DEA method application to evaluating the efficiency of heat and wind generating complexes

N V Zenyutkin¹, I V Kovalev¹,²,³, M V Karaseva¹,², V V Dvirny⁴, A A Melkomukov⁴and N V Lukinin⁴

¹Siberian Federal University, 79, Svobodny Av., Krasnoyrsk, Russian Federation
²Reshetnev Siberian State Aerospace University 31, Krasnoyarsky Rabochy Av., Krasnoyarsk, Russian Federation
³Krasnoyarsk State Agrarian University, 90, Mira pr., Krasnoyarsk, 660049, Russian Federation
⁴JSC "Information Satellite Systems" Academician M.F. Reshetnev " 52, Lenin st., Zheleznogorsk, Krasnoyarsk Krai, Russian Federation

E-mail: nvzenutkin@gmail.com

Abstract. The article considers the thermal power enterprises’ impact on the ecology of Krasnoyarsk Krai. It gives the characteristic of the general state in the region’s heat power industry taking into account problems of providing heat to remote communities. A heat and wind generating complex is considered as an alternative thermal energy source. The problem of calculating the efficiency of such complexes is introduced. The DEA method based on the calculation of the boundary performance is treated. The input and output parameters of modern heat and wind generating complexes are described. The DEA method modernization based on the adjustment factors generation is justified.

1. Introduction
Nowadays, the environmental problem in Krasnoyarsk Krai is very acute. Invariably, non-ferrous metallurgy and thermal power enterprises are the main chemical pollutants of atmospheric air in Krasnoyarsk Krai. So, the total emissions from stationary sources were recorded in general as 2,318.9 thousand tons in 2018. It amounted to 88.7% of the total number of emissions into the atmosphere (2613.8 thousand tons) [1].

The well-known fact is that the Mining and Metallurgical Company (MMC) “Norilsk Nickel” is the main air pollutant in Krasnoyarsk Krai. In 2018, emissions of pollutants into the atmosphere from this enterprise amounted to 1789.0 thousand tons (77.2% of the total volume of emissions from stationary sources) [1].

2. Statement of the problem
The subject of this article is the enterprises of the power industry. A share of atmospheric emissions of such enterprises as JSC Krasnoyarsk Electric and Power Supply - 1 (HEC-1), Krasnoyarsk HEC-2, a branch of JSC Yenisei TGK (TGK-13), Krasnoyarsk HEC-3, a branch of JSC Yenisei TGK (TGK -13) amounts to 43.9 thousand tons. The main fuel of such stations is coal, in the process of its burning the electricity and heat are generated.
These enterprises are located in large cities of the region. However, 33% (about 950 thousand people) live in remote municipalities of the region with a population of less than 20 thousand people [2]. In these communities, local heating plants are built to provide heat. But sometimes they are non-existent. Such local heating plants require a certain type of fuel; its constant delivery to remote communities can be associated with high financial costs.

Due to the large financial service expenses of such local heating plants, as well as the inefficiency of heat energy generation, a large cost of 1 Gcal arises. For example, in Kansk, heat tariffs from the Kansk Electric and heating supply (Kansk HEC) amount to 1371 rubles/Gcal, from HEC “Teplosbytservice” it is 2472 rubles. And the heat of the local heating plant “Gortepl,o" is released at 3894 rubles/Gcal [3]. Kansk cannot be referring to “a remote city” in Krasnoyarsk Krai. Nevertheless, the expenses of 1 Gcal of the local heating plant are very high.

In 2019, Research and Development Office “Mikron”, included in “Kaneks” group, announced the Heat and Wind Generating (HWG) complex, which will be able to generate heat thanks to wind energy and provide it to consumers in remote areas and, possibly, solve the described problems of providing heat and electricity, as well as significantly reduce the cost of thermal energy. This HWG complex will be built at the 18th kilometer of a deep pass-by of Krasnoyarsk outside the Solnechny micro district, which will provide heat to the Research and Development Office “Mikron”. In future, it is planned to provide heat to remote communities in Krasnoyarsk Krai with the help of such local plants. Here, other types of thermal energy are not economically profitable or efficient. Thus, it means a problem about the efficiency of the heat and wind generating complexes.

The efficiency of these heat and wind generating complexes is directly related to the efficiency of wind power plants. As for the general situation with the wind energy, Krasnoyarsk Krai, has only small wind energy complexes with low and very low power capacity. For example, according to the information from [5], one should mention the following wind energy complexes:

- Wind power. It consists of two wind power plants (wind turbines), in the Evenki municipal district in the settlement Tura. These wind turbines provide with the power a commercial enterprise [5];
- Wind-diesel power station (VDPS). It provides with the power a cellular relay. This VDPS is located near the cafe “Taiga” on the R-257 highway and it is currently operating [5];
- Decentralized power supply through wind turbines. Its carried out on the tourist base located in an inaccessible territory of the Eastern Sayan [5].

As one can note, the wind power is not sufficiently developed in Krasnoyarsk Krai, and there is no thermal wind power at all.

At first glance, it might seem that wind power plants are not popular due to the lack of the most important efficiency component of such objects as sufficiently high mean annual wind force. However, based on an analysis of the average annual wind speed for a lot of years reduced conditions of open territory on flat or convex landforms at the altitude of 10 m from the earth’s surface Krasnoyarsk the average annual wind force is 3.8 m/s. And in the northern regions (Dikson, Dudinka) it exceeds 7 m/s per year [5].

The plant applied for Research and Development Office “Mikron” has a maximum generator power of 200 kW with a rotor axis height of 35 meters, and with a sweeping blade area of 35 meters. With an average annual wind speed of 3.8 m/s, the average annual power of such a plant will be 70 kW [6].

Note that the efficiency of such plant is affected not only by wind speed, but also by a number of other parameters. Among other things, the plant for Research and Development Office “Mikron” is not just wind power, but heat and power. That is, in addition to the wind generator itself, the elements of the autonomous wind turbine include the elements shown in Figure 1. These elements undoubtedly also affect the efficiency of the whole plant.
3. Proposed solution

Taking into account the information given above, we can conclude that we have a certain set of data (inputs) and one or more indicators (outputs) of the working result of the input data set. However, in order to have a complete understanding whether our plant is effective, we need an object to compare their efficiency. In this case, we also will not be able to give recommendations for improving the plant for more efficient operation.

To solve this problem, it is necessary to choose the appropriate method for evaluating the efficiency taking into account the following restrictions:

- method should take into account only input and output indicators of the studied objects, since we do not have others. For example, the index method is not suitable, since it involves the consideration of weighting coefficients determined by experts that we do not have at this stage [7];
- result of the method is to be one integral indicator for each object. Each object should be ranked by this indicator, and specific changes in the input and output parameters should be evaluated to increase the efficiency of the object. For example, cluster analysis will well cope with task of ranking objects, but an expert will have to evaluate the resulting groups (clusters). Also, cluster analysis will not be able to give recommendations for improving the efficiency of the object [7];
- for a reliable estimation of changes in input and output parameters, we need a certain boundary performance to derive inefficient objects.

Taking into account the limitations described above, the Data Envelopment Analysis (DEA) method can be applied to evaluate the efficiency of heat and wind generating complexes. Give a brief descriptive part of this method.

Suppose we have a certain set of objects $N$ with each set of input data $K$ and set of output data $M$. $K$ and $M$ are represented by column vectors $x_i$ and $y_i$ respectively for each $i$-th object. Then, it is possible to proceed to the problem of mathematical programming using a matrix of input parameters $X$ of dimension $K \times N$, and a matrix of output parameters $Y$ of dimension of $M \times N$ for all objects $N$[8]. Formulate the problem described above on the basis of the duality theory in the following form [9]:

$$
\begin{align*}
\min_{\theta, \lambda} & \quad \lambda(0), \\
& \quad -y_i + Y\lambda \geq 0, \\
& \quad \theta x_i - X\lambda \geq 0, \\
& \quad \lambda \geq 0,
\end{align*}
$$

(1)

where $\theta$ is a scalar; $\lambda$ is a vector of dimension constant $tN \times 1$. 

![Figure 1. Schematic diagram of the HWG complex. 1 - wind generator; 2 - heat storage unit; 3 - thermal battery; 4 - electric heater; 5 - heat exchanger; 6 - block of auxiliary systems (electric energy storage, pumping equipment); 7 - pipeline of the heating system; 8 - consumer.](image)
The resulting scalar $\theta$ will be the efficiency measure of the $i$-th object. Moreover, $\theta$ cannot be greater than one. Thus, solving the problem $N$ times, we get a set of objects for which the scalar $\theta$ equals one, i.e., these objects will be on the boundary performance. Such a boundary is formed as piecewise linear. Objects with $\theta$ less than one can be projected into the boundary performance so that each of these objects will be equal to a linear combination $(X^*, Y^*)$. Some elements of the vector $\lambda$ have nonzero values. These elements correspond to the object, which is the reference for the evaluated object. In turn, a linear combination of reference objects forms a hypothetical reference object located at the boundary performance. In other words, we get an object that, if it existed, would be a reference. The variable’s values of such an object are the objective for the real object.

This model is called an entry-oriented model with a constant scale effect. Also, the output-oriented models and the models that can take a variable scale effect by introducing restrictions on the sum of weight coefficients into the model have been developed [9]. The DEA method can also take into account environmental variables. These variables differ from ordinary inputs, since they make adjustments to calculations that cannot be influenced by solving the problem.

So, to build a mathematical model, we are to known input parameters of the concrete objects. Consider the input parameters of the HWG complex model. In the general case the input parameters for wind power plants, taking into account a heat storage unit, are presented in table 1.

| Parameter Category                      | Input parameters                                                                 |
|----------------------------------------|----------------------------------------------------------------------------------|
| Wind generator parameters              | Wind wheel diameter (m)                                                          |
|                                        | Hub height (m)                                                                   |
|                                        | Rotation speed (r/min)                                                           |
| Wind speed:                            | - starting (m/s)                                                                 |
|                                        | - rated (m/s)                                                                    |
|                                        | - stopping (m/s)                                                                 |
| Rated power (kW)                       | Network Frequency (Hz)                                                           |
| Rated voltage (V)                      | Rotation speed (r/min)                                                           |
| Type                                   |                                                                                  |
| Heat storage unit parameters           | Drive capacity (m$^3$)                                                           |
|                                        | Heat carrier power (kW)                                                          |
| Climatic parameters                    | Wind speed (m/s)                                                                 |
|                                        | Air density (kg/m$^3$)                                                           |
| Wind power                             | Specific wind energy (per month, per season, per year)                           |
| Territorial parameters                 | Remoteness of the object from administrative centers                             |

The output of the model will be the efficiency indicator of this plant, equal to one if the plant is effective or from zero to one, depending on how far the object is from the boundary performance.

Consider the inputs of the model again. The inputs related to the parameters of the wind generator and heat storage unit are optional. They can vary depending on the amount of heat consumption or other circumstances. Climatic and territorial parameters are permanent, depending on the geographical
location of the object. Therefore, it is necessary to use coefficients reflecting the territorial and climatic conditions of implementation in calculating the efficiency of the plant.

It is necessary to modify the DEA method to implement the proposed approach. A feature of this modification will be the formation of a set of correcting factors for model outputs that will take into account the territorial and climatic components of the HWG complexes implementation.

4. Conclusion
As a result, a hypothetical ideal object can be established applying the modified DEA method for a set of HWG complexes with different initial parameters (inputs). On its basis it will be possible to identify the efficiency of a particular complex from our set. The main idea is the modification of the DEA method development that takes into account correcting factors for the efficiency of the implemented HWG complexes identification. Further investigation will be directed to the development of the DEA method modification, its software implementation with testing on the complex of wind generation plants both in Krasnoyarsk Krai and other regions of the Russian Federation and abroad.

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