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Abstract: Using renewable energy off-grid power supply and choosing the right equipment that meets the operating conditions in the Arctic can provide companies with reliable power sources for producing gas at facilities located in remote areas and will reduce capital and operating costs associated with the construction of power transmission lines. For more than 15 years, a remote control system powered by renewable energy has been used in parallel with power transmission lines by Gazprom to operate its multiwell pads in Russia's Far North, which validates the relevance of this study. The subject of the study is a group of gas condensate wells that consists of four multiwell pads operated by Wintershall Russland GmbH. The article discusses a stand-alone renewable-based power system as an option for powering remote oil and gas production facilities. The procedures used in the study include calculating such parameters as power output and power consumption, choosing equipment, describing the design features of a power supply system for a multiwell pad, conducting an economic assessment of the project, comparing different power supply options, analyzing project risks, and developing measures to mitigate these risks.

Keywords: renewable energy; energy efficiency; stand-alone power system; off-grid solutions; gas condensate wells; Arctic

1. Introduction

Numerous facts prove that using stand-alone power systems to operate multiple gas condensate wells is a promising option and using renewable energy sources at gas production facilities is economically feasible. First, there is a global shift toward using renewable energy sources to power mining as well as oil and gas facilities. Second, there has been a decrease in the cost of equipment that runs on renewable energy sources, with operating costs also being low. Moreover, energy storage systems have significantly improved to ensure that the system operates flawlessly.

This article evaluates the viability of using a combination of solar panels and a wind turbine along with backup batteries to power the monitoring and control system of multiple gas condensate wells operated by the joint venture between Gazprom and Wintershall DEA (Deutsche Erdoel AG). This option looks promising as the system under consideration does not require a lot of energy. Also, constructing power transmission lines in the Arctic is associated with high project costs due to the fact that the production facility is located in a remote area.

The issues of using power generated by renewable energy sources in the mining industry and the oil and gas sector have been widely discussed in different contexts. Researchers have been exploring such aspects as making decisions on the integration of renewable energy sources into the mining industry [1,2], the economic feasibility of using renewable energy sources [3], determining

The technical and economic feasibility of introducing energy storage systems to power supply systems used by production facilities that rely on renewable energy [4], using hybrid wind and solar electric systems [5], economic structure transformation and low-carbon development [6], and improving photovoltaic cell models [7]. Special attention is paid to the role of stand-alone hybrid renewable energy systems in off-grid energy planning and consumer energy supply, and to developing forecasting models with the aim of fostering the sustainable development of local energy sectors [8,9].

The role and prospects for the use of renewable energy sources in Russia's Arctic have been discussed in a number of articles by Russian researchers [10]. They have considered the issues of integrating renewable energy systems in the Arctic climate [11], improving energy efficiency and the reliability of energy supply to remote oil and gas facilities in Russia [12–14], improving energy quality in off-grid systems [15], the management and economics of stand-alone power systems based on renewable energy sources [16], the development of the renewable energy sector and wind energy policies [17–19], methods for mitigating risks in managing the development of a local power industry [20], and prospects for binary-cycle power plants [21].

Technical aspects of using renewable energy sources in power supply systems have also been discussed by Russian researchers. Studies in this area are devoted to how wind turbines operate as part of energy systems [22], how off-grid systems are used in leak detection systems for oil pipelines [23], and what parameters offshore wind turbines should have to operate in the Arctic [24].

Researchers at St. Petersburg Mining University considered in detail the issues connected with the development of Russia's Arctic such as the organizational and economic mechanism of oil and gas projects in the Russian Arctic shelf [25], the role of innovation infrastructure and legal regulation [26,27], environmental and economic damage from the development of offshore oil and gas fields in the Arctic [28], the problems of extracting unconventional gas resources [29,30], and the use of renewable energy sources as a factor influencing the social and economic development of Russia's Arctic [31,32].

It is very important that a large number of studies dealing with climate change have recently been carried out and the use of renewable energy sources is considered to be one of the factors that contribute to the reduction of carbon dioxide emissions into the atmosphere [33], changes in economic structures, and the development of low-carbon and other strategies aimed at reducing greenhouse gas emissions [34], including carbon capture and storage (CCS) [35,36]. Due to the rapid decrease in the costs of renewable energy sources and storage systems, national power systems can be decarbonized more quickly [37].

According to the study conducted by the International Renewable Energy Agency (IRENA) on renewable power generation costs in 2019 [38], it is safe to say that over the past decade, there has been a steady decrease in the cost of producing renewable energy sources due to the ongoing improvements in technology, economies of scale, competitive supply chains, and the experience that engineers in the sector have accumulated. New solar and wind projects are serious competitors against coal-fired power stations. It is estimated that replacing the costliest 500 GW of coal with solar energy and wind energy will dramatically cut power system costs and reduce annual CO_2 emissions by about 1.8 gigatons. The continuing decline in costs confirms that competitive renewable energy sources are a low-cost solution to the issue of climate change and a useful tool for decarbonization that fosters a balance between short-term economic needs and medium- as well as long-term sustainable development goals [38–40].

Both key players in the energy sector and small companies, including Shell, BP, Schneider Electric, Gazprom, and Wintershall DEA, are moving toward more environmentally friendly fuels with lower CO_2 emissions in their strategic development. In particular, they invest in gas projects, turn to methane as a source for hydrogen production, build storage facilities for hydrogen and carbon dioxide, and introduce renewable energy sources (biofuels, solar energy, and wind power) in their energy supply systems.

An important statement was made by Schneider Electric in the 2018 Sustainability Report: "We are on track to go carbon neutral by 2030" [41]. This can only be achieved by developing projects for the introduction of renewable energy systems or upgrading the already existing production facilities to meet the zero-carbon footprint principle. The shift toward renewable energy sources in the energy mix is an important point for market players in terms of their investment strategies.

A share of the energy sector is taken by off-grid solutions and mini-grids. Off-grid solutions are currently becoming more and more competitive in both domestic and industrial applications. The reason for this is that they are economically more viable than such options as power transmission lines, diesel generators, and gas compressors. They become even more attractive from the cost-saving point of view if the facility being powered is located far from the already existing energy infrastructure.

This study considers an off-grid solution that supplies energy generated from renewable sources to gas and gas condensate production facilities. This energy can be used in such processes and systems as a system for injecting corrosion and gas hydrate inhibitors, devices for enhanced gas or condensate recovery, lighting systems, radio communication systems, cathodic protection of well casings and flowlines, automation systems, etc. Introducing a stand-alone power system based on renewable energy sources will significantly reduce development costs, the load on the primary distribution network, and labor costs associated with servicing the power supply system.

The purpose of the study is to analyze whether it is technically and economically feasible to use off-grid systems to power multiple gas condensate wells by using renewable energy sources at gas production facilities in Novy Urengoy.

The main objectives of the study are to calculate the parameters of a power supply system factoring in the local weather conditions, to carry out a feasibility study of the proposed design, and to compare the costs of the proposed power supply system using renewable energy sources and the costs of building a power transmission line. It should be noted that all the system's components must meet the operational requirements in the Arctic to prevent accidents and equipment breakdowns. These measures will ensure that hydrocarbon production will not be interrupted.

2. Materials and Methods

The reliability of the conclusions and recommendations given in this article is ensured by the detailed analysis of theoretical materials on the issue, statistical information, documents provided by production and energy companies, methodological recommendations for assessing the economic performance of investment projects, and reports published by rating and consulting agencies.

The methodology of the study is based on books and articles by leading researchers in the field of assessing projects for using renewable energy sources to power production facilities [1–3,16,23]. It is also based on corporate reports and data provided by Gazprom and Wintershall DEA.

In describing the economic indicators of power systems, the general principles of economic analysis and assessment were applied, such as the principles of consistency, comprehensiveness, and comparative analysis.

In the course of the study, the authors applied the decomposition method to the engineering solutions used on site. The system being analyzed is the monitoring and control system used to operate multiple gas condensate wells in Western Siberia in the Arctic Circle. This system is designed to transport the extracted gas to the header, control gas pressure, measure and control the flow rate, shut off flowlines, blow the wells and the header through flare valves, and to discharge gas from the safety valves to the flare when the pressure in the flowline rises to 16 MPa.

The energy consumption system should be provided with a stable power supply as it ensures stable gas and condensate production and guarantees safe operation in case of an emergency. It consists of:

1. Choke manifold (for lowering the pressure and performing flow control),
2. Christmas tree (for regulating gas condensate flow from the wellhead),
3. Wellhead manifold (for lowering wellhead pressure),

4. Flowline and methanol pipeline connector (for hydrate prevention),
5. Ground flare piping (a combustion system for utilizing extra gas),
6. Test separator (a moveable unit that is used once a year to measure and separate gas),
7. Gas condensate testing equipment (a moveable unit that is used once a year to measure and separate condensate),
8. Storage tank (for gas, water, and condensate separation after the wellhead and before transportation to the gas processing unit),
9. Radio communications (for sending measurement results to the gas processing unit).

In this system, power is constantly consumed by the choke manifold, the Christmas tree, the wellhead manifold, the flowline and methanol pipeline connector, the ground flare piping, the storage tank, and the radio communications. The test separator and the gas condensate testing equipment are not permanent components of the system; they are transported to the site approximately once a year to carry out tests and they are powered by separate batteries.

To calculate the parameters of the system, several assumptions were made:

1. There is no electric heating (equipment that can withstand low temperatures is used).
2. There is no cathodic protection system to protect well casings and flowlines as the well casings operate in a medium that is not corrosive and the flowlines do not touch the ground.
3. There is no lighting system for multiwell pads (the service interval for the off-grid power supply system is one year; the staff is off-site when the system is not being serviced).

Parameters will be calculated for the three-well pad that is located farthest from the existing infrastructure and for a group of multiwell pads (two three-well pads and two four-well pads). The number of choke manifolds, Christmas trees, and wellhead manifolds is proportional to the number of wells. Therefore, multiwell pads will differ in terms of power consumption (135.9 W for a three-well pad and 167.9 W for a four-well pad).

Two power supply options are considered for this facility: a power transmission line as stated in the design documentation and renewable energy sources (solar panels and a wind turbine) with backup batteries. The option of building a power transmission line does not necessitate a feasibility study since this is a standard option while designing a power supply system based on renewable energy sources requires conducting an analysis of weather conditions, developing a design that will meet local conditions, calculating such parameters as power output and power consumption, carrying out an economic assessment, and developing risk prevention measures.

Analyzing weather conditions is necessary to develop solutions for adapting the system for the local environment and to calculate output power. To carry out this analysis, we used data on weather observations provided by Gazprom and Wintershall DEA and data collected in Yamalo-Nenets Autonomous Okrug by the Hydrometeorological Research Centre of the Russian Federation [42]. The main atmospheric characteristics are presented in Table 1.

Table 1. Monthly and average atmospheric characteristics.

Parameter/Month	January	February	March	April	May	June	July	August	September	October	November	December	Avg
Wind speed (at 10 m height), m/s	3.3	2.9	3.5	3.9	4.2	4.4	3.5	3.4	3.5	4.1	3.3	3.3	3.6
Calm periods, %	20	21	17	11	7	8	16	16	16	7	15	19	14.4
Solar irradiance, kWh/m^2	0.0	31.1	78.3	157.5	224.7	240.3	246.9	177.5	98.6	33.9	9.4	0.0	108.2
Temperature, °C	−26.4	−26.4	−19.2	−10.3	−2.6	8.4	15.4	11.3	5.2	6.3	−18.2	−24.0	−7.8

The key feature of this region is that the polar day and the polar night occur there. The polar day is characterized by high solar irradiance while the polar night lacks in sun and is characterized by low wind speeds and extremely low temperatures (in January and February, the average temperature is −26.4 °C, with the minimum temperature as low as −60 °C). This means that solar irradiance levels vary greatly throughout the year and solar panels have to be removed for the period between October and February due to lack of sun.

It should be noted that the wind speed at a height of 10 m is not sufficient to generate electricity from a wind turbine. This speed equals the minimum energy generation requirement. In such a situation, the wind turbine generates several times less electricity than the nominal capacity. In this regard, it is recommended that the tower should be higher than 10 m.

The average annual temperature is quite low (−7.8 °C), and there is a risk that ice and frost may accumulate on the equipment, which requires the implementation of additional ice protection measures to ensure a smooth power supply. Also, at temperatures below 0 °C, there are huge electricity losses in backup batteries. To prevent these losses, it is recommended that wells should be drilled to a depth of 20 m, where the temperature remains constant (+5 °C) all year round. These wells will also be used for a controller and an inverter, as their operating temperature ranges are above 0 °C.

The wind turbine should be customized to meet some challenges that the Arctic climate poses, including soil subsidence in permafrost conditions (as the top layer of the soil starts thawing in summer) and equipment failure due to low temperatures or icing (for example, the wind turbine may stop if the grease freezes). It is necessary to holistically adapt individual components: the rotor, the nacelle, and the tower. This is the approach adopted by Russian specialists in the renewable energy sector [11]. A list of measures proposed to adapt the system for the Arctic climate is presented in Table 2.

Table 2. Measures to adapt the equipment for the Arctic climate.

Structural Component	Measure	Aspect
Rotor	Using blades made of steel for low-temperature applications	Conventional steel becomes brittle and less wear-resistant at low temperatures, which can result in a breakdown or power cut
	Hydrophobic coating	An increase in surface tension at the water-metal interface prevents ice from accumulating
	Ice detection system (produced by Enercon)	Sensors show information on power output and wind speed
Nacelle	Additional insulation	A decrease in heat loss in the generator; the grease will not freeze
	Low-temperature grease	The generator will not stall at low temperatures (lower than −15 °C)
	Generator shutdown system	Storm damage prevention
Tower	Using steel for low-temperature applications	Conventional steel becomes brittle and less wear-resistant at low temperatures, which can result in collapse under heavy loads due to poor weather conditions
	Designing the foundation taking into account such factors as permafrost and thawing	Structural stability

Backup battery capacity depends on the weather conditions because the power supply system must provide a multiwell pad with electricity in windless periods. The worst situation that can happen is a windless period that starts in January and ends in February with a total number of 12.3 calm days (Figure 1). For a multiwell pad to run for 12.3 days on backup batteries, the battery charge should be 1930.1 A/h for a three-well pad and 2363.0 A/h for a four-well pad. Such capacity will ensure a smooth power supply throughout the year.

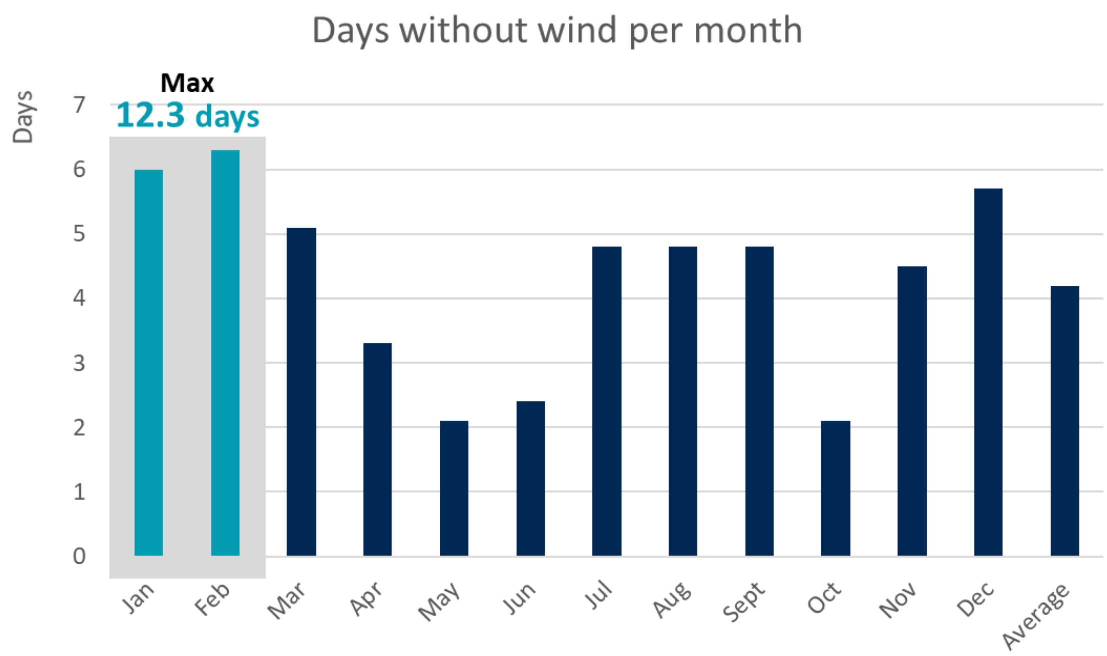

Figure 1. The number of windless days per month. Source: designed by the authors.

3. Results and Discussion

The off-grid system based on renewable energy sources for powering gas wells consists of:

1. A wind turbine with a steel tower,
2. Ground-mounted solar panels,
3. Backup batteries.

To mount the system and connect it to the multiwell pads, the following components and facilities are required:

1. Two twenty-meter-deep wells for electrical equipment (batteries, an inverter, and a controller) with a bottom hole temperature of +5 °C,
2. A road from the multiwell pad (100 m long),
3. A power cable along the road (100 m long),
4. A two-meter-high embankment as a measure against the swampy ground,
5. A wind turbine foundation,
6. Piles and well foundations.

On the Russian market, there are power supply systems of this kind offered by Vympel R & D [43]. This company can act as a contractor to design a power supply system. Their design is shown in Figure 2.

This system, which is adapted for the Arctic climate, will ensure a smooth power supply for multiple gas condensate wells.

In the process of selecting equipment for each type of multiwell pads, the parameters of the wind turbine (the rotor radius and the tower height) and backup battery capacity were analyzed (Figure 3).

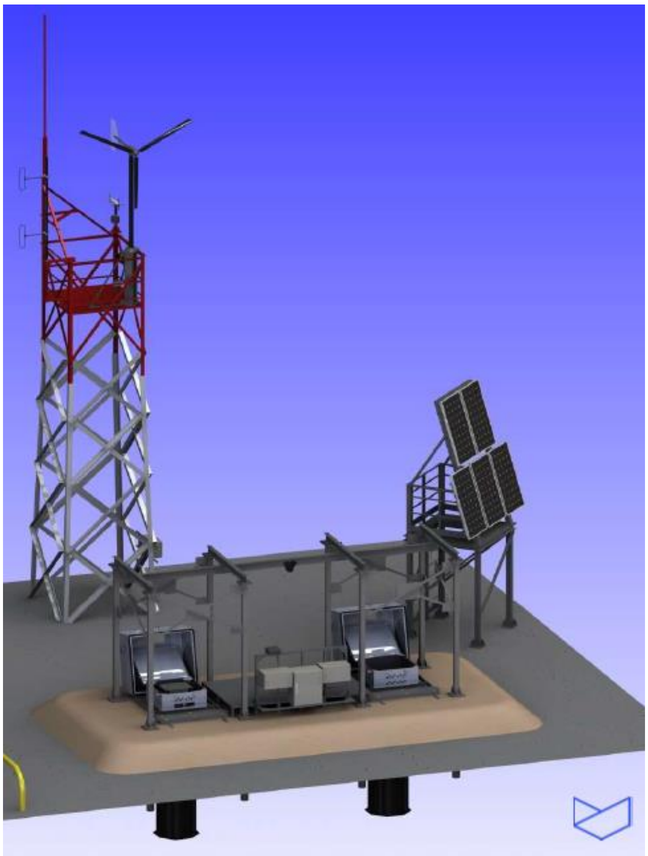

Figure 2. A power supply system based on renewable energy sources [43].

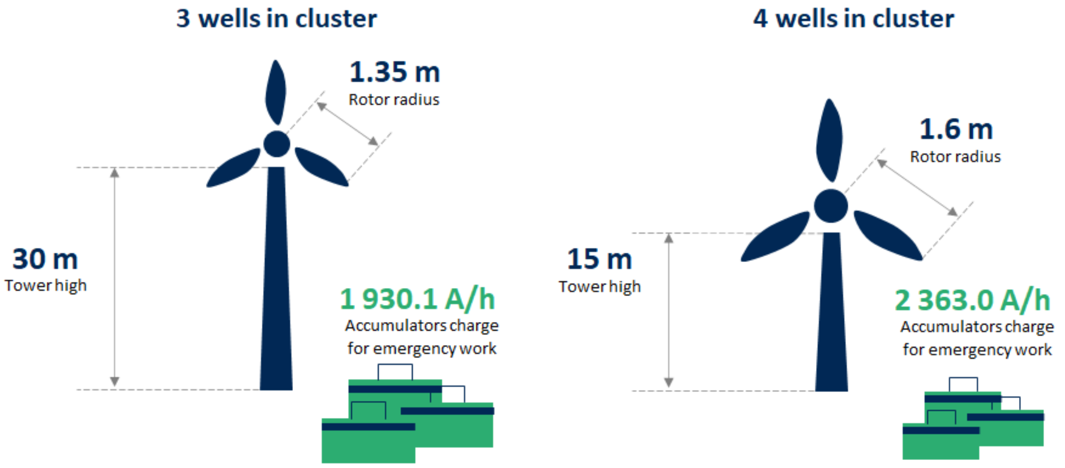

Figure 3. Components in the power supply system used to power three-well pads and four-well pads. Source: designed by the authors.

Based on the power output produced by a particular model of a wind-power generator at a certain height, the difference between power output and power consumption was calculated for each month considering the number of windless days. Then the energy budget of the system was designed so that the power output always exceeds the power consumption (even in winter, when the solar panels are removed, and the number of windless days is large). In the situation when the solar panels have been dismantled, the wells will be powered only by batteries during windless periods. There will be a need to drill 20-meter-deep wells for backup battery storage. Therefore, the capital costs of the whole system will be higher. The results of energy budget calculations for different types of pads are shown in Figures 4 and 5.

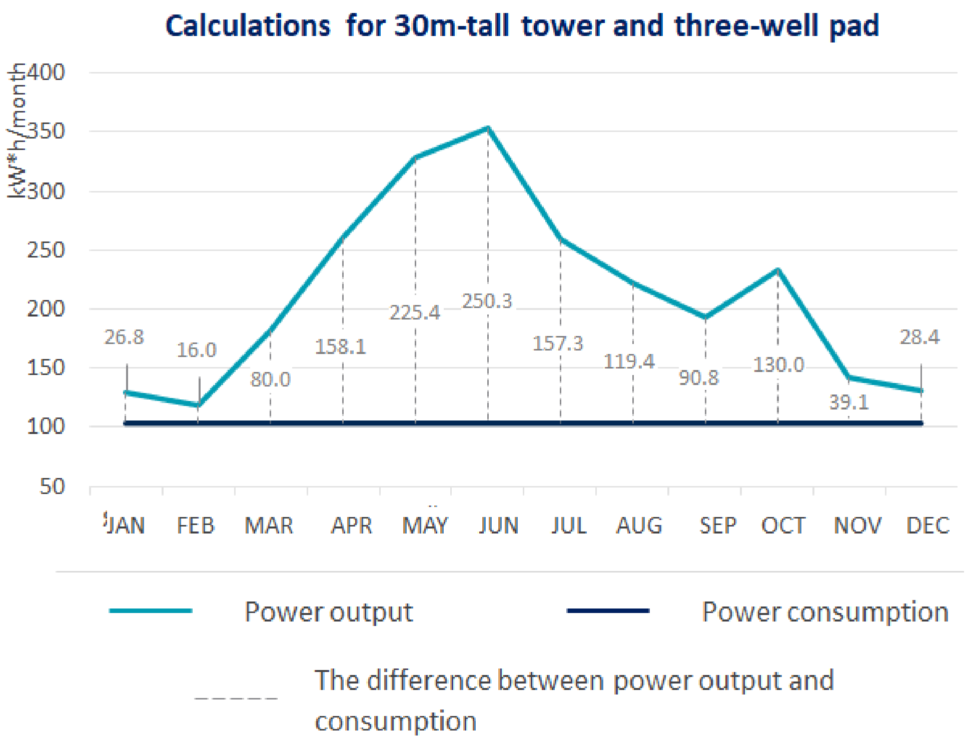

Figure 4. The energy budget of the power supply system designed for a three-well pad with the wind turbine tower having a height of 30 m.

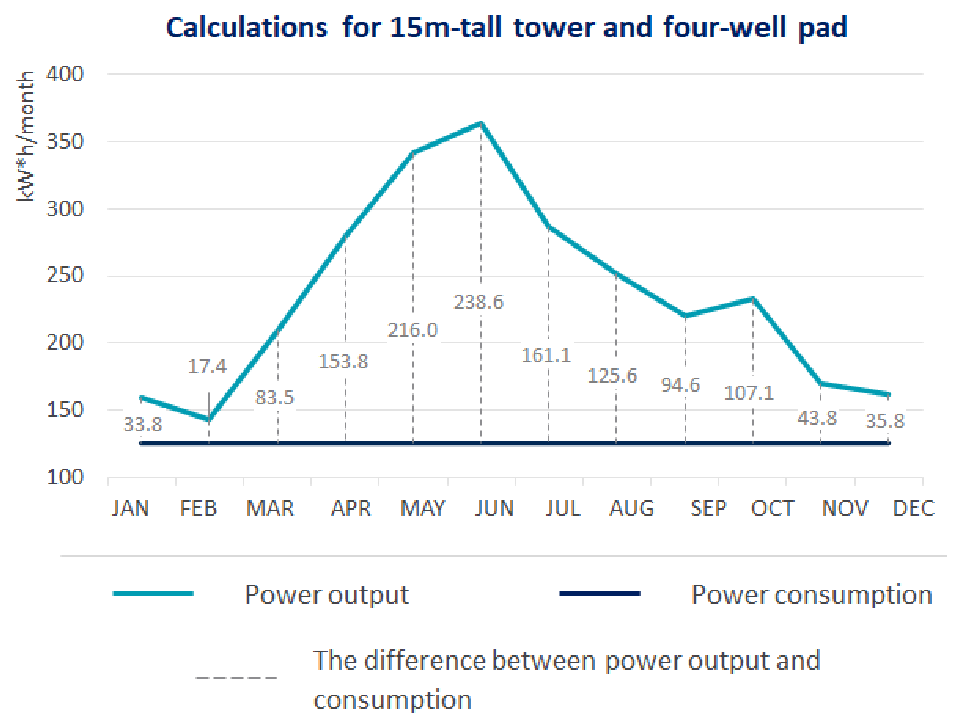

Figure 5. The energy budget of the power supply system designed for a four-well pad with the wind turbine tower having a height of 15 m.

When analyzing economic indicators, such costs were compared as capital costs for buying and installing the power supply system running on renewable energy and those for building a power transmission line, and also operating costs. Table 3 shows the capital and operating expenditures for powering a three-well pad, a four-well pad, and a group of multiwell pads (two three-well pads and two four-well pads) using renewable energy sources.

Table 3. Capital and operating expenditures for using renewable energy.

Renewables	Well Pad A024 (3 Wells), USD Thousand	Well Pad A01 (4 Wells), USD Thousand	Group of Multiple Wells A024(3), A01(4), A02(4), A04(3), USD Thousand
CAPEX (2019)	122.46	123.60	492.11
Unit design calculations	7.42	7.42	29.67
Equipment with logistics	33.58	34.72	136.6
Construction and installation works	81.46	81.46	325.84
Annual OPEX	1.31	1.31	5.22
Operation and Maintenance	1.31	1.31	5.22
PV@7,5% (20 years)	127.22	128.28	510.99

As can be seen from Table 3, the total capital costs of the proposed power supply system based on renewable energy sources amount to approximately 123 thousand US dollars. Equipping the whole group of multiple wells with this technology will cost 492.11 thousand US dollars. It should be noted that the annual operating costs, which include maintenance operations and repairs, will be only 5.22 thousand US dollars.

Capital expenditures for the construction of a power transmission line and operating expenditures, including maintenance and energy costs paid to Gazprom Energosbyt Tyumen JSC, are shown in Table 4.

Table 4. Capital and operating expenditures for using the standard option (a power transmission line).

Power Transmission Line	Well Pad A024 (3 Wells), USD Thousand	Group of Multiple Wells A024(3), A01(4), A02(4), A04(3), USD Thousand
CAPEX (2019)	274.88	1383.56
Construction of a power transmission line (Achim Development Project documentation)	274.88	1383.56
Annual OPEX	2.14	10.58
Operation and Maintenance	2.02	10.02
Electricity (payments to Gazprom Energosbyt Tyumen JSC)	0.13	0.56
PV@7,5% (20 years)	277.52	1394.89

By comparing the indicators in Tables 3 and 4, it can be said that capital costs for powering a three-well pad by using renewable energy are 57% lower than if a power transmission line is used. If this option is used for the whole group of wells, capital costs will be 65.9% lower. It is also worth noting that operating costs will decrease by 97.45 thousand US dollars as there will be no need to pay the electricity provider for the services.

A comparative analysis of capital costs for powering a three-well pad and the group of multiple wells using the two power supply options is shown in Figure 6.

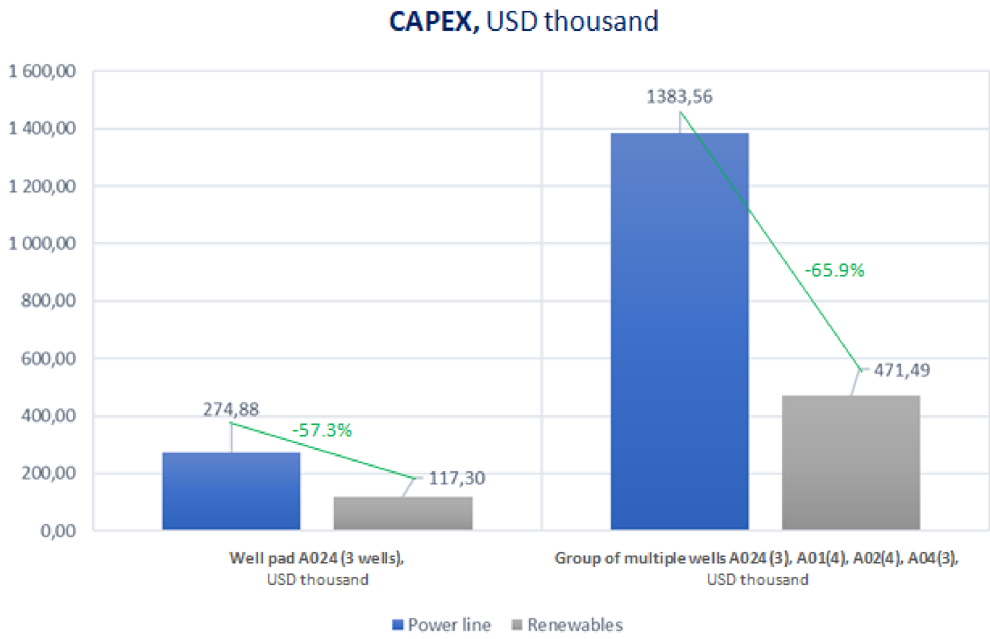

Figure 6. Capital costs for using renewable energy sources and a power transmission line. Source: designed by the authors.

To ensure equipment reliability, an analysis of possible risks was carried out and measures to mitigate them were proposed (Figure 7 and Tables 5 and 6). All risks are associated only with wind turbine operation and the communications between the components of the structure. Solar energy generation should not pose any problems as solar panels will be removed for the period from October to February when they can suffer damage from snow and ice accumulation.

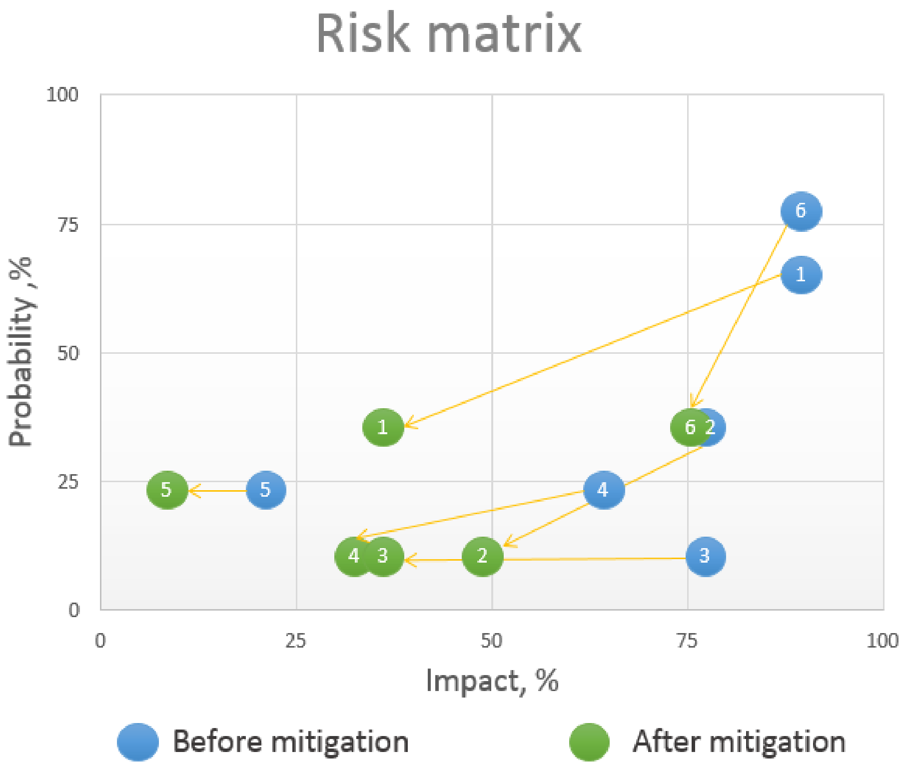

Figure 7. Risk matrix. Source: Designed by the authors.

Table 5. Risks and their mitigation.

Risk	Mitigation Tools
1. Low wind speed	• A thorough analysis of the average wind speed and calm periods on site • Backup batteries • A diesel generator
2. Hurricane	• A thorough analysis of weather conditions • An automatic shutdown system • Backup batteries • A diesel generator
3.Emergency shutdown	• Backup batteries
4. Faulty insulation	• A ground loop
5. Lightning and thunderstorms	• A lightning rod
6. Icing	• Anti-icing measures (Table 2)

Table 6. Weighted average indicators of expert risk assessment.

Risk	Before Mitigation		After Mitigation	
	Probability (Weighted Average Indicators)	Impact (Weighted Average Indicators)	Probability (Weighted Average Indicators)	Impact (Weighted Average Indicators)
1. Low wind velocity	65.0%	90.0%	35.0%	37.5%
2. Hurricane wind	35.0%	77.5%	10.0%	50.0%
3. Emergency shutdown	10.0%	77.5%	10.0%	35.0%
4. Insulation breakdown	22.5%	65.0%	10.0%	35.0%
5. Thunderstorms	22.5%	22.5%	22.5%	10.0%
6. Icing	77.5%	90.0%	35.0%	77.5%

Risk assessment, as well as minimization in terms of the probability of occurrence and the degree of their impact on the production process, was carried out using the expert method. The experts were employees of the company Wintershall DEA and specialists from the Vimpel R & D company engaged in the design of off-grid energy systems. The experts were offered four variants of risk assessment (low <10%, medium <35%, high <65%, very high <90%). The weighted average indicators of experts on the probability of occurrence of risks, as well as the degree of their impact before and after the application of the proposed measures, are presented in Table 6.

All the risks that were identified can be minimized in terms of their probability and impact by using various measures. To ensure a safe and smooth power supply, mitigation measures must be taken for each type of risk (1–6).

4. Conclusions

The main purpose for researchers in this article was to provide technological and economic justification for the feasibility to use off-grid systems to power multiple gas condensate wells by using renewable energy sources at gas production facilities in the harsh climatic conditions of Russia's Arctic.

By conducting the study, the following results were obtained:

1. An energy budget was compiled to ensure that gas condensate wells located in Russia's Arctic (multiple gas condensate wells in Novy Urengoy, Western Siberia in the Arctic Circle) are provided with smooth power supply. As a result of the study, critical temperature indicators were determined at the gas production facility. The authors identified the need to implement measures to adapt the wind generator to Arctic conditions in order to prevent soil subsidence in permafrost conditions and equipment failure due to low temperatures or icing. A list of measures for adaptation to Arctic weather conditions of individual elements of the power plant design was proposed.

2. Equipment was selected for a power supply system based on renewable energy sources and the design parameters of this system were calculated taking into account the necessity to adapt the equipment for the Arctic climate. In the process of selecting equipment for each type of multiwell pads, the parameters of the wind turbine (the rotor radius and the tower height) and backup battery. All the components of the system ensure a smooth power supply, which prevents possible interruptions in hydrocarbon production.
3. Capital and operating costs were analyzed for using the proposed system to power a three-well pad, a four-well pad, and a group of multiwell pads (two three-well pads and two four-well pads). They were compared with costs for the construction of a power transmission line. The total capital costs of the proposed power supply system based on renewable energy sources amount to approximately 123 thousand US dollars. Equipping the whole group of multiple wells with this technology will cost 492.11 thousand US dollars, it can be said that capital costs for powering a three-well pad by using renewable energy are 57% lower than if a power transmission line is used. If this option is used for the whole group of wells, capital costs will be 65.9% lower.
4. Risks were analyzed and measures were proposed to mitigate them to ensure the reliability of the proposed power supply system. As a result of expert assessment of the identified risks and proposed measures to mitigate them, it was found that after taking measures, a number of risks are reduced to a minimum (the probability of occurrence is less than 10%), and most of the risks are reduced by 12.5–25%. However, the most possible risk remains the icing of the power plant design elements. Despite proposed measures such as hydrophobic coating, ice detection system (from Emercon), and low-temperature lubrication for Arctic conditions, the probability of risk is at least 35%.

At the end of 2019, a decision was made to test the proposed system at a multiwell pad operated by the joint venture between Gazprom and Wintershall DEA. In this project, it is proposed to use renewable energy to power the control and monitoring system and the radio communication system, with the lighting system. If the proposed system operates successfully in winter and produces enough energy, it is planned that the joint venture will use the off-grid solution to power other multiwell pads. Unfortunately, due to a number of problems that are primarily connected with the spread of COVID-19 around the world, which negatively affected project implementation, and because of some disagreements between the contractors that were supposed to carry out design, construction, and commissioning operations, the final version of the project has not yet been approved. In August 2020, the project to commission a power supply system based on renewable energy sources to generate electricity for a multiwell pad operated by the joint venture between Gazprom and Wintershall DEA was postponed indefinitely.

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