Megawatt PV-diesel power stations in the Arctic

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Abstract. The work of hybrid energy complexes of significant installed capacity based on photovoltaic and diesel generation in the northern regions of Yakutia is considered. The considerable remoteness of settlements from the country's central energy system, the cargo delivery inaccessibility, as well as extreme climatic conditions determines the use of a hybrid energy complex with continuous diesel generation (without energy storage use).

1. Introduction

There are many areas without access to centralized electricity supply on the territory of the Russian Federation. There are remote areas of Siberia and the Far East. For example, there are about 130 isolated power supply systems situated in Sakha Republic, their total installed capacity is of 210 MW. Decentralized power supply systems of settlements are built, as a rule, using diesel power plants (DPP) of different installed capacity. Delivering diesel fuel to remote, hard-to-reach areas with undeveloped infrastructure significantly increases the cost of electricity produced. The fuel component in the tariff for electric energy can reach 50 ÷ 80% of the total cost of diesel power plant operation [1, 2].

It is possible to improve the technical and economic characteristics of diesel power supply systems by including in their composition generating plants of renewable energy, in particular photovoltaic power plants (PV). This is achieved by saving diesel fuel and the lifespan of DPP [3].

The most common variants for the schematic construction of photovoltaic diesel hybrid power plants (PVD) are: a) separate work of diesel power station and PV power station; b) PV power plant operation in parallel with the local electrical grid formed by DPP; c) hybrid variant, providing for the possibility of separate and joint work PV and DPP. Variant of parallel work PV and DPP provides for the DPP continuous operation with the part replacement of the diesel generation with the energy of the photovoltaic power station. The advantage of this option is the ability to maximize the use PV installed capacity without expensive storage batteries of electricity [4]. The disadvantage of this option is the need to limit the network inverters power at the level of less than half of the current generation power of the diesel power complex. This limits the contribution of “green energy” to the PVD power station energy balance.

2. Experimental

2.1 Goal of work

The photovoltaic component installed power optimization of an autonomous PVD with continuous diesel generation in the North according to technical and economic criteria.

2.2 Subject of research

The PVD power supply system of the northern village, in particular – Batagay, Yakutia. Batagay village is a large settlement located beyond the Arctic Circle with geographic coordinates 67.65^0 N,

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134.64^0 E and population of 3676 people (for 2017), characterized by the significant electrical load level: $P_{load.max}$ = 5186 kW (winter), $P_{load.min}$ = 907 kW (summer). The installed capacity of the existing diesel power plant is 11 MW. Insolation during the year varies from the polar day to the polar night [5].

2.3 Research methodology

Optimization objective functions are: maximization of installed capacity utilization factor (ICUF) and minimization of produced energy cost price. ICUF – it is the ratio between actual energy production to theoretical, determined according to expression:

$$ICUF = W/P_{INS}\cdot T \quad (1)$$

Where: W – the energy volume produced by part of the hybrid power plant (PV or DPP), for the reading period, kWh; P_{INS} – installed capacity of hybrid power plant part, kW; T – reference period, h.

kWh electric energy cost price – is one of the most important parameters reflecting the economic feasibility of options for constructing generating facilities. For PVD power plants determined according to expression:

$$C_{total} = (p_{N.DPP}\cdot K_{DPP} + C_{DPP} + p_{N.PV}\cdot K_{PV} + p_{N.BS}\cdot K_{BS})/W \quad (2)$$

Where: K_{DPP}, K_{PV}, K_{BS} – investments for hybrid complex construction consisting of diesel, PV power plants and batteries; In the case of building a system operating in parallel with a grid formed by DPP (without batteries) K_{BS} = 0. C_{DPP} – operating costs for the diesel station functioning.

Operating costs for servicing the PV part of the PVD station functioning are not taken into account, due to their relatively small size.

Operating costs for maintenance of battery storage for the considered PVD option are missing.

$p_{N.DPP}$, $p_{N.PV}$, $p_{N.BS}$ – diesel, photovoltaic power plants and batteries profitability coefficient.

Target functions optimization is carried out using a computer model of the power supply system with PVD built on the basis of a specialized software product for designing photovoltaic systems PVsyst and software complex MS Excel. The optimization algorithm for the scheme with continuous diesel generation is shown in Figure 1.

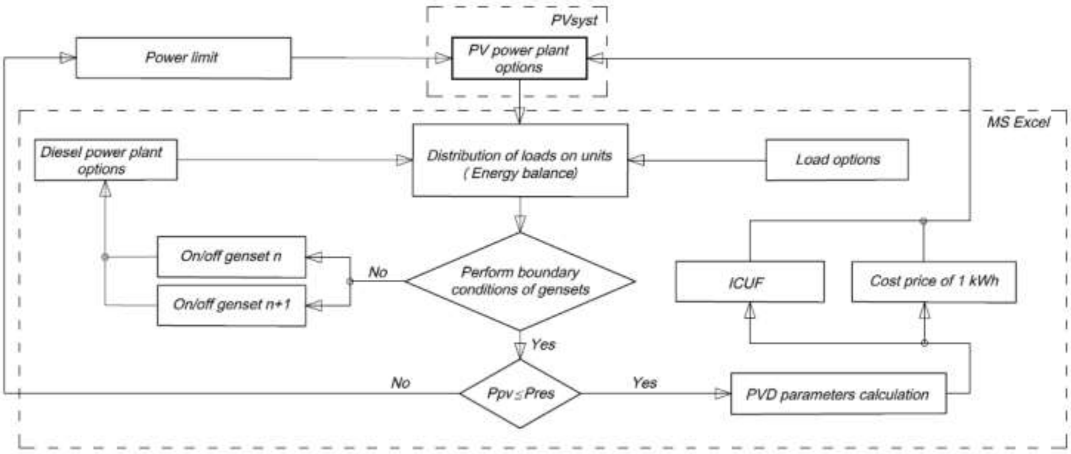

Figure 1. The optimization algorithm of installed capacitance PV power plant working parallel with local diesel power supply system.

According to the presented algorithm, the PV part initial data of the hybrid power plant are entered into PVsyst: current daily insolation with hourly sampling, PV panels quantity taking into account their orientation to the terrain, PV panel's type, spacing between rows, etc. At the output, the operator gets hourly data on the electrical energy production from PV power plant which are further exported to MS Excel, and averaged to the characteristic days of each month by insolation.

In the MS Excel software environment, the hourly data of the village load schedule are recorded, which are also reduced to the characteristic days of the month for the electricity consumed. As a result, characteristic days of each month are formed, taking into account electricity consumption and the diesel and photovoltaic parts of PVD generation.

Information on the DES composition and diesel units parameters (installed capacity, load limits) is entered. The diesel units loading optimized between operating and backup generators by redistribution taking into account the stability conditions of the PV network inverters – limiting its current capacity at the 30-40% level of PVD generation [6, 7].

If the conditions are met, the values of the objective functions are calculated: the ICUF and the electricity cost. The obtained values are analyzed by the operator, and, if necessary, the study is repeated with the modified PV installed capacity to obtain optimal results.

It should be noted that for the PVD with continuous diesel generation, the required power of the diesel power plant is not static, it is constantly changing and depends on many factors: varying seasonal and daily insolation, corresponding changes in the electricity consumption schedules of the electrification facility, etc.

Daily change graphic dependencies in the generated power of the PVD are shown in Figure 2. In the winter period, the decrease in the DPP power in the daytime is determined by the PV generation, corresponding to the change in insolation. With the PV installed capacity, PPV =1.5 MW all the energy in February is consumed by the load, replacing the corresponding part of the DPP energy. The current values of the PV and DPP generated capacity in this month correspond to the conditions for the stability of their parallel operation. Together with the increase in the length of daylight in April, the intensity of solar radiation goes up too, growing the photovoltaic part contribution of the energy complex to the PVD energy balance. For the considered installed capacities, the conditions for the parallel operation stability of the power plant photovoltaic and diesel parts at noontime of the April characteristic day are violated (see Figure 2).

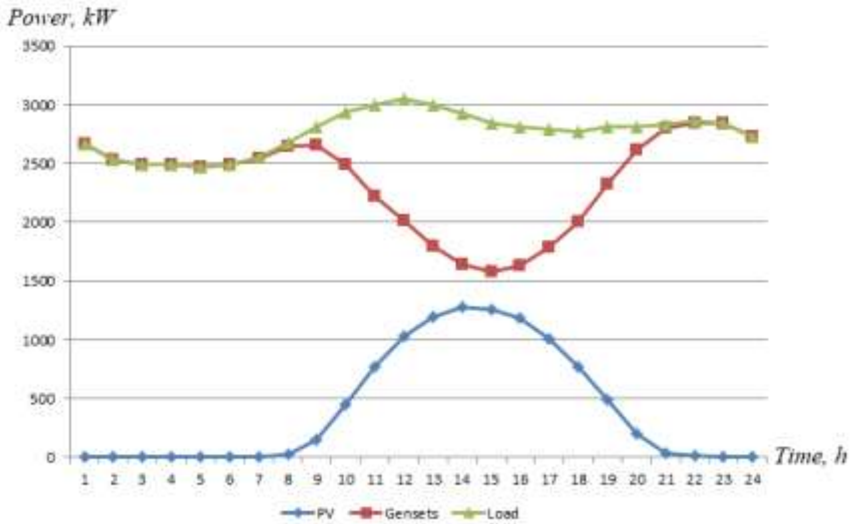

Figure 2. Hybrid complex power change, PPV =1.5 MW.

Using the developed PVD mathematical and computer models in accordance with the algorithm shown in Figure 1, the main energy indicators of the hybrid power supply system photovoltaic part in the Batagay settlement were optimized.

3. Research results

In the research process, optimal values of target functions and their monthly changes during the year were determined (see table 1). The meteorological station Verkhoyansk, nearest to the Batagay settlement, was used as a source of initial meteorological data.

Table 1. Main characteristics of hybrid power plants.

Month	*PV power capacitance*					
	1 MW		*1.5 MW*		*2 MW*	
	ICUF PV, %	En. cost, rub/kWh	ICUF PV, %	En. cost, rub/kWh	ICUF PV, %	En. cost, rub/kWh
Jan.	0.70	88.46	0.70	89.98	0.70	91.18
Feb.	8.82	51.19	8.82	51.94	8.82	52.53
Mar.	22.49	37.74	22.49	38.15	22.19	38.46
April	27.22	32.01	27.22	32.25	25.01	32.43
May	23.34	28.79	23.35	28.92	21.32	29.03
June	21.53	27.23	18.57	27.32	15.25	27.41
July	20.00	26.04	16.33	26.10	13.17	26.17
Aug.	16.53	24.77	15.45	24.79	13.51	24.84
Sept.	12.92	23.09	12.92	23.09	12.92	23.10
Oct.	9.29	21.51	9.29	21.48	9.29	21.48
Nov.	2.86	20.16	2.86	20.13	2.86	20.12
Dec.	0.00	18.93	0.00	18.91	0.00	18.90
Yearly	13.81	18.93	13.17	18.91	12.09	18.90

The diesel generators installed capacity currently participating in joint work with PV was determined in accordance with the optimization algorithm shown in Figure 1.

Graphic dependences, built according to the table 1 data, are shown in Figures 3 and 4 shows averaged annual ICUF values as a function of the PV power plant installed capacity.

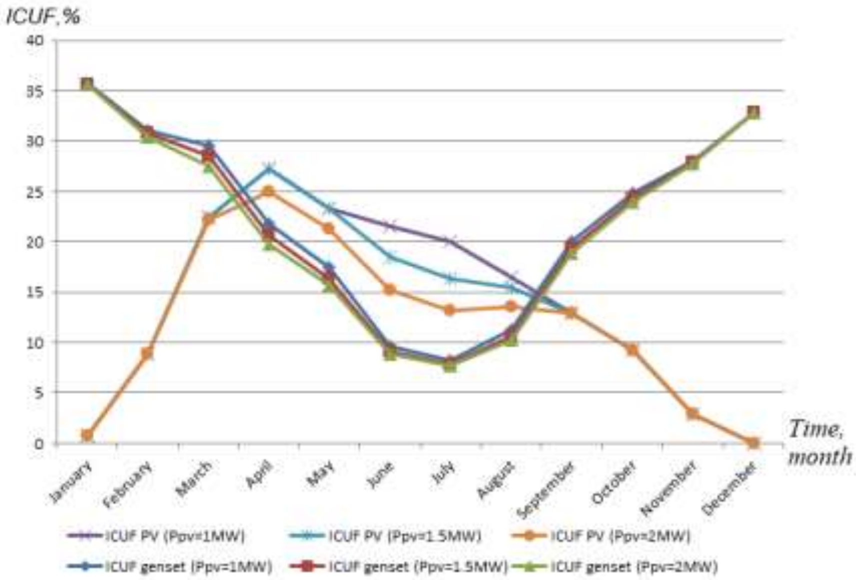

Figure 3. Hybrid power plant ICUF change during the year depending from installed PV plant capacitance.

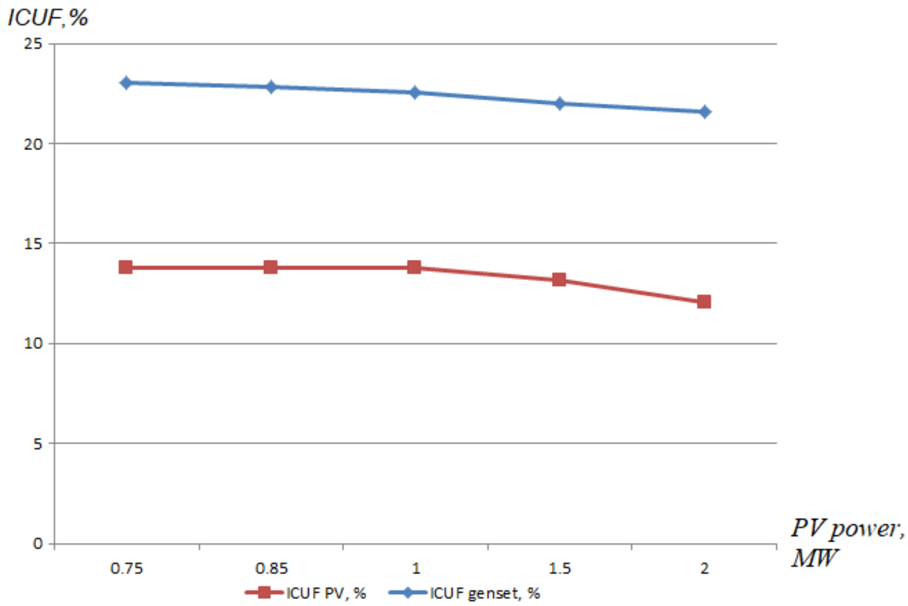

Figure 4. Hybrid power plant ICUF annual change depending from installed PV plant capacitance.

Analysing the table data, as well as the graphical dependencies given, it can be noted that with an increase in the PV part installed power of the hybrid power plant, the photovoltaic generation volume is grown too. Hence, the amount of saved diesel fuel for the electrical energy production increases, which leads to a decrease in the ICUF of the PVD diesel power plant (Figures 3 and 4).

With the growth of the photovoltaic part installed power of the hybrid energy complex, in the sunniest seasons of the year, increase in energy is observed, exceeding the requirements of the grid inverters stable operation for the local diesel power supply. As a result, the installed capacity utilization factor of the PV installed power is reduced. With the PV installed power of 1 MW, the PV ICUF has the maximum value throughout the year. With an increase in the PV power to 1.5 MW, in summertime during the hours of the sun greatest activity and the reduction of the PVD power load, an excess of electricity appears. With further increase in the PV power, the possible electricity "overproduction" begins to manifest itself in the offseason: autumn, spring. Consequently, for the considered example, an increase in the PV power above 1 MW is accompanied by a drop in the PV ICUF value, in the context of day, month and year.

Reducing the PV installed capacity below 1 MW is also not advisable for the reasons of fuel economy - the fuel saved amount will be less, which will lead to an increase in the cost of energy produced by the hybrid power plant.

For the conditions under consideration, the installed power of a 1 MW FES is the optimum point for the indicated objective functions.

Based on the calculated values of the electricity cost, shown in table 1, a graphical dependence (see Figure 5) of the PVD electricity cost change for the changes range in the PVD installed power from 1 to 2 MW was constructed.

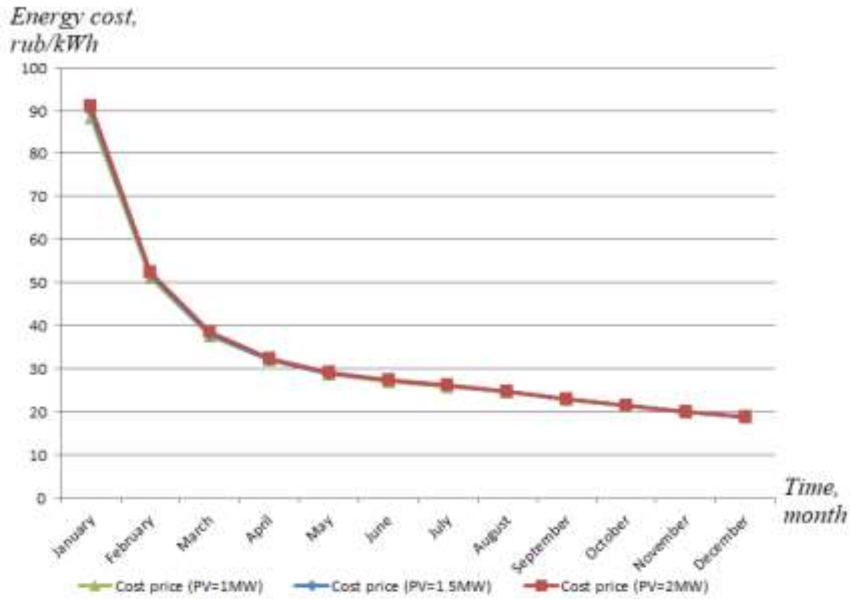

Figure 5. Annual changing of Hybrid power plant kWh depending from PV installed capacitance.

The kWh production cost of electric power of the hybrid power plant with a change in the PV installed power from 1 to 2 MW practically does not change, therefore, an increase in the installed power of the photovoltaic station by more than 1 MW for PVD Batagay village does not provide economic benefits (difference 1 ÷ 3 kopecks). The large PV installed capacity is accompanied by an increase in investments, approximately compensated by the resulting fuel savings.

In the southern Yakutia regions, the annual solar radiation arrival to the earth surface has great importance relative to the northern ones. In this regard, an additional study was conducted on the operation of a hybrid power plant with continuous diesel generation in the south of Yakutia. Studies have been conducted for a PVD power plant in the area of the Aldan city with coordinates 58.60 N, 125.40 E.

Based on the study results, we can conclude - the displacement of the PVD installation site from the northern to the southern territories gives an increase in the average annual PV utilization factor. Due to this, an increase in the optimum installed power of the photovoltaic component of the hybrid energy complex is observed. For Batagay village the optimal capacity is 1 MW, if this complex is shifted to the latitude of the city of Aldan, the optimal PV installed capacity can be increased to almost 1.5 MW. This has a positive effect on the change in the cost of energy produced by PVD.

The results are valid for the existing DPP equipment of the Batagay village. It can be expected that modern diesel generators will improve the achieved technical and economic characteristics of the PVD in Batagay village.

Consider the variant of diesel power plant modernization, providing for the replacement of the existing diesel generators fleet with more modern, automated ones. Modern automated gensets of a large manufacturers number allow their long-term loading in the range from 30% to 100%, without significant negative consequences. The operating range expansion of the generated power leads to an increase in the total reserve power (P_{res}), which diesel generators can provide at any one time and, accordingly, to better use of the photovoltaic component potential of the PVD, while maintaining the stability of its operation. By increasing P_{res}, it becomes possible to reduce the required value of the power produced by the diesel part of the hybrid power plant, which contributes to a certain increase in the PV ICUF, reducing the diesel fuel consumption and, as a result, the electricity production cost. All this improves the characteristics of the hybrid energy complex as a whole.

The DPP provision redundancy is achieved by meeting the conditions for ensuring the maximum load (P_{load}) when two of the most powerful generators exit the operation, it is determined by the expression:

$$\Sigma P_i - 2P_{max} > P_{load.max} \quad (3)$$

Where: P_{max} – units with the highest installed capacity; P_i – unit with i-th installed capacity; $P_{load.max}$ – maximum load power.

To modernize the diesel power plant of the Batagay settlement, it is necessary to install: 1000 kW diesel units – 6 pcs., 750 kW diesel units – 3 pcs. The total installed capacity of diesel power plants will be 8250 kW, which is less than the existing one. For a simulated emergency, the installed capacity of diesel power plants will be 6250 kW, which fully meets the requirements of a reliable power supply of the village.

Units installation with different installed capacity is advisable to ensure greater units maneuverability f a diesel station and to create the possibility of maintaining the required power level at different load levels with the best technical and economic indicators of a hybrid power plant.

The study results before and after the diesel composition replacement of the hybrid power plant reflect a significant increase in the utilization rate of the PV installed power due to the expansion of the gensets operating range.

There is also significant fuel savings due to a decrease in specific fuel consumption for the production of electrical energy from 250 g/kWh to 222 g/kWh.

Some comparative characteristics of the PVD with the existing and modernized DPP, with different installed PV capacities, are shown in table 2.

Table 2. Hybrid power plants characteristics before and after modernization.

	PV power plant capacitance, MW	***0***	***1***	***1.5***	***2***	***2.5***
Fuel consumption (yearly, tn)	Before gensets modernization	5881	5544	5432	5349	5301
	After gensets modernization	5176	4870	4754	4654	4580
PV utilization factor (yearly,%)	Before gensets modernization	0	1	0.89	0.8	0.72
	After gensets modernization	0	1	0.96	0.9	0.84

Based on the values of table 2, graphical dependencies are plotted, shown in Figures 6 and 7, respectively.

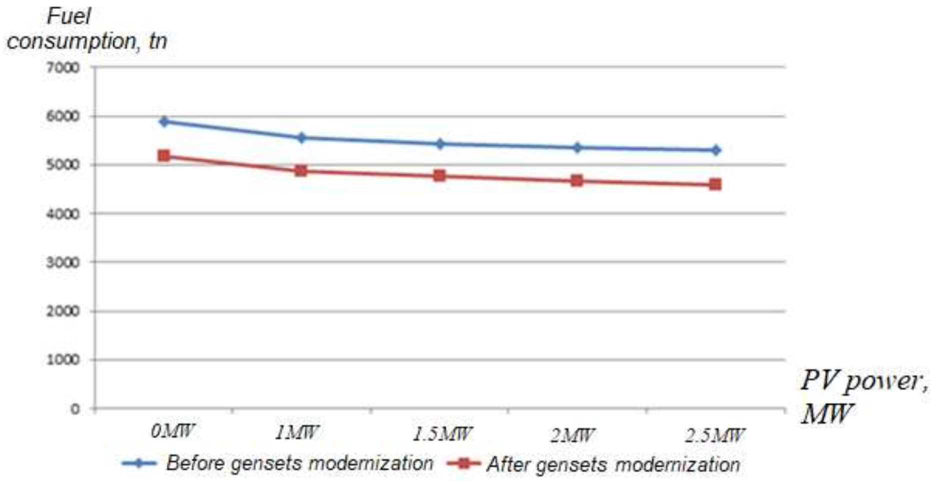

Figure 6. Diesel consumption yearly schedule depending from PV plant installed capacitance for existing and modernized gensets.

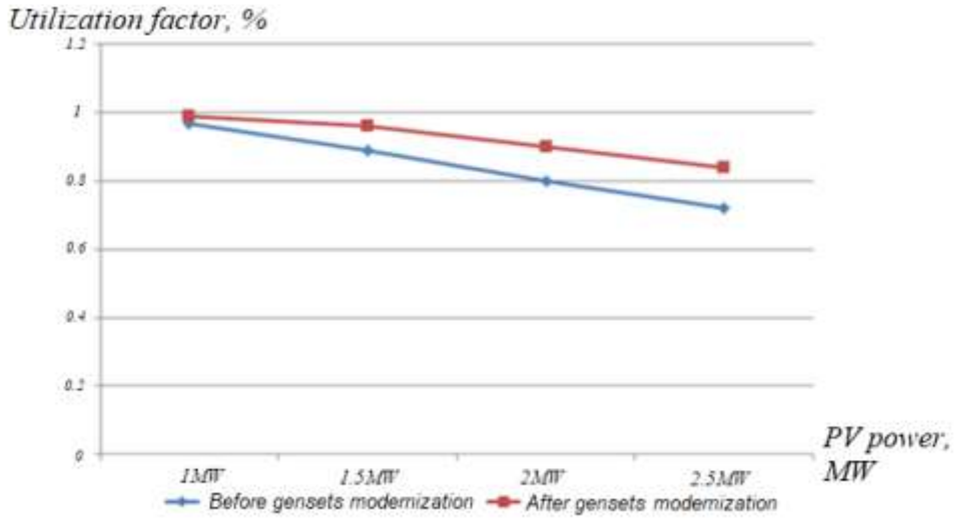

Figure 7. Utilization factor yearly change depending from PV plant installed capacitance for existing and modernized gensets.

When creating a PVD with a modernized diesel power plant, it is advisable to increase the PV installed power to 2 MW, despite the under-utilization of part of the energy (the station loses no more than 25% of solar energy in the summer months), because in addition to the greater amount of fuel saved, the hybrid station gets the best performance at the cost of electricity produced. A further increase in the PV installed capacity is not advisable because of the need to significantly reduce the beneficial use of the energy generated by it in the spring and summer months.

When constructing high-power hybrid PVD power stations based on a continuous diesel generation scheme, it is recommended to upgrade local diesel power stations to ensure the best technical and economic characteristics. This will reduce the dependence degree of the settlement on imported diesel fuel by reducing its specific consumption for the kWh electricity production by new diesel units, as well as expanding their load range. This will increase the PVD sustainability and make it possible to more fully utilize the PV power station capabilities. Also, the upgrade will eliminate the error of personnel when switching by automating the work of the hybrid power plant components.

4. Conclusions

Autonomous PV-diesel power plants with an installed capacity of 1 MW and more, in remote areas conditions with harsh climate, for technical and economic reasons require the use of PVD with continuous diesel generation, without using power storage devices.

The optimization of the PVD technical and economic characteristics with continuous diesel generation was carried out on the basis of a particular example of the Batagay settlement.

It is shown that the PV power plants installed capacity with continuous diesel generation of significant power (several MW) at latitudes similar Batagay village should be about 20% of the maximum electrical load value.

The study was conducted of the terrain latitude influence on the optimal composition of the PVD power plants equipment. With the displacement of a hybrid PVD with continuous diesel generation similar Batagay in the southern territories of Yakutia, the PVD installed power can be increased to 30% of the maximum load value due to the higher solar radiation intensity in the spring and autumn periods when the amount of power consumed by the load is large enough.

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