Implementation of Power Plants Based on Renewable Energy Sources in the Primorsky Krai

A A Chernyavsky¹, O A Ivanin¹, A L Shevchenko¹, V M Zaichenko¹

¹Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS), Moscow, Russia

E-mail: shev@jiht.ru

Abstract. The results of calculations presented in the article show the effectiveness of the transition from diesel power plants using imported fuel to installations using renewable energy sources – solar cells and wind generators. Studies have shown that for Primorsky Krai such a transition is justified, despite significant capital costs, and the payback period for new power plants based on renewable energy sources is about 8 years.

1. Introduction

Up to 70% of the territory in Russian Federation is out of coverage area of centralized power supply. In many such regions, including Primorsky Krai, diesel power plants using imported fuel are used to provide electricity. By the end of 2020 electric power industry of Primorsky Krai included five large thermal power plants with a total capacity of 2706.5 MW, three mini-CHP plants with a total capacity of 49.8 MW on Russky Island and 74 diesel power plants (DPP) with a total capacity of N_{dpp} = 21.5 MW [1].

Most of the diesel power plants are located in Krasnoarmeisky, Terneisky and Chuguevsky regions. They provide electricity and heat supply to individual enterprises, organizations, villages, private households, etc. in areas where there is no centralized power supply. Primorsky Krai is an energy-deficient region.

The average electrical power of a diesel power plant is N_{av} = 290.5 kW. The annual electricity generation by all diesel power plants in Primorsky Krai is W_{dpp} = 14.9 million kWh [1], i.e. the average number of hours of using their installed capacity is equal to: t_{ceu} = W_{dpp}/N_{dpp} = 693.0 h/year. With an annual fund of time t = 8760 h/year, t_{ceu} corresponds to the use of fixed assets of diesel power plants by only 8%. The situation is aggravated by the high cost of diesel fuel and its delivery to remote DPP sites. Therefore, the cost of electricity production for a DPP in Primorsky Krai reaches 40-100 rubles/kWh. At the same time, the one-rate tariff for electricity supply at low voltage in effect in 2021 is 6-10 rubles/kWh. And, despite the small share of diesel power plants in the total power supply system of Primorsky Krai, the operation of diesel power plants adversely affects the performance of the power system of the province and requires significant budget subsidies.

For a noticeable improvement in the energy supply indicators of Primorsky Krai and to eliminate the need for budget subsidies, it is recommended to replace diesel power plants with power plants based on renewable energy sources (RES). There are significant potentials of solar and, especially, wind energy in Primorsky Krai, also there are large quantities of industrial and agricultural organic waste of
biomass. Together with these renewable energy sources, it is necessary to use certain energy storage systems for guaranteed energy supply to consumers [2]. Heat pumps can be used for heat supply.

2. Usage of solar energy

As an example, we considered an energy complex with average electric power \( N = 300 \text{ kW} \) and heat power \( Q = 350 \text{ kW} \).

In order to completely reject imported fuel, heat supply to the consumer is carried out by means of heat pumps. The conversion factor of heat pumps lies, as a rule, in the range \( \mu = 3.0 \ldots 6.0 \). Let us take \( \mu = 3.5 \) for our case. Then, for the operation of heat pumps with total heat capacity of \( Q = 350 \text{ kW} \), electric power \( N_{hp} = Q/\mu = 350/3.5 = 100 \text{ kW} \) will be required. In this case, the total average annual electric capacity of the power complex will be:

\[
N_{sum} = N + N_{hp} = 300 + 100 = 400 \text{ kW},
\]

Let us assume that the installed capacity utilization factor for the local energy complex is equal to 0.5, which corresponds to the average annual operating time of the equipment equal to \( t_{op} = 4380 \text{ hours} \). In this case, the annual electricity generation must be at least \( N_{sum} \cdot t_{op} = 400 \cdot 4380 = 1752 \cdot 10^3 \text{ kWh/year} \).

Let's compare the efficiency of using solar and wind energy in the Primorsky Krai under the indicated conditions.

To calculate the generation of electricity (kWh/m\(^2\)) by solar photovoltaic (PV) converters \( W_{pv} \), we will use the well-known relationships [3]:

\[
W_{pv} = W_{sr} \eta_o \left( 1 + \beta (T_o - T_{pv}) \right) \left( 1 + \gamma ln \frac{E}{E_o} \right),
\]

where \( W_{sr} \) is the average daily rate of total (direct and scattered) solar radiation arriving at the surface of a PV module with a given angle of inclination to the horizontal, kWh/m\(^2\); \( \eta_o \) is the efficiency of the PV system, determined under standard irradiation conditions (the power of the solar radiation flux \( E_o = 1000 \text{ W/m}^2 \), atmospheric mass = 1.5, the surface temperature of the PV module \( T_o = 40 ^\circ\text{C} \)); \( \beta \) is a coefficient that takes into account the effect of deviation of the equilibrium temperature from the standard temperature on the efficiency of the PV system; \( T_{pv} \) is the surface temperature of the PV module calculated for a given month; \( \gamma \) is a coefficient that takes into account the effect of deviation of irradiance from the standard one on the efficiency of PV module.

The value of \( T_{pv} \) is determined by the formula:

\[
T_{pv} = T_o + \alpha \frac{E}{E_o},
\]

where \( \alpha \) is a solar heating factor for a PV module.

The value of \( \gamma \) is determined by the formula:

\[
\gamma = \frac{W_{pv}}{t_{dh} - 2},
\]

where \( t_{dh} \) is the average number of daylight hours for a given month.

For PV of Russian production, the following values of the initial data can be taken for calculations: \( \eta_o = 0.20; \alpha = 25^\circ\text{C}; \beta = 0.005^\circ\text{C}; \gamma = 0.07 \).

The average long-term daily air temperature \( T_o \) was determined according to the data of climatic reference books as the arithmetic mean of the hourly mean temperatures from sunrise to sunset, excluding the first hour after sunrise and the last hour before sunset.

For solar power plants in Primorsky Krai, in accordance with NASA satellite observations [4] given in Table 1, we find the values of electric power generation for equatorially oriented PV modules using formulas (2) - (4). The angle of inclination of the modules to the horizontal was taken equal to 50\(^\circ\) and the total installed capacity of PV modules was taken equal to 1100 kW which corresponds to the area of PV elements equal to 5500 m\(^2\). The calculation results are also shown in Table 1.
Table 1. Electric Energy Generation by Solar Photoelectric Converters in Primorsky Krai.

| Calculation period | Janu ary | Febru ary | March | April/May | June | July | Augu st | Septem ber | Octob er | Novem ber | Decem ber | YEAR |
|--------------------|---------|----------|------|-----------|------|------|---------|------------|----------|-----------|-----------|------|
| Number of days in a month, days/month | 31 | 28 | 31 | 30 | 31 | 30 | 31 | 30 | 31 | 30 | 31 | 365 |
| The sum of direct and scattered solar radiation for a PV module with an inclination of $50^\circ$ to the horizontal, kWh/m$^2$ | 192.0 | 194 | 206 | 0 | 186 | 178 | 136 | 163 | 204 | 205 | 169 | 173 | 2131.0 |
| Average air temperature $T$, $^\circ$C | -13.1 | -10.1 | -2.4 | 4.5 | 9.7 | 12.9 | 17.4 | 19.5 | 15.3 | 8.3 | -1.1 | -9.4 | 4.3 |
| The average temperature of PV module, $^\circ$C | 41.1 | 41.0 | 41.2 | 41.1 | 41.1 | 40.8 | 40.7 | 41.0 | 41.2 | 41.2 | 41.0 | 41.0 |
| Average power generation, kWh/m$^2$ | 29.9 | 29.9 | 32.3 | 28.8 | 27.6 | 20.5 | 18.8 | 25.1 | 31.8 | 32.1 | 26.0 | 26.7 | 329.6 |
| Electricity generation by solar power plant with PV area = 5,500 m$^2$, thousand kWh | 164.7 | 164.5 | 7 | 4 | 151.7 | 112.8 | 103.3 | 137.9 | 175.1 | 176.8 | 142.8 | 147.1 | 1812.7 |
| Average power of solar power plant, kW | 221 3 | 244.7 | 8 | 1 | 203 9 | 156.6 | 138.8 | 185.3 | 243.2 | 237.6 | 198 3 | 197 7 | 207 2 |
| Installed capacity of PV modules, kW | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 |

3. Usage of wind energy

To calculate the average annual electricity generation by wind power units in Primorsky Krai, we will use the values of the probability of the distribution of wind speeds according to gradations in the territory under consideration. This distribution is calculated using the two-parameter Weibull function [3]:

```
\[ F(v) = \left(\frac{v}{c}\right)^{(k-1)} \exp\left( -\left(\frac{v}{c}\right)^k \right), \]  

where \( v \) is the value of wind speed in the considered range, m/s; \( c \) is a scale factor m/s; \( k \) is a form factor. The values of the parameters are taken according to the reference data [3]: \( c = 8.5 \) m/s; \( k = 1.9 \).

The results of calculating the Weibull function are shown graphically in Fig. 1.

![Graph of the Weibull function](image)

**Figure 1.** The values of the Weibull function according to the gradations of wind speeds in the territory of Primorsky Krai for a measurement height of 10 m above the earth's surface.

Further calculation of the wind power plants (WPP) parameters was carried out taking into account the dependence of the power of the wind turbine WINCON 200-26.0 on the wind speed according to passport data of the supplier. The results of calculating the main parameters of the WPP are presented in Table 2.

**Table 2.** Calculation of the average power and electric energy generation for wind power plants including two wind power units wincon 200-26.0.

| Estimated range of wind speeds, m/s | Average speed at a height of 10 m, m/s | Average speed at a height of 50 m, m/s | Probability, share | Duration, h/year | Wind turbine power, kW | Electricity generation, kWh |
|-------------------------------------|----------------------------------------|----------------------------------------|-------------------|------------------|----------------------|--------------------------|
| 0...1                               | 0.5                                    | 0.8                                    | 0.0789            | 691.2            | 0.0                  | 0.0                      |
| 2...5                               | 3.5                                    | 5.5                                    | 0.3753            | 3287.7           | 10.0                 | 32877.2                 |
| 6...10                              | 8.0                                    | 12.6                                   | 0.3884            | 3402.6           | 183.3                | 623705.2                |
| 11.15                               | 13.0                                   | 20.4                                   | 0.1562            | 1368.7           | 184.0                | 251833.9                |
| > 15                                | > 15                                   | > 25.0                                 | 0.0012            | 10.2             | 184.0                | 1869.7                  |

| 1.00                               | 8760                                   | 910285.9                               |

Initial data for calculating the monthly output of WPP:
- rated power of the wind turbine, kW – 200;
- the number of wind turbines in a WPP – 2;
- installed electric power of WPP, kW – 400;
- average power of wind turbines, kW – 103.9;
- average power of WPP, kW – 207.8;
- Average annual output of wind turbines, MWh/year – 910.2;
- Average annual output of WPP, MWh/year – 1820.5;
- Installed power utilization factor – 0.52;
- Height of the axis of rotation of the propeller, m – 50;
- Height conversion factor \( Z = (50/10)^{0.28} = 1.569 \);
- Wind turbine diameter, m – 26.

The calculation of the monthly electricity generation and the average power of the wind farm is performed using the data on wind speeds given in the NASA database for the territory of the Primorsky Krai of the Russian Federation [4]. The results of these calculations are shown in Table 3.

### Table 3. Calculation of capacity and generation of wind in Primorsky Krai.

| Parameters                                      | Parameter values for calculation periods |
|-------------------------------------------------|------------------------------------------|
| Wind speed at a height of 10 m, m/s              | January – 6.9, February – 6.5, March – 6.1, April – 6.5, May – 5.9, June – 5.5, July – 5.6, August – 6.5, September – 6.5, October – 6.5, November – 6.5, December – 6.2 |
| Wind speed at a height of 50 m, m/s              | January – 10.8, February – 10.7, March – 9.6, April – 10.2, May – 10.9, June – 8.6, July – 8.6, August – 8.8, September – 10.2, October – 10.2, November – 9.9, December – 9.7 |
| Average power of a wind farm with two wind turbines WINCON 200-26.0, kW | January – 346, February – 331, March – 239, April – 289, May – 276, June – 216, July – 175, August – 175, September – 185, October – 289, November – 289, December – 263, Year – 256 |
| The number of hours in the calculation period     | January – 744, February – 744, March – 744, April – 720, May – 744, June – 720, July – 744, August – 720, September – 744, October – 720, November – 744, December – 8760 |
| Electricity generation of WPP, thousand kWh      | January – 258, February – 223, March – 178, April – 208, May – 206, June – 156, July – 131, August – 131, September – 133, October – 215, November – 208, December – 196, Year – 224 |
| Installed capacity of WPP, kW                    | January – 400, February – 400, March – 400, April – 400, May – 400, June – 400, July – 400, August – 400, September – 400, October – 400, November – 400, December – 400, Year – 400 |

*The conversion factor of the wind speed to the height of the wind turbine axis of 50 m is adopted according to Helman's law*

Thus, a wind farm with an installed capacity of 400 kW (2 units of 200 kW each) in excess provides the required electricity generation in the conditions under consideration – 1752 MWh/year or 146 MWh/month. Solar power plant requires installed power of 1100 kW (5500 m² of PV modules).

The values of electricity generation by WPP and solar power plant by calculation periods are demonstrated for comparison on Fig.2.

It can be seen that the WPP provides greater stability of the power supply system. It’s power reserve is more than required. When designing a real wind farm, the required investments can be reduced by replacing a scheme with two wind turbines of 200 kW by a scheme with three turbines of 50-60 kW.
Figure 2. Changes in electricity generation for solar and wind installations throughout the year.

When electricity is supplied in the amount of 1752 MWh/year, the cost of producing this energy by diesel power plants will be about $R = 1752 \times 10^3 \times 40$ rubles/kWh = 70.08 million rubles/year.

Let us also compare the volumes of required investments in the construction of the considered solar and wind power plants (see Table 4).

Table 4. Approximate Calculation of Investments for the Projects in Consideration.

| Name                        | Units      | Solar power plant | Unit price, thousand roubles | Sum, mln. roubles | Wind power plant | Unit price, thousand roubles | Sum, mln. roubles |
|-----------------------------|------------|-------------------|-----------------------------|------------------|-------------------|-----------------------------|------------------|
| PV modules                  | m²         | 5500              | 36,0                        | -                | -                 | -                          | -                |
| Wind turbines               | kW         | -                 | -                           | -                | -                 | -                          | -                |
| Inverters 0.4 kW, 50 Hz     | kW         | 1100              | 10,0                        | 11,0             | 400               | 10,0                        | 40         |
| Switchgear 0.4 kV           | kW         | 1100              | 5,0                         | 5,5              | 400               | 5,0                         | 2,0              |
| Electrolysis plants         | m³/h       | 540               | 60000                       | 60               | 540               | 60000                       | 60,0             |
| Fuel cell electrochemical generators | kW | 200 | 80 | 16 | 200 | 80 | 16,0 |
| Other equipment             | Set        | 1                 | 3000                        | 3,0              | 1                 | 3000                        | 3,0              |
| Mounting materials          | Set        | 1                 | 12000                       | 12,0             | 1                 | 8000                        | 8,0              |
| Buildings and constructions | Set        | 1                 | 20000                       | 20,0             | 1                 | 30000                       | 30,0             |
| Total                       | -          | -                 | -                           | 325,5            | -                 | -                           | 163,0            |
| Limited costs               | %          | 30,0              | -                           | 97,7             | 30                | -                           | 48,9             |
| Research and development    | %          | 20,0              | -                           | 65,1             | 20,0              | -                           | 32,6             |
| Total Investments (I)       | -          | -                 | -                           | 488,3            | -                 | -                           | 244,5            |

Let us estimate the payback period (PP): $PP = I/(NP + DD)$, where NP is the net profit equal to the difference between sales volumes and operating costs, including taxes; DD - depreciation deductions,
constituting 5% with a service life of power plants of 20 years. You can take \( NP = 0.5R = 0.5 \times 70.08 = 35.04 \text{ million rubles/year.} \)

Thus, the payback periods will be:

\[
PP_{\text{spp}} = \frac{488.3}{(35.04 + 5\% \times 488.3)} = 8.2 \text{ years;}
\]

\[
PP_{\text{wpp}} = \frac{244.5}{(35.04 + 5\% \times 244.5)} = 5.2 \text{ years.}
\]

For power facilities with a service life of 20 years, the calculated payback periods are quite acceptable.

Note that under normal conditions solar power plants are more efficient for the southern regions of the Russian Federation. But in Primorsky Krai there is a large number of days with rains and fogs in summer, which leads to a decrease in insolation and greatly reduces the efficiency of SPP. At the same time, the wind potential in Primorsky Krai is very high, due to the proximity of the ocean coast. Therefore, the use of WPP is a priority. The required capacity of equipment for wind farms is much less, electricity generation is higher, capital costs and payback periods are lower, and the reserve capacity is higher.

4. Conclusion
The transition to renewable energy sources is currently a global trend in the development of energy. In connection with Primorsky Krai, replacing diesel power plants with installations using renewable energy sources can significantly reduce the cost of generated electricity, abandon government subsidies, reduce harmful emissions into the atmosphere and improve the environmental situation in the region. The presented calculations show the possibility and economic feasibility of switching from diesel power plants to power generation with renewable energy sources.

To continue further research in this area, it is advisable to create a test site, where to get practical recommendations on the use of solar power plants, wind farms and energy storage.

5. References
[1] 2021 Energy of Primorsky Krai FreeJournal / Economy
[2] Zaichenko V, Chernyavskij A 2020 Creation of guaranteed energy supply systems using combined energy sources Energy policy 10 pp 90-103
[3] 1997 Atlas of wind and solar climates of Russia ed. M M Borisenko and V V Stadnik (St. Petersburg .: The Voeikov Main Geophysical Observatory) 173
[4] 2007 The NASA (National Aeronautics and Space Administration) Surface Meteorology and Solar Energy Data Set eosweb.larc.nasa.gov/sse

Acknowledgments
This work was supported by the Ministry of Science and Higher Education of the Russian Federation.