Justification of project and operation modes of hybrid energy complexes for arctic conditions

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Abstract. Currently, one of the priorities based on the "Energy strategy of Russia's development to 2030" is the development of energy infrastructure of the Arctic and Far Eastern regions of Russia, which geographically make up about 65% of the country and located in the areas of decentralized power supply. The total installed capacity of diesel power plants (DPP) operating in the northern regions are more than 500 thousand kW with the production of about 2.5 billion kW·h, which requires the consumption of about 1 million tons of diesel fuel per year. Diesel fuel delivery to these regions carried out in the framework of the "northern" delivery. The article considered methods of hybrid systems based on renewable sources design, allowing optimize technical and economical parameters and increase the penetration of diesel fuel imported to the northern territories to provide consumers with the energy. The first method is a 3-level sequence of the wind energy resources (WER) assessment at a specific point of the energy complex location, for enhancing the reliability of which reanalysis database of satellite observation are used and most accurately describes the wind flow in the Russian northern regions. The second method is the operation modes justification of the power distribution between diesel generators at the diesel power plant. Both methods have been tested at the existing hybrid system 1000 kW (800 kW – diesel part, 200 kW – wind part) in the village Anderma (Nenets Autonomous District, Russia).

1. Introduction
Almost the entire Russian Arctic territory is located in the isolated (autonomous) power supply zone and mainly provided with electricity from diesel power plants (DPP) operating on imported fuel.

The cost of energy production for such DPP is 0.25-2.0 Euro / kWh, which is much more expensive than in the areas of centralized power supply. At the same time, the wind energy potential in autonomous power supply areas is high and can be used by creating autonomous hybrid systems - wind-diesel power plants (WDPP).
Parameters and operating modes justification of such WDPP is an important scientific and practical task, the competent solution of which will ensure efficient and modern power supply to consumers, a high penetration of diesel fuel, a reduction of diesel delivery volume from the north, saving of a diesel engine life and reducing the economically justified tariff. The solutions of these tasks consist of two main subtasks: 1 – reliable assessment of the available wind energy resources in limited natural and climatic information conditions; 2 - parameters and operating modes of the hybrid systems justification to ensure the maximum replacement of diesel fuel.

2. Description of the approach for estimating wind energy resources using reanalysis databases for the Arctic territories

The assessment of wind energy resources in Russia is based on methods [1-6], using materials of regular observations from the meteorological stations of the USSR State Committee of Hydrometeorology and the Russian Hydrometeorological Committee. Available datasets from meteostations are often insufficient due to the low density of the meteorological network. However, due to the low density of the meteorological station network, the available data are often insufficient, since the distance between them can significantly exceed the characteristic scale of the spatial variability of the wind characteristics. The average coating density of hydrometeorological stations (HMS) in Russia is about 51582 km², which corresponds to the distance between the network HMS stations about 227 km [7]. In the Far North the meteorological coverage density is even lower and the value of wind resources at the location of the wind farm remote from the HMS may significantly differ from the values measured on it.

In the lack of high-quality meteorological information the authors proposed a methodology of a three-level wind potential assessment [4] to improve the accuracy of electricity generation forecast at the wind farms, using the second-level mesoscale evaluation of the reanalysis databases developed by various international organizations and institutions. Reanalysis data is based on satellite observations processed in global numerical weather prediction models (NWP) and represent as datasets of synthesized values (wind speed and direction) at each point of mesh. The main disadvantage of using reanalysis data is different validation in different regions of the world [8, 9].

From the existing reanalysis databases were selected covering all territory of Russia (CFSR [10], MERRA [11], NCEP/NCAR [12]) and data of the secondary reanalysis (Met Office [13]) and Vortex [14]), which scales traditional reanalysis data with using NWP models with higher resolution.

The algorithm for resources estimating using reanalysis bases is shown in Figure 1.

![Algorithm of wind resource assessment based on reanalysis data](image)

Figure 1. The algorithm of wind resource assessment based on reanalysis data.

Algorithm is conducted in several stages:

2.1. *Implementation of short-term in-situ measurement*

Observations were carried out with specialized wind monitoring complex in accordance with international standards [15, 16].
2.2. Statistical analysis of measured data. Calculation average values of wind speed \( V \) and power density \( N_e \) during the measurement period

During statistical processing measured data was filtered by invalid values in cases of anemometer icing and tower shading. The power density of wind flow in each moment is determined by the equation:

\[
N_e_i = \frac{1}{2} \cdot \rho \cdot V_i^3,
\]

where \( \rho \) - air density, \( V_i \) – wind speed in each moment.

2.3. Conducting Measure-Correlate-Predict (MCP) analysis with a processed series of full-scale measurements, determining correlation coefficients and synthesizing the long-term wind statistics.

MCP analysis allows to estimate a correlation of time series by linear regression. Correlation degree is determined by the coefficient \( r^2 \), characterizing the dispersion (standard deviation) of the measured values from the line that describes the relationship between the time series [17]. Measurements in compared datasets (target and reference time series) may be done at different heights and in different points of terrain. The main conditions for the selection pair of time series is their homogeneity and location within one climate zone.

A comparison of the series using the MCP analysis can be performed with different intervals, which significantly affect the resulting value of the determination coefficient. In case of very small comparing intervals the ranks may differ due to various micro-climatic factors in the measuring point. In case of large comparing intervals, the characteristics of wind speed stroke can be flatten and not reflect the real picture. The optimal value of comparing interval is determined by the empirical relationship [18]:

\[
\Delta t \approx \frac{D}{\nu},
\]

where \( D \) is distance between points of compared datasets [m], \( \nu \) is mean wind speed [m/s].

Interval comparison is assumed to be optimal, except the cases with greater frequency measurements in the series.

The recommended value of the determination coefficient \( r^2 \) in the international practice of wind monitoring is 0.7-0.8, which ensures a good comparability of the two time series and is considered to be acceptable to synthesize a long-term wind statistics with high accuracy [19].

Because of the small and of similar value of correlation coefficients for different reanalysis database and taking into account the scope of further use of these data (direct evaluation of the WER at the point without comparison with the field observations), it is advisable to compare the WER value estimates with the period of in-situ measurements.

2.4. Annual wind resource assessment (for the period of in-situ measurements) based on reanalysis data using numerical simulations

For wind resource assessment based on reanalysis data, geographically remote from a particular point, microscale modeling is performed in the WindPRO software package, taking into account the influence on the wind flow of the relief and the roughness of the underlying surface. To enable direct comparison of results with the wind monitoring results, the measurement period was assumed equal to the period of field observations [20].

For each reanalysis database calculations were made separately for each grid node, and also based on several series simultaneously (using weight coefficients depending on the distance from the calculated point).

For the time series, geographically located at the same point (secondary reanalysis data), conducted wind speed distribution by the gradations description of Weibull distribution and its further vertical extrapolation to the respective vertical profiles.

Assessment of the gross wind potential is major step in the design of wind farm, however the large differences in wind power estimates could significantly affect the estimates of annual wind farm power output due to the non-linearity of the wind turbine power curves. Therefore, the generation of electricity for a specific wind turbine located at the point of in-situ measurement was also calculated.
As the wind turbine was considered nED 100 [21] manufactured by Norvento enerxia (Spain) with the installed capacity of 100 kW and a tower height of 29.5 m. The wind turbine type was selected out of using in the northern regions wind turbines with small capacity and an extended operating temperature range [22].

2.5. Analysis of the results obtained. Selection of reanalysis database, which describes the wind flow in the northern regions of Russia the most accurately

Choosing the most suitable reanalysis database is based on an analysis of two criteria: the determination coefficient and the estimates of wind resources obtained by numerical simulation. The determination coefficient reflects the considered series correlation with the in-situ measurement data, identifies the series most suitable for synthesizing a long-term statistics based on short-term observations (statistical modeling). The use of in-situ measurement data at a specific location allows to verify the series obtained at numerical modeling and thereby increase the reliability of the WER estimation. The introduction of the correction factors for $V_{ave}$ and $N_e$ allows to evaluate the WER in the proposed construction site directly on the basis of the reanalysis data (numerical modeling) without in-situ measurements.

2.6. Wind resource assessment based on long-term wind statistics with using statistical and numerical modeling. A comparison of the values with the existing estimates (based on data from the meteorological station)

Statistical modeling is synthesizing the long-term wind statistics using the MCP analysis based on short-term in-situ measurements (target data) and reanalysis data time series with the highest correlation. In this case synthesized long-term wind statistics presents the characteristics of wind flow in the point and at the height of wind monitoring.

Numerical modeling is similar to paragraph 2.4 and based on long-term time series from selected reanalysis database.

3. Distribution of power between the generating equipment of diesel power plant and wind power plant

The main criterion of functioning when designing a WDPP with a high penetration in arctic conditions is the minimization of the consumption of diesel fuel while providing a balance of production and consumption of electric energy. To achieve this criterion, it is required to ensure maximum power generation for wind turbines in all operating modes.

The main characteristic in the distribution of power in the energy system is the power balance at each given time, which ensures the stabilization of the frequency and voltage of the autonomous network and is given by formula:

\[
\begin{align*}
\Sigma P_S &= \Sigma P_L \\
\Sigma Q_S &= \Sigma Q_L
\end{align*}
\]

where $\Sigma P_S, \Sigma Q_S$ – active and reactive power of all sources, kW; $\Sigma P_L, \Sigma Q_L$ – active and reactive load powers, kW.

If there is an excess of power $+\Delta P$, this value is useful for charging the accumulating system (AS). For this purpose, it is checked the condition "state of the charge (SOC) = 100%". By 100%, the excess capacity can be reset to a ballast load or to reduce the output from the wind farm by the pitch control of the blades. Underestimation of output is useful when increasing the load power, as a frequency or spinning reserve.

When there is a shortage of power, amount $-\Delta P$ is created, covered by switching off the ballast load, connecting the spinning reserve or the stored energy from the AS. In view of the high inertia of the diesel-generator system, the power redistribution functions at the time of switching off the diesel generators are assigned to the AS with a bi-directional power converter. When predicting a continuous shortage of power, the diesel generators is sequentially switched on, beginning with smaller units of
smaller capacity, due to the lesser inertia of the latter. When the condition "SOC is less than the minimum", a part of the power from the DPP goes to the charge of the AS.

In this moment, the optimal distribution of power between the generators makes using DPP more efficiently, additionally saving fuel. At the same time, it prevents the work of equipment in the non-recommended area.

The objective function for this task is to minimize fuel consumption Q and reduce the number of cycles of on/off DPP:

\[
\begin{align*}
Q & \rightarrow \min \\
n & \rightarrow \min
\end{align*}
\]  

Since the diesel generator in the hybrid system with a high penetration at any moment of time is in the off state, the required power value denoted in the previous section \( \Delta P \) is covered either by one diesel generator or by a combination of generators from condition:

\[
P_{50} < \Delta P < P_{90}
\]  

where \( P_{50}, P_{90} \) – power of i-generator with loading ration between 50% and 90% (security of claim of energy reserves in case of system fluctuations without loss of the operational efficiency of the DPP).

When performing this condition it is switched on only the most efficient generator, which saves the runtime of other generators, which will reduce the number of outages in the system and increase the operating time to failure. The determination of the most effective installation is based on a comparison of the approximate functions of the fuel consumption on the unit's power \( Q(P) \):

\[
Q = a \cdot P^b + c,
\]  

If condition (5) is not fulfilled, the optimal distribution must be considered as a solution of the equation system:

\[
\begin{align*}
Q &= a_1 \cdot x_1^{b_1} + c_1 + a_2 \cdot x_2^{b_2} + c_2 + \cdots + a_n \cdot x_n^{b_n} + c_n \\
x_1 + x_2 + \cdots + x_n &= \Delta P, \\
50\% &< x_i < 90\%
\end{align*}
\]  

To solve such an equation system, it is apply the Lagrange multiplier method with the Kuhn-Tucker condition [22]:

\[
\begin{align*}
\frac{\partial L}{\partial x_1} &= a_1 \cdot b_1 \cdot x_1^{b_1-1} + \lambda = 0, \\
\frac{\partial L}{\partial x_2} &= a_2 \cdot b_2 \cdot x_2^{b_2-1} + \lambda = 0, \\
\vdots \\
\frac{\partial L}{\partial x_n} &= x_1 + x_2 + \cdots + x_n - \Delta P = 0
\end{align*}
\]  

By solving this system, we obtain a solution for the optimal distribution of active power at the diesel power plant.

However, with a continued increase in power, it is required to recalculate the Lagrange function (8), which can cause additional outages in the system. For example, the variant of the possible loading of DPP is shown in Figure 2. For some value of \( \Delta P_1 \), DG#2 is in the off state. If the Lagrange function is recalculated for a new value \( \Delta P_2 \), it may occur a situation when it is necessary to turn off the DG#3 and turn on the DG#2, which causes additional commutations in the system and increasing switching times. Thus, if the continuous operation of the DPP is occur, the system uses a "greedy" algorithm, the basis of which is to maximize the use of already included equipment (Figure 2).
When the power is increased by any amount of $\Delta 1$, the system analyzes the switched-on DGs, selecting those that operate in the non-recommended (low-efficiency) area. To ensure an increase in power by an amount $\Delta 1$, the system alternately increases the power of each such DG to 50%, choosing them in order of efficiency. Thus, the most efficient diesel fuel consumption is the first to be loaded. If this increase in power at the DPP does not cover the value of $\Delta 1$, the DGU at the current capacity is once again evaluated for efficiency. Thus, the system continues to load the most efficient diesel fuel consumption to 100%. An example of the algorithm is shown in Figure 2. Based on the example of a DES consisting of 5 DGUs, located in the figure from left to right in efficiency, an algorithm is shown for loading the plant with a power increase by $\Delta 1$.

If the power is reduced by $\Delta 2$, the system reduces the load of the most inefficient fuel consumption of the diesel generator from the end to the value of 50%, so that it remains possible to reduce the load to 40% with an additional reduction in power.

4. Research results on the WDPP in the village Amderma
Approbation of methods was carried out during the design and operation of the WDPP in the village Amderma in the Russian Arctic area [4, 19, 23]. As a result of filter observations of wind monitoring, time series of wind speed and direction at a height of 40.8 m was obtained. Average value of the wind speed is 8.23 m/s. Mean wind flow power density is 666 W/m². The data were used in the design of
WPP and justification of its production. The vertical profile of wind speed distribution is described by a power law and corresponds to the profile index $\alpha = 0.196$.

Based on the results of numerical simulations, assessment of gross wind resources based on reanalysis data significantly underestimated (13 to 64%). This exceeds the accuracy of modeling that characterizes the quality of reanalysis database as insufficient for using without a comparison with in-situ measurements or climatological data directories. The greatest uncertainty in the estimates is given by secondary database reanalysis (Vortex and MetOffice), that justified higher resolution mesoscale modeling data series. Such datasets does not recommended to be considered when microscale numerical modeling can be proceeded. Despite the fact that the best estimate of the average accuracy rate was obtained from one of the series CFSR, the simulation results based on each point of the mesh differ. Most similar values of wind resource estimates have reanalysis database MERRA, indicating a high precision used in its NWP simulations digital models of orography and roughness.

As expected, the errors of technical wind resource assessment were significantly less than errors of gross values. Apart from the Vortex series, all datasets give the error not more than 20%, it is comparable with the errors of numerical modeling. The closest indicators (8-9% error) have reanalysis databases CFSR and MERRA. The proximity of the simulation results based on a series MetOffice is attributed to random coincidences due to the intersection of the vertical profiles at the height of the wind power plant tower. The solution to this problem can be solved in two cases:

- Establishment of correction coefficients for the gross ($a_g$) and technical ($a_t$) wind resources based on relationships:

$$a_g = \frac{N_{e_{vic}}}{N_{e_i}}, \quad a_t = \frac{W_{vic}}{W_i},$$

where $N_{e_i}, N_{vic}, W$ and $W_{vic}$ are estimates of the wind flow power density ($N_e, \text{W/m}^2$) and annual power output ($W, \text{MWh/year}$) based on reanalysis data and in-situ measurements at the same period respectively.

- Establishment of a correction coefficient for wind speed ($a_v$). In this case, the numerical simulation of the wind flow is based on the modified time series of wind speed in each point of mesh for corresponding reanalysis database.

$$a_v = \frac{V_{vic}}{V_i} = \sqrt[3]{\frac{N_{e_{vic}}}{N_{e_i}}} = \sqrt[3]{a_g},$$

where $V_i$ and $V_{vic}$ are mean values of wind speed for reanalysis data and in-situ measurements at the same period respectively.

Correction coefficients were calculated for reanalysis databases CFSR and MERRA. The values of gross and technical wind resources in point of wind monitoring were calculated with using these corrections, except $Ne_{MC}$ and $WMCP$, which were defined with using time series synthesized on the base of in-situ measurements using MCP analysis (table 1).

| Reanalysis database | $a_{g}$ | $a_{t}$ | $a_{v}$ | $Ne_{ag}$, W/m² | $W_{ag}$, MWh/year | $Ne_{at}$, W/m² | $W_{at}$, MWh/year | $Ne_{av}$, W/m² | $W_{av}$, MWh/year | $Ne_{MC}$, W/m² | $WMCP$, MWh/year |
|---------------------|--------|--------|--------|-----------------|---------------------|-----------------|---------------------|-----------------|---------------------|-----------------|------------------|
| CFSR                | 1.52   | 1.08   | 1.15   | 783             | 442                 | 709             | 462                 | 678             | 442                 |
| MERRA               | 1.43   | 1.09   | 1.13   | 723             | 422                 | 734             | 456                 | 595             | 430                 |

The consumption of the DGs at the station due to the application of the methodology decreased by an additional 10% per year [23], thus reducing the cost of own needs by three times (from 510 to 160 ths. kWh per year). Saving diesel fuel per year for WDPP without the use of accumulating systems is 303 thousand liters per year (by 40%), maintenance costs for DES disappeared 1.3 times, and CO₂ emissions decreased by 600 tons per year.

5. Conclusion
In order to improve the accuracy of the natural and technical resources assessment in the absence of meteorological observations in the proposed location of wind farms vicinity in the Nenets Autonomous District, it is recommended to use the MERRA reanalysis database and apply a correction factor for wind speed equal to 1.13. Calculation of correction factors for wind speed and gross technical potential of the other Russian Arctic regions recommended to be carried out similarly according to the procedure described above.

Reanalysis databases allows to obtain short-term (up to 10 minutes) long-term series of wind statistics, in contrast to the use of reference data, containing integral characteristics of wind speed and wind energy resources. The use of wind speed series obtained allow to justify the choice of WDPP equipment and to improve the accuracy of the electricity production forecast at the wind farm and the operation modes of its cooperative work with the DPP.

An algorithm for the distribution of power at the DPP was developed to reduce the inefficient fuel consumption. The mathematical apparatus of this algorithm is adapted to the DPP practical implementation, taking into account the reduction of the diesel sets in the operating time associated with the number of switching on/off the particular diesel generators. The developed methodology allows to further reduction of the diesel fuel cost at DPP, increasing the operating time of the equipment.

Application of proposed methods in the design of WDPP for Arctic conditions and optimization of its operating modes allows increasing the share of diesel fuel replacement, which is reflected in the amount for subsidies reduction when covering economically justified tariff for the settlements located in the Arctic regions. For the WDPP project in the village Amdemra economically justified tariff is reduced by 38% (about 750 thousand $).

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