind turbines can be regarded as a saving technology for expensive fuel oil used at the boiler room, with tangible economic, energy and environmental effects.

2. A feasibility study of the wind power plants construction has been carried out, that showed the project can be beneficial for all possible participants: an owner, investors, a bank and the state. Three wind power plants construction scenarios were considered, which calculation results showed the project's discounted payback period is quite acceptable and is approximately 7–8 years under either scenario, and the accumulated funds in the positive quantity area and by the end of the wind power plants scheduled service life (20 years) make up 130–180 % of the seed funding. In other words, for each US dollar invested, the wind power plants owner can make 130–180 US cents profit, taking into account the repayment of a US dollar invested.

3. Practical application of the results obtained, through their disseminating to other heat and power facilities in the future may encourage the large-scale use of wind energy for the heat supply needs.

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