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Optimization of the Nominal Capacity of an Energy Storage System for Ensuring Security of the Electrical Energy Supply

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Abstract:
This paper presents an optimization model for determining the nominal capacity of an energy storage system that transfers excess amounts of electrical energy from solar power plants as part of a group of distributed generation power plants, based on the criterion of the minimum cost of supplying electricity to end consumers. The use of the developed optimization model allows one to determine the optimal parameters of the energy storage system to achieve an economic balance between the excess amounts of electric energy of solar power plants that are transferred and the number of restrictions on inverters that are subject to payment. Based on the developed method and on the forecast level of electric energy consumption and statistical data on the level of electric energy production at wind and solar power plants for the territory of Ukraine, the installed capacity of the wind, solar, reserve power plant, and the nominal capacity of the two-hour energy storage system were determined, which will provide the minimum levelized cost of energy of supplying to consumers during the entire period of commercial operation of a group of distributed generation power plants.

Keywords: *optimization model, distributed generation, solar power plant, wind power plant, backup power plant, energy storage system*

1. Introduction

The Law of Ukraine "On the Electric Energy Market" [1] defines power plants with an installed capacity of 20 MW and below as belonging to distributed generation, while the state policy in the field of electric power should promote the introduction of new capacities of distributed generation power plants and energy storage system. The Law of Ukraine "On Alternative Energy Sources" [2] (amended No. 3220-IX, dated 30.06.2023) stipulates that the Cabinet of Ministers of Ukraine must approve a state program to stimulate the development of distributed generation, specifically for those types of power plants that produce electrical energy from alternative energy sources and energy storage facilities, including those installed at critical infrastructure facilities to increase the reliability of the electricity supply to consumers.

Distributed generation, which is usually connected to the networks of the distribution system operator, has some advantages over centralized power plants of much higher capacity. The main advantages of the decentralization of generating capacities with the dispersal of less powerful power plants in power nodes are the improvement of the security of the supply of electrical energy to consumers, ensuring the appropriate level of operational security even in the event of system accidents in the power system, reduction of losses in power transmission lines, and the convergence of facilities that produce electricity with facilities that consume it. In addition, in the absence of an electrical connection with the power system, in particular, in the event of an emergency in the power system, most modern power plants of distributed generation can participate in the power island mode of operation and perform autonomous start-ups, providing a service for restoring the operation of the power system after the occurrence of system accidents. At the same time, following the provisions of the Transmission System Code, technical requirements for autonomous start-up and participation in the island mode of operation are mandatory for generating units with an installed capacity of 20 MW and above [3].

Power plants of distributed generation that generate electrical energy from alternative sources of energy, including wind and solar power plants, are superior to others, and there is no need to supply the fuel for their operation. This allows for significantly lower operational costs equal to those of other types of power plants. In this case, according to the research of the transmission system operator [4], the implementation of new functions of wind and solar power plants must be accompanied by increased maneuvering pressures and energy storage systems.

According to the statistical data of the transmission system operator [4] for the territory of Ukraine, the average annual capacity factor of wind power plants is 36 percent, which, with the same installed power, will provide greater volumes of electricity production, unlike solar power plants, for which the capacity factor is 14 percent. The advantage of solar and wind power plants is that they are subject to better scaling due to the low power of the power-generating equipment (which include photovoltaic modules and conversion inverters); the relative ease of implementation of this technology; and the absence of noise during operation.

The installed capacity of solar power plants can vary from tens of kilowatts to tens of megawatts, depending on the installed capacity and the number of converting inverters.

To ensure the reliability of the electricity supply to consumers, including in the event of an emergency, individual power plants with a significant share of wind and solar power plants must have backup power plants, which can be maneuverable gas turbine units, gas pistons, or diesel generators. At the same time, the maximum possible number of hours of operation of the standby power plant during the day is determined based on the technical capabilities of the power plant, namely, the speed of increasing/decreasing power, and the possibility of frequent stops. It starts during the day, with specific fuel consumption. The selection of the composition of power plants for implementation is carried out by achieving a balance of electrical energy between the daily volume of consumption and production, taking into account losses in power transmission lines. The profitability assessment of the implementation of new power plants is carried out based on capital investment costs during implementation, construction costs, operating costs during the further commercial operation of power plants, which consist of conditional fixed and conditional variable costs, and fuel costs.

2. Problem Statement

Implementation of energy storage systems and implementation of demand management is a generally accepted approach used to increase the share of renewable energy sources with an unstable level of generation that depends on weather conditions in distribution networks [5]. Optimizing the parameters of the energy storage system, namely, its nominal capacity and energy intensity, functioning as part of the solar power plant as an option, can be carried out through the comprehensive optimization of economic indicators, in particular, the internal rate of return (IRR), net present value (NPV), and the investment payback period [6].

In a study [7] of the optimal location of energy storage systems in electric energy nodes of the distribution system, the flows of electric energy from hydroelectric, thermal, solar, and wind power plants were taken into account. The objective function of the model is the minimization of the component cost of electricity production at power plants, the cost of unsupplied electricity, and the cost of storing electricity, plus the price of charging and discharging. It was determined that the introduction of energy storage systems ensures the reliability of electricity supply to consumers, increases the voltage level, and allows for the minimization of the costs of electricity production due to the possibility of increasing the share of capacity of renewable energy sources.

Studies conducted [8] based on the optimization model for determining the energy intensity of the introduction of an energy storage system in the distribution network of Saudi Arabia to transfer electric energy over time showed that taking into account the cost of transformer substations and power transmission lines that must be implemented, the economic feasibility of implementing storage facilities is achieved when reducing their capital investment cost by at least five times.

The use of statistical data on the level of electrical energy production of renewable energy sources allows for high accuracy in determining the optimal capacity for new implementation without an excessive increase in capital costs and with the achievement of electrical energy balance [9]. At the same time, the evaluation of the effectiveness of the implementation of the energy storage system is carried out through the determination of the levelized cost of energy (LCOE) for the cost of stored energy.

The hourly balance of electrical energy within one day for a separate energy node is provided by charging and discharging the energy storage system. The technical structure of the energy storage system is determined from the nominal power of the inverter equipment and the required nominal energy capacity, which, considering the depth of possible discharge, must provide the necessary range of electrical energy available for charging and discharging, and the range for frequency and active power regulation, including in conditions where there is autonomous operation in the power island mode without connection to the power system. For an energy storage system, the main technical indicators are rated power (kW) and rated energy capacity (kWh). The ratio between the nominal energy capacity and power characterizes the time during which the energy storage system can release previously stored electrical energy into the network.

Taking into account the significant cost of implementing an energy storage system, its construction with excess capacity leads to an increase in capital investments and, accordingly, to an increase in the cost of supplying electricity to consumers. On the other hand, insufficient capacity of the energy storage system leads to limitations of the level of generating capacities, which also increases the cost of electricity for the end consumer due to the decrease in the volume of useful electricity supply. In addition, if distributed generation power plants are used at full capacity, the energy storage system must ensure the availability of reserve energy capacity necessary for frequency regulation and active power, including for the operation of distributed generation power plants in energy island conditions.

The purpose of this work is to develop an optimization model for determining the nominal capacity of an energy storage system that carries out the transfer of excess amounts of electrical energy from solar power plants as part of a group of distributed generation power plants according to the criterion of the minimum LCOE of supplying to consumers during the entire period of commercial operation of a group of distributed generation power plants.

3. Methodology

The well-known methodology for determining the LCOE [10] was adopted as the basis for researching the profitability of implementation and further economic functioning of power plants, according to which the ratio of discounted capital investment costs (CAPEX) and operating costs is found (OPEX) to the discounted volume of electricity production during the entire life cycle of the power plant.

It is advisable to use the LCOE methodology to assess the investment attractiveness of the introduction of new power plants operating in market conditions, as discounting makes it possible to estimate the value of invested funds in future periods. When calculating the LCOE for wind and solar power plants, it is characteristic that only fixed costs for operation and maintenance (O&M) of equipment are taken into account in OPEX, since such power plants do not need fuel. For a standby power plant, in addition to fixed costs, OPEX also includes variable costs that depend on the volume of electricity production and fuel cost, which depends on the cost of purchasing fuel (e.g., natural gas).

The well-known methodology for determining the levelized cost of storage (LCOS) [11] was adopted as the basis for conducting a study on the profitability of the implementation and further economic functioning of the energy storage system, according to which the ratio of discounted capital investment costs (CAPEX) and operating costs (OPEX) to the discounted volumes of electrical energy storage during the entire life cycle of the installation. For an energy storage system, OPEX includes fixed O&M costs. At the same time, to reduce the amount of contingent and fixed costs, it is advisable to generate income from the market of auxiliary services for the provision of frequency and active power regulation services.

The LCOE methodology for the development of an optimization model for minimizing the weighted average daily cost of electricity production for a solar power plant was used to determine the optimal ratio of the installed direct current (DC) power of photovoltaic modules and alternating current (AC) of inverter equipment based on the level of solar radiation intensity [12]. The optimization model for minimizing the levelized daily cost of energy production was developed with the introduction into the structure of the solar power plant an energy storage facility for the accumulation of excess electrical energy that occurs when the set DC power is increased over the set AC power (i.e., DC/AC overloading) [13].

The objective function of the optimization model is to minimize the LCOE of supplying to consumers (LCOES) during the entire period of commercial operation of a group of distributed generation power plants,

$$LCOES = \frac{LCOE \cdot \left(W^{WIND} + W^{PV} + W^{RES}\right) + LCOS \cdot W^{BESS}}{W^{WIND} + W^{PV} + W^{RES}} \rightarrow \text{min}, \tag{1}$$

where $LCOES$ is the levelized cost of energy of supplying (€/MWh); $LCOE$ is the levelized cost of energy (€/MWh); $LCOS$ is the levelized cost of storage (€/MWh); W^{WIND} is the volume of electricity production at the wind power plant during the year (MWh); W^{PV} is the volume of electricity production at the solar power plant during the year (MWh); W^{RES} is the volume of electricity production at the reserve power plant during the year (MWh); and W^{BESS} is the volume of electrical energy storage in the battery energy storage system (BESS) during the year (MWh).

In addition to the LCOE, the LCOES also takes into account the part of the electricity that is stored in an energy storage system, so LCOS is taken into account.

For a group of power plants of distributed generation (wind, solar, and reserve power plants), the LCOE is determined relative to the share of the volume of released electrical energy for each individual power plant,

$$LCOE = \frac{L^{WIND} \cdot W^{WIND} + L^{PV} \cdot W^{PV} + L^{RES} \cdot W^{RES} + L^{CURT} \cdot W^{CURT}}{W^{WIND} + W^{PV} + W^{RES}}, \tag{2}$$

where L^{WIND} is the LCOE at a wind power plant (€/MWh); L^{PV} is the LCOE at a solar power plant (€/MWh); L^{RES} is the LCOE at a reserve power plant (€/MWh); L^{CURT} is the LCOE of curtailment at a solar power plant (€/MWh); and W^{CURT} is the volume of curtailment at the solar power plant during the year (MWh).

The proposed definition of LCOE for a group of distributed generation power plants considers the cost of curtailment at a solar power plant, which is different from the cost of generating electricity at a solar power plant. The volume of curtailment at the solar power that is part of a distributed generation group during the year are determined to be the difference between excess electric energy and the daily storage volume using an energy storage system,

$$W^{CURT} = \sum_{d=1}^{D} \left(W_d^{EXC} - W_d^{BESS}\right), \tag{3}$$

where D is number of days d during the year; ${W_d}^{EXC}$ is the daily volume of excess electrical energy (MWh); and ${W_d}^{BESS}$ is the daily storage volume at the energy storage system (MWh).

Surplus electricity generated during the day is determined by the difference between production and consumption volume,

$$W_d^{EXC} = W_d^{WIND} + W_d^{PV} + W_d^{RES} - W_d^{CONS}, \tag{4}$$

where W_d^{WIND} is the daily volume of electricity production at the wind power plant (MWh); ${W_d}^{PV}$ is the daily volume of electricity production at the solar power plant (MWh); ${W_d}^{RES}$ is the daily volume of electricity production at the reserve power plant (MWh); and ${W_d}^{CONS}$ is the daily amount of electricity consumption, taking into account losses in power transmission lines (MWh).

The daily storage volume at the energy storage system is determined from the condition,

$$W_d^{BESS} = \left[\begin{array}{l} C^{BESSchrg}, W_d^{EXC} - C^{BESSchrg} > 0 \\ W_d^{EXC}, W_d^{EXC} - C^{BESSchrg} \leq 0 \end{array} \right. , \quad (5)$$

where $C^{BESSchrg}$ is useful energy capacity of charging at the energy storage system (MWh).

Minimization of the LCOES is determined by achieving a balance between the maximum value of excess electrical energy and the time during which the energy storage system will operate at maximum capacity during the day,

$$C^{BESSchrg} = \max_{d=1 \div D} \left\{ W_d^{EXC} \right\} / x^H, \quad (6)$$

where x^H is the variable characterizing the time during which the energy storage system will operate at maximum capacity during the day.

Constraints are introduced into the optimization model because the nominal capacity of the energy storage system should not be less than the smallest installed capacity of the wind or solar power plant and should not be greater than the total installed capacity of the wind and solar power plant. The minimum limit was introduced so that the capacity of the energy storage system was sufficient to compensate for the power level of the power plant that was suddenly out of order, for example, because of an emergency shutdown when the backup power plant did not have time to gain the required power. The maximum limit is introduced so that the capacity of the energy storage system is sufficient to absorb the total amount of electricity produced by the wind and solar power plants in the event of a sharp decrease in the level of electricity consumption, for example, in the event of an accident on a power transmission line. Thus, the nominal capacity of the energy storage system, expressed through the ratio of the useful energy capacity of charging to the nominal number of hours of operation of the energy storage system, is limited to

$$\min \left\{ P^{WIND} + P^{PV} \right\} \leq \frac{C^{BESSchrg}}{H^{BESS}} \leq P^{WIND} + P^{V}, \quad (7)$$

where P^{WIND} is the installed capacity of the wind power plant (MW); P^{PV} is the installed capacity of the solar power plant (MW); P^{BESS} is the nominal capacity of the energy storage system (MW); and H^{BESS} is the nominal number of hours of operation of the energy storage system during the day.

To ensure proper project functioning of the energy storage system, when implementing the facility and calculating capital investments, it is advisable to take into account the increase in the useful energy capacity of charging the energy storage system by a fraction that includes the possible depth of discharge of the batteries,

$$C^{BESS} = C^{BESSchrg} / \eta^{DOD}, \quad (8)$$

where C^{BESS} is the nominal energy capacity of the energy storage system (MWh) and η^{DOD} is the depth of discharge of the energy storage system.

4. Input Data and Modeling Results

The daily distribution of electric energy consumption is based on the actual statistical data on the electric load schedule and the level of electric energy production at wind and solar power plants in the IPS of Ukraine for the year 2020 [14]. The electric load schedule is adjusted to the consumption capacity of local consumers of the local energy hub. The maximum daily amount of electricity consumption during the year at the level of 96.0 MWh (average electricity consumption of 4 MWh during each hour of the day) was recorded on December 10; the minimum amount of electricity consumption during the year at the level of 57.2 MWh (average electricity consumption of 2.4 MWh during each hour of the day) was recorded on June 7. According to the statistical data, the total amount of electricity production required to provide electricity to consumers at the local energy hub, taking into account the losses in the power transmission lines for the year, was determined to be 26,727.2 MWh.

The installed capacity of the wind power plant was chosen based on the analysis of statistical data, according to which the maximum power of generating electricity at the wind power plant during any day of the year should not exceed the minimum level of electricity consumption of the local energy node. The installed capacity of the solar power plant was chosen based on the arithmetic mean value of covering daily amounts of electrical energy consumption; therefore, with a significant intensity of solar radiation, excess electrical energy will be generated, which is partially transferred over time with the help of an energy storage system. The operation algorithm of the energy storage system consists in carrying out one complete cycle of charging (with significant intensity of solar radiation during the afternoon hours) and discharging (with the maximum level of consumption during the evening peak) of batteries within one day. If the useful energy capacity of the energy storage system is insufficient, the excess electrical energy of the solar power plant is limited to inverters (i.e., the electrical energy produced is not released into the network). During periods of time when there is free energy capacity of the energy storage system, it is used to provide auxiliary services for automatic regulation of frequency and active power.

The daily model takes into account the fact that in the absence of a sufficient level of electricity production at the wind and solar power plant to cover consumption needs, a gas turbine power plant is started, which can set the nominal power for a period not exceeding 15 min.

To determine the discount rate through the weighted average cost of capital (WACC) during the research period, the following was adopted: the share of owned funds is 30.0 percent, the share of borrowed funds is 70.0 percent, the income tax rate is 25.0 percent, the cost of equity is 12.0 percent, and the discount rate of the National Bank of Ukraine is 14.5 percent [15] (as of March 15, 2024). The calculated WACC, according to the generally accepted approach, is 11.21 percent. In addition, during the research period, the following was adopted: the term of construction of power plants and energy storage system is 1 year, the term of commercial operation is 20.0 years, the euro-to-UAH exchange rate is 41.0, the euro-to-US-dollar exchange rate is 1.08, and the share of construction costs (EPC) is 14 percent of CAPEX. For a solar power plant, the annual degradation of photovoltaic modules is taken at the level of 0.7 percent, and the DC/AC ratio is 1.3. The cost of limiting generation at a solar power plant is set at 219.5 €/MWh, which is roughly twice the cost of electricity production at a solar power plant, based on the assumption that the curtailment of electrical energy needs to be paid for.

For the installation of an energy storage system based on lithium-ion batteries, when determining the nominal energy capacity, the following is accepted: conversion efficiency is 98 percent; the depth of possible discharge is 80 percent; and annual degradation and the corresponding decrease in the ability to transfer amounts of electrical energy over time is 3 percent. The cost of providing auxiliary services is set at the level of 22.9 €/MWh, based on a share of 70 percent of the current marginal price of providing auxiliary services for symmetric primary regulation of frequency and active power in the power system (FCR) [16]. The duration of the provision of the auxiliary service is taken at the level of 12 h during each day, based on the free volume of energy capacity, which in total during the year is about 50 percent. Specific capital investments, conditionally permanent and conditionally variable fuel costs were accepted in US dollars from the LAZARD study [17].

Table 1 shows the input data for distributed generation power plants (wind, solar, and reserve power plants) with an installed capacity of 1 MW. For a two-hour energy storage system (EES) with a nominal capacity of 1 MW, the useful energy capacity of charging is taken at the level of 2 MWh and, accordingly, the nominal energy capacity is 2.5 MWh.

The block of cells "Modeling results (before optimization)" shows the installed capacity of distributed generation power plants determined necessary to cover the consumption needs of local consumers.

Table 1. Input data and modeling results

Name	Wind	PV	RES	BESS
Input data				
Specific CAPEX, $/kW	1350.0	700.0	925.0	80.0
Specific CAPEX, $/kWh	–	–	–	385.0
Specific fixed costs, $/kW	4.0	10.9	5.0	2.0
Specific variable costs and fuel, $/kWh	–	–	35.5	–
CAPEX, million €	1.7	1.1	1.2	1.0
Capacity factor, %	36.0	14.7	15.0	25.0
Production (storage) energy, GWh/year	3.2	1.7	1.3	0.2
LCOE (LCOS), €/MWh	81.2	108.1	189.8	377.2
Modeling results (before optimization)				
Installed capacity, MW	3.6	14.0	3.7	16.0
Nominal capacity, MWh	–	–	–	40.0
CAPEX, million €	6.2	12.1	4.4	15.4
Capacity factor, %	33.1	16.2	15.8	31.6
Production (storage) energy, GWh/year	10.5	15.3	5.1	3.7
Volume of curtailment at the solar, GWh/year	–	–	–	0.4
LCOES, €/MWh	147.9			
Modeling results (after optimization)				
Installed capacity, MW	3.6	14.0	3.7	3.9
Nominal capacity, MWh	–	–	–	9.7
CAPEX, million €	6.2	12.1	4.4	3.8
Capacity factor, %	33.1	16.2	15.8	48.5
Production (storage) energy, GWh/year	10.5	15.3	5.1	1.4
Volume of curtailment at the solar, GWh/year	–	–	–	2.7
LCOES, €/MWh	136.7			

Before optimizing the power of the energy storage system, its energy capacity was selected based on the total installed capacity of the wind and solar power plants, minus the average daily power consumption.

The block of cells "Modeling results (after optimization)" shows the nominal parameters of the energy storage system determined by the developed optimization model, which will ensure the minimum levelized cost of supplying energy to consumers during the entire period of commercial operation of a group of distributed generation power plants.

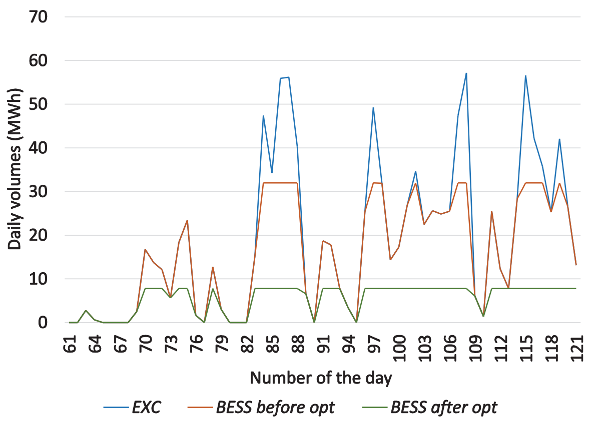

Figure 1. The daily amount of excess electrical energy of the solar power plant, the amount of electrical energy transfer using the BESS before optimization and after optimization for March and April of the year studied

From the simulation results given in the table, it can be seen that the optimization of the nominal capacity of the two-hour energy storage system and, accordingly, its nominal energy capacity, provides a reduction in the LCOE of supplying electricity to consumers during the entire period of commercial operation of a group of distributed generation power plants by 8.2 percent (from 147.9 to 136.7 €/MWh) and a reduction of CAPEX in total for the power plant and energy storage facilities by 44.2 percent (from 38.1 to 26.4 million euros).

As a result of the optimization, the amount of transfer of excess electrical energy of the solar power plant with the use of the energy storage system decreases from 24.1 percent to 9.0 percent, and accordingly, the amount of limitation on inverters increases from 2.6 percent to 17.7 percent. Before and after optimization, about 73.3 percent of the total amount of electricity produced at the solar power plant is transmitted to consumers at the same time as when it is produced.

Figure 1 shows the daily amount of excess electrical energy of the solar power plant, the amount of electrical energy transfer using the energy storage system before optimization (with useful energy capacity at the level of 32 MWh) and after optimization (with useful energy capacity at the level of 7.8 MWh) for March and April of the year studied.

It can be seen from the figure that, because of the optimization, the amount of electrical energy transferred using the energy storage system is significantly reduced compared to the amount before optimization. At the same time, the operation of the energy storage system at the specified energy capacity is stabler, with smaller daily fluctuations, which clearly demonstrates the increase in the utilization ratio of the capacity factor of the energy storage system (from 31.6 percent to 48.5 percent during the year).

5. Conclusion

While ensuring the stability of electricity supply to consumers with the help of distributed generation power plants (wind, solar, and reserve power plants), it is necessary to implement an energy storage system that is necessary for transferring excess amounts of electrical energy. However, compliance with the condition with the transfer of all excess amounts of electrical energy produced at the solar power plant leads to an excessive increase in the energy intensity of the energy storage system, which, taking into account the cost of the equipment, leads to an increase in capital investments. On the other hand, not ensuring the preservation of all excess electrical energy leads to the limitation of the level of generation and, accordingly, to the increase in the cost of electricity production for the end consumer. The proposed optimization model for determining the nominal capacity of energy storage systems that transfer excess amounts of electrical energy of a solar power plant as part of a group of distributed generation power plants allows for the minimization of the cost of electricity production for the end user throughout the entire period of commercial operation of power plants. According to the developed optimization model, a balance is achieved between the amount of transfer of excess electrical energy produced at the solar power plant using the energy storage facility and the amount of restriction on inverters.

Based on the results of the research, it was determined that for the territory of Ukraine, ensuring the maximum daily level of electricity consumption at the level of 96 MWh (with an average electricity consumption of 4 MWh during each hour of the day) is achieved by implementing a wind power plant with an installed capacity of at least 3.6 MW, an installed capacity of the reserve power plant of 3.7 MW, and an installed capacity of the solar power plant of 14 MW. At the same time, based on the optimization model, it was determined that the nominal capacity of the two-hour energy storage system should be at least 3.9 MW, with a useful charging energy capacity of 7.8 MWh and a nominal energy capacity of 9.7 MWh. The determined parameters of the energy storage system will ensure the transfer over time of about 9.0 percent of the total amount of electrical energy produced at the solar power plant and at the same time, the amount of limitation of excess electrical energy at the solar power plant will be about 17.7 percent.

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