Power supply of the center for development of gifted children in Kaliningrad region based on renewable energy sources

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Abstract. One of the modern vectors of world energy development is the transition to an energy self-sufficient principle of functioning of geographically limited local facilities. The paper presents an analysis of the possibility of the transition and the concept of using renewable energy sources in the transition to an autonomous mode of electricity and heat supply of the Center for the Development of Gifted Children in Kaliningrad Region.

1. Introduction
In Kaliningrad Region, there is a Center for the Development of Gifted Children (hereinafter referred to as the Center). At present, power supply of the Center is provided by the electric grid company Yantarenergo JSC with the emergency diesel generator for redundant power supply, and heat is supplied from a gas boiler house. One of the current trends in the global energy development is transition to an autonomous principle of electricity and heat supply using renewable energy sources. Therefore, the transfer of the Center power supply system to solar, wind and thermal energy of the earth (heat pump) is of high relevance. Implementation of this concept is particularly important for formation of an adequate attitude of the younger generation to one of the major trends in the global energy development.

2. Analysis of the structure and electrical loads of the Center
The center is located on the shore of the bay in Kaliningrad region (Figure 1a). It occupies the territory with a total area of 84700 m² and is designed to receive 150 children per session.
The Center is supplied with power from the transformer substation TP No. 09–25 with 15/0.4 kV voltage (Figure 1b), which is powered by a 15 kV power transmission line from the grids of Yantarenergo JSC. The installed capacity of the electrical equipment of 160 kW provides electricity for the Center facilities, including dormitory blocks, a dining room, a boiler house, treatment facilities, outdoor illumination, water intake and an administrative building. The highest power consumption and the maximum power consumption of 65 kW is recorded in August (Figures 2 and 3).

The analysis of the existing power supply system of the Center shows that it is necessary to develop technical solutions for autonomous operation of the Center using renewable energy sources: the annual electricity consumption of 190 thousand kW*h with regard to the highest monthly load in August (20 thousand kW×h), and maximum one-time load (65 kW).

3. Providing heat load of the Center by means of a heat pump
Heating and hot water supply to the Center (Table 1) is currently provided from a gasified boiler house. The heat supply network maintains pressure of 3 kgf/cm² and temperature in the range from 70 °C to 90 °C.

| Facility          | Installed capacity, kW (Gcal/h) |
|-------------------|---------------------------------|
|                   | Heating                        | Hot water supply         |
| Dormitory block 1 | 42                             | 117                       |
| Dormitory block 2 | 38                             | 117                       |
| Dormitory block 3 | 40                             | 117                       |
| Guest House       | 35                             | 35                        |
| Total             | 155 (0.133)                    | 386 (0.322)               |
The analysis of the structure of installed heat capacities and predicting the calculated heat loads took into account the independence of the heat load of hot water supply (HWS) from climatic conditions and the probabilistic pattern of the dependence of the heat load of the heat supply on the ambient temperature (Figure 4).

A heat pump (HP) is the most promising heating, hot water supply and air conditioning system worldwide. The analysis of various heat pump-based systems has shown that the most optimal way to ensure the heat load of the Center is a ground-water heat pump with vertical arrangement of heat exchangers (ground probes).

In Kaliningrad region, a geothermal source of hot water is located at a depth of 1–2 km from the earth surface, therefore, thermal energy stored in the upper layers of the ground (60–110 m) should be used [1].

A comparative analysis of the operating modes of heat pumps relative to the temperature profile of the projected heat supply network determined the bivalent HP operating mode as optimal, when the heat pump functions as the main heat generator up to a certain temperature of the ambient air; at lower temperature, the second heat generator is activated in parallel or alternative mode [2–4].

Based on calculations, the coverage of the heat load of the Center with a geothermal heat pump is 156 kW, i.e. design heating load provided by three heat pump units (HPU) Nibe F1345-60 with a nominal unit heating capacity of 57.7 kW.

The thermal diagram of the designed HPU for bivalent operation is shown in Figure 5.
The calculation of the characteristics of the primary circuit equipment revealed the following:

- length of the vertical probe ensuring the required power of the heat flow from the ground to the primary circuit coolant:
  \[ L_z = \frac{P_{GHP} + P_{WH}}{Q_S}, \]  
  where \( Q_S \) is the ground heat transfer of the soil, W/m; \( P_{WH} \) is power required for water heating, W; \( P_{GHP} \) is geothermal heat pump power, W.

- the number of probes for the maximum permissible depth of 100 m:
  \[ N_z = \frac{L_z}{L_{max}}, \]  
  where \( L_{max} \) is the maximum allowable probe insertion depth, m; \( h \) is hydraulic losses in the probe pipes:
  \[ h = \lambda_F \frac{L}{D} \cdot \frac{v^2}{2g}, \]  
  where \( \lambda_F \) is the hydraulic friction factor; \( L \) is the pipeline length, m; \( D \) is the inner diameter of the pipe; \( v \) is flow velocity, m/s; \( g \) is gravitational acceleration, m/s².

For boreholes, a site was selected in the territory of the Center with sandy-clay soil and water-saturated sedimentary rocks. The average value of the heat flow during heat removal in vertical boreholes for this type of soil is \( Q_S = 70 \) W/m.

The probe package should include 24 earth probes in the form of a U-tube with a burial depth of 100 m with a diameter of \( D_u = 50 \times 4.5 \) mm. The total length of the pipes is 4800 m.

The geometrical characteristics of the earth probe and vertical borehole are shown in Figure 6.
Figure 6. Design of the borehole with geothermal probe.

The boreholes are supposed to be located in accordance with the corridor scheme with the longitudinal and transverse spacing equal to 8 m. The total area of the site allocated for boreholes is 900 m².

The average power consumption by heat pumps for heating and hot water supply, and by the heating element of the storage tank in thousand kWh/month by months of the year is graphically presented for the bivalent mode (Figure 7). Estimated power consumption for the bivalent heat supply mode is 144 thousand kWh/year.
Figure 7. Average power consumption for heating and hot water supply by months of the year.

The heat pump unit of the considered configuration uses geothermal heat to satisfy the heat load in the entire probable range of changes in the ambient temperature of the atmospheric air within a year. The HWS heat load is covered by the peak fuel-consuming heat generator. Full coverage of the entire heat load through ground geothermal heat is possible by means of a monovalent cascade scheme or a combined HPU scheme, for example, using vacuum solar collectors in the HWS system.

4. Analysis of the potential of solar energy in the territory of the Center and design of the solar plant

In the territory of the Center, the average level of insolation (the amount of energy received from the Sun per unit area) is 1073 kWh/m² per year [5].

The change in global insolation against the angle of inclination and geographic orientation of the modules is presented in Table 2 and Figure 8 [6].

| Table 2. Change in global insolation (kWh/m²) against the angle of inclination and geographical orientation of the modules. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Horizontally | January | February | March | April | May | June | July | August | September | October | November | December | Year |
| Horizontally | 19 | 23 | 75 | 128 | 160 | 166 | 158 | 134 | 94 | 51 | 26 | 15 | 1073 |
| 10° South | 23 | 39 | 84 | 138 | 165 | 170 | 162 | 142 | 103 | 58 | 33 | 19 | 1140 |
| 30° South | 30 | 48 | 96 | 150 | 167 | 167 | 161 | 146 | 116 | 70 | 44 | 25 | 1220 |
| 37° South | 32 | 50 | 98 | 151 | 165 | 163 | 157 | 148 | 118 | 72 | 48 | 28 | 1230 |
| 45° South | 34 | 52 | 100 | 150 | 160 | 156 | 152 | 145 | 118 | 74 | 49 | 28 | 1220 |
| 60° South | 36 | 53 | 98 | 142 | 145 | 139 | 136 | 134 | 115 | 75 | 52 | 30 | 1150 |
| 90° South | 33 | 47 | 81 | 104 | 95 | 87 | 87 | 94 | 91 | 65 | 49 | 29 | 861 |
| 45° South/ East / West | 28 | 44 | 89 | 140 | 157 | 156 | 150 | 139 | 108 | 65 | 40 | 23 | 1140 |
| 45° East / West | 17 | 30 | 68 | 115 | 141 | 146 | 139 | 120 | 86 | 46 | 24 | 14 | 944 |
| 90° East / West | 11 | 20 | 45 | 76 | 90 | 92 | 87 | 78 | 57 | 31 | 16 | 9 | 611 |
Based on the analysis of the data shown in Table 2 and Figure 8, it can be concluded that the maximum average annual insolation of 1230 kWh/m² per square meter can be attained on a surface oriented to the south and inclined at an angle of 37° to the horizon.

The advisable realization of the solar energy potential is most efficient through installation of solar panels on the roof of the Center buildings (Table 3).

**Table 3.** Roof area of the Center buildings.

| Total roof area of the Center buildings, m² | The area of the roof of buildings suitable for installation of solar panels oriented to the azimuth, m² |
|-------------------------------------------|--------------------------------------------------------------------------------------------------|
|                                           | South | South-West | South-East | Total |
| 2855                                      | 1125  | 150        | 300        | 1575  |

Analysis of the existing solar panels showed that the maximum total capacity of a solar power plant can be attained using the JA Solar JAM72D10/MB 400W monocrystalline solar panel (Table 4, Figure 9).

**Table 4.** Technical parameters of the solar panel JA Solar JAM72D10/MB 400W.

| Parameter                          | Value |
|------------------------------------|-------|
| Rated power, W                     | 400   |
| Open-circuit voltage, V            | 48.56 |
| Short-circuit current, A           | 10.5  |
| Rated voltage, V                   | 40.45 |
| Rated current, A                   | 9.90  |
| Panel efficiency, %                | 19.9  |
| Illumination, W/m²                 | 1000  |
| Temperature, deg                   | 25    |
| Panel area with frame edging, m²   | 2.12  |
Figure 9. Current-voltage characteristic of the solar panel.

With regard to the construction features of the roofs of the Center buildings, calculation was carried out for 600 m² area of the building roofs to install 283 solar panels of the given model. In this case, the total nominal installed capacity of all solar panels is 113.2 kW.

Thus, provided that the solar panels efficiency is 19.9% and the proposed inverter efficiency is 97%, the overall system efficiency will be 19.3%.

The maximum expected total annual power generation ($W_Y$) is calculated using equation (4):

$$W_Y = GHR \cdot S_{U} \cdot E_s \cdot k,$$

(4)

where $GHR$ is the maximum average annual insolation per square meter of the surface, $S_{U}$ is the used roof area of the Center buildings, $E_s$ is the system efficiency (solar panels and inverter), and $k$ is the correction factor applied to additional losses and external factors ($k=0.75$).

Thus, the estimated value of electric power generation will be 106,825.5 kWh/year.

The data in Table 5 show that solar panels with the given parameters do not cover the Center’s power consumption (190 MW×h/year), especially in winter.

Table 5. Power generation by solar panels calculated for 600 m² area of the building roofs (MW×h).

| Month   | Power generation |
|---------|------------------|
| January | 2.8              |
| February| 4.3              |
| March   | 8.5              |
| April   | 13.1             |
| May     | 14.3             |
| June    | 14.2             |
| July    | 13.6             |
| August  | 12.9             |
| September| 10.2           |
| October | 6.3              |
| November| 4.2              |
| December| 2.4              |
| Year    | 106.8            |

In this regard, the additional use of wind power plants should be considered. It should be noted that all the roof areas facing south used for solar panels can provide 200.3 MW×h/year.

5. Choosing wind turbines
When choosing wind turbines for the Center, the following factors were taken into account: the number and capacity of wind turbines; distance from the residential sector; the wind rose (Figure 10) [7].
According to [8], the lower part of the wind turbine blades should be 8 meters higher than the highest obstacle observed within 150 m. In the Center area, the height of the obstacle is 10 m. Based on the analysis of the characteristics of wind turbines produced for such objects, the Eocycle eo25 wind turbine class III was chosen (Figure 11, Table 6) [9].

The wind speed \( v_2 \) at the height of the wind turbine hub is calculated using equation (5) with regard to the data provided in Figures 11, 12 and Table 6 [10].

\[
\text{Equation (5)}
\]

Given the wind rose and the requirements for the location of the wind turbines at a distance of 10 diameters of the wind turbine, two wind turbines are taken for installation (Figure 11a).
\[ v_2 = v_1 \left( \frac{h_2}{h_1} \right)^m \]  

(5)

Power generation (Table 7) was calculated using equation (6) [11] with regard to the data presented in Figures 11b and 13:

\[ W = K_U \cdot K_M \cdot n \cdot P_{rated} \cdot T, \]  

(6)

where \( K_U \) is the coefficient of the installed power of the wind turbine (Figure 13); \( K_M \) is the coefficient of the mutual impact of wind turbines; \( n \) is the number of wind turbines; \( T \) is time of the estimated power generation.

**Table 7.** Wind speeds (m/s) and power generated by one Ecocycle eo25 wind turbine class III (MW*h).

| Month   | January | February | March | April | May | June | July | August | September | October | November | December | Year |
|---------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|------|
| Wind speed | 7.04    | 6.4     | 6.0  | 5.76  | 5.34 | 4.7  | 4.6  | 4.6    | 5.55      | 6.0    | 6.51     | 7.04     | 6.52 |
| Power generation | 6.96    | 5.17    | 4.9  | 4.2   | 4.0  | 2.62 | 2.9  | 2.9    | 4.2       | 5.16   | 5.8      | 6.9      | 63.7 |

The power generated by the wind turbine can be calculated more accurately by the Reilich method [12]. However, the above estimates are sufficiently accurate for engineering calculations.

If it is necessary to provide the Center with additional energy, the following should be considered: installation of three wind turbines based on the analysis of the wind rose, the permissible space between wind turbines and other factors; installation of the wind turbine on a hill where the wind speed at the level of the wind wheel hub is higher which ensures higher power generation.

6. Choosing a storage device based on a storage battery

Due to the abruptly variable operating mode of wind turbines, the dependence of power generation by solar panels on solar activity, as well as to ensure the reliability of power supply to the Center, a storage device based on storage batteries (SB) should be used (Figure 14). During the period of low loads of the Center (Figure 3) and excess of generated power, the batteries are charged using a controlled rectifier (CR) (Figure 14, \( W_{CR} \)). The power accumulated in batteries to the power-supply system of the Center is supplied via a controlled inverter (CI) (Figure 14, \( W_{P} \)) [13].
Figure 14. Scheme for connecting the battery to the Center grid.

Figure 15. Daily profile of average power consumption in January.

\[
W_{CH} = \int_{T_1}^{T_2} (P_{av} - P_i) \, dt / \eta \quad (7) \quad \frac{W_R}{\eta} = \int_{T_2}^{T_3} (P_i - P_{AV}) \, dt / \eta \quad (8)
\]

where \(W_{CH}\) is energy received by RB from the Center grid; \(W_R\) is the power supplied by RB to the Center grid; \(P_i\) is current power value; \(\eta\) is efficiency of rectifier and inverter; \(P_{AV}\) is basic (average) load power.

Taking into account the data presented in Figures 3 and 15, and Table 8, the storage device must supply up to 40 kW of power to the grid.

**Table 8.** Energy balance of power in the Center (MW*h).

| Generation and consumption                  | MW*h/year |
|--------------------------------------------|-----------|
| 3* wind turbines                           | 191.1     |
| Solar panels                               | 200.3     |
| Power (excluding boiler room)              | 177.2     |
| Power consumption for heat pump operation  | 144.0     |
| Balance                                    | +70.2     |

Tesla Ins is currently the world leader in the production of storage devices based on lithium-ion batteries, and the Russian leader is the Liotech plant [14]. Among the products manufactured by the Liotech plant, the LT-LFP 300 battery with improved energy characteristics is of interest (Table 9, Figures 16 and 17).

**Table 9.** Technical data of the LT-LFP 300 lithium-ion battery.

| Capacity, A·h | Specific energy, W | \(U_{rated}\), B | \(I_{rated}\), A | Pulse current, A | Cycles: charge–discharge |
|---------------|--------------------|------------------|-----------------|------------------|------------------------|
| 300           | 107                | 3.2              | 60              | 600              | up to 5000             |
Based on the accumulators produced by the Liotech plant, batteries with an output voltage $U_B = 12.24.36.48$ V are currently being developed. The battery voltage fits the output parameters of the controlled rectifier and inverter. The number of batteries connected in series ($N_{SER}$) is determined using the equation:

$$N_{SER} = \frac{U_{d0} \cdot K_R}{U_{SB}}$$

(9)

where $K_R$ is the coefficient of the decrease in battery voltage during the discharge period (Figure 16), $U_{d0}$ is the constant voltage at the inverter input.

In this case, the power and capacity of the storage device is calculated using the equations:

$$P_{SD} = U_{d0} \cdot K_R \cdot I_{discharge}$$

(10)

$$C_{SD} = P_{SD} \cdot I_{discharge}$$

(11)
The calculation results for the power and capacity of the battery obtained using equations (10)–(11) with regard to the recommendations on inadmissibility of the battery discharge below 0.8 $C_{\text{rated}}$, are shown in Table 10.

| $U_{\text{B}}$, V | $N_{\text{ser}}$ | $N_{\text{par}}$ | Battery discharge current, A | $P_{SD}$, kW | $C_{SD}$, kWh |
|-----------------|-----------------|-----------------|-----------------------------|--------------|---------------|
| 48              | 2               | 7               | 60                          | 40           | 186           |

where $N_{\text{par}}$ is the number of parallel branches in the storage battery.

7. **Power-supply system of the Center**

The developed concept of the RES-based power-supply system for the Center is shown in Figure 18.

![Figure 18](image18.png)

**Figure 18.** The RES-based power-supply system of the Center: SP – solar panels; EDG – emergency diesel generator; CI – controlled inverter; RIU – rectifier-inverter unit; SB – storage battery.

To control, monitor and manage the autonomous energy system of the Center based on RES, a network control room (NCR) should be created in the Center. The NCR core is a server for the system remote control with Supervisory for Control And Data Acquisition (SCADA). Thus, it should be possible to transfer the necessary data on the state of equipment and network parameters (including power consumption and generation) to the server. The principle of managing the RES-based power-supply system of the Center is shown in Figure 19.

![Figure 19](image19.png)

**Figure 19.** The principle of managing the RES-based power-supply system of the Center.
8. Conclusions

The power-supply system, and power and heat loads of the Center were analyzed. Calculation was made and a heat pump unit scheme was proposed to satisfy the heat load using geothermal energy within the entire possible range of annual temperature changes. Full coverage of the heat load due to ground geothermal energy is possible by means of a monovalent cascade scheme or a combined HPI scheme.

The potential of solar energy in the Center area was analyzed and a solar plant was proposed.

The wind potential of the Center area was estimated and wind turbines were chosen.

Due to the abruptly variable operating mode of wind turbines, the dependence of power generation by solar panels on solar activity, and to ensure the reliability of power supply to the Center, a storage device based on storage batteries was proposed.

The set of preliminary technical solutions proposed in the study showed the possibility of ensuring the power supply of the Center through the use of renewable energy sources.

In addition to the measures developed, the power-supply audit of the Center should be performed to assess the potential of power conservation and to outline the ways of its implementation.

The implementation of the concept of ensuring power conservation based on renewable energy sources with subsequent development of power conservation measures is particularly relevant for development of appropriate attitude of the younger generation towards the main trends in the world energy.

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