Optimization and Feasibility Analysis of Solar Grid Systems for Pumping Stations in Central Asia

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Abstract: Solar energy is a clean and renewable technology with significant potential for sustainable electricity generation. This study investigates the design, optimization, and feasibility of solar grid systems for pumping stations in Central Asia, where high solar insolation and available land provide ideal conditions. The main components of the solar power plant - photovoltaic panels, inverters, batteries, and control systems - were analyzed for optimal configuration and placement. Experimental studies on two-layer and three-layer solar cells demonstrated efficiency improvements of up to 30% and 40%, respectively, highlighting the potential for enhanced energy output. The operating point of photovoltaic panels was determined by intersecting volt-ampere characteristics with load conditions to maximize performance. A comprehensive feasibility assessment was conducted, considering energy generation, reliability, and economic aspects, including cost-effectiveness and payback period. The findings indicate that solar grid systems can provide a reliable, environmentally friendly solution for pumping stations, contributing to regional energy security and sustainable development. This research supports the large-scale implementation of solar energy in Central Asia and provides practical guidance for optimizing system performance and investment efficiency.

1 INTRODUCTION

Maintaining energy security and addressing climate change are common challenges facing scientists, while accelerating the development of green energy opens up common global opportunities. Global energy development trends that meet national conditions and the demands of the times are developing in leading countries. While advancing its own energy transformation, China is actively promoting the global energy transition in all areas of global energy governance reform.

The Chinese company LONGi Green Energy, specializing in solar energy, has developed a comprehensive plan for the implementation of renewable energy technologies (RES), which play an important role in the future of global energy [1], [2].

As the global energy transition accelerates, the renewable energy industry is entering a new phase with elements of improved management methods for the operating conditions of machine channels. An analysis of the use of renewable energy sources in the operation of primary equipment and hydraulic structures in Central Asia is provided [3], [4].

The global energy system is evolving towards more sustainable energy sources. Replacing global energy with renewable energy sources reduces global energy consumption by 30%. Renewable energy sources require only 0.4% and 0.5% more land for solar panels worldwide. It is advisable to provide 100% of new energy using renewable energy sources and replace existing energy by 2050 [5], [6].

Uzbekistan has great potential for the development of solar energy, as the country has a high level of solar insolation - more than 300 sunny days per year and about 1500-2500 kWh/m^2 per year.

In addition, Uzbekistan has a large area of unoccupied land that can be used for installing solar panels/batteries. According to the Ministry of Energy of Uzbekistan, the country plans to build several large solar power plants with a total capacity of more than 9 GW by 2030. Thus, solar energy is a promising direction for improving energy security in Uzbekistan.

2 MANUSCRIPT PREPARATION

The potential of renewable energy sources, as shown in Table 1, is quite significant in the Central Asian region. The potential of small hydropower ranges from 275 to 30,000 MW, solar photovoltaic energy from 195,000 to 3,760,000 MW, and wind energy from 1,500 to 354,000 MW [7].

Table 1: Renewable energy potential in Central Asia.

Country	Small hydropower	Solar photovoltaic energy		Wind energy	
	MW	MW	TWh/year	MW	TWh/year
Uzbekistan	1180 (≤10)	593000	1195	1600	1685
Kazakhstan	4800 (≤35) 2707 (≤10)	3760000	6684	354000	11388
Kyrgyzstan	900 (≤30) 275 (≤10)	267000	537	1500	256
Tadjikistan	30000 (≤30)	195000	410	2000	146
Turkmenistan	1300	655000	1484	10000	1992

Hydropower potential is defined as the annual energy that is potentially available if the entire natural flow to the sea (or to the boundary of a region when calculating regional potential) could be utilized at all locations without any loss of energy.

Solar energy is the only one that comes from outside, from the surrounding space. The idea of using solar energy arose long ago, but only after the emergence of appropriate technologies, it was embodied in reality. After the invention of photovoltaic batteries and solar collectors for collecting and converting thermal energy into electrical energy, the development and implementation of solar power plants began at a rapid pace. A solar power plant is a device that converts solar energy into electrical energy. The solar power plant consists of arrays of solar cells (batteries) designed to convert the energy of the sun into electrical energy, batteries that perform the function of storing electrical energy, a static voltage converter that solves the function of voltage stabilization and a static voltage converter that performs the function of an inverter for communication with the power grid (Fig. 1).

Figure 1: Solar power plant complex.

Research has shown that the development of cost-effective and promising solar cells is a realistic goal. Due to the high efficiency of solar energy conversion, these devices are of particular interest as next-generation technologies. The new solar cells produce more energy than organic thin-film solar cells, with a maximum energy conversion efficiency of over 21% [7], [8].

Maxeon Solar Technologies has developed its fifth generation of bifacial solar panels designed for use in large power plants and pumping stations. According to the company's published data, these panels have a number of innovative features that ensure high performance and durability. Their commercial implementation ensures the creation of a total solar power plant capacity of more than 5 GW worldwide [9], [10].

The 25% growth rate of global solar and wind generation, if maintained, would result in roughly 10-fold growth within a decade. Within 11 years, the annual growth of global solar and wind power would exceed the entire annual growth of global energy supply (GES). By that point, global solar power, providing only 10% of global energy consumption, will reduce the total annual growth of more traditional forms of energy to about zero.

The generated electricity can be stored or used directly, returned to the grid line, or combined with one or more other electricity generators. Main components of a solar grid power plant (Fig. 2).

The solar panel converts sunlight into direct current electricity. The inverter converts the direct current output into alternating current. The charge controller regulates the voltage and current coming from the panels to the equipment. It prevents overcharging, extending their service life. The battery stores energy for possible critical loads or in the complete absence of sun in the evening and at night. Additionally, auxiliary sources can be used as part of the pumping station - a diesel generator or other renewable energy sources.

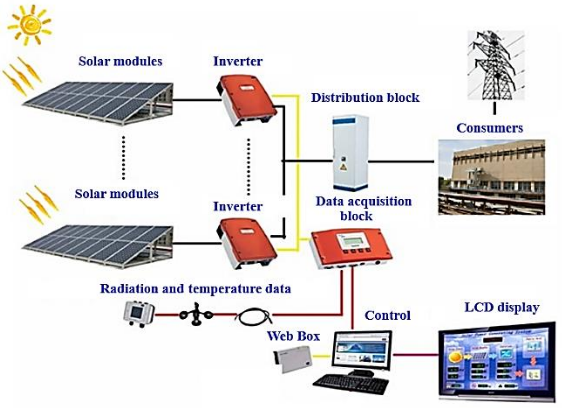

Figure 2: Main components of a solar system for a pumping station.

A feasibility study (FS) for assessing the economic feasibility of a project draws conclusions from calculations about its effectiveness and further implementation [11], [12].

The feasibility study is developed taking into full account the specifics of the facility and specifies the prospects for using the solar power plant. The following components of the power plant are checked as standard: solar panel options; capacity and placement of structures and equipment.

The first step is to develop, determine the power system capacity and power consumption of all load options.

Different modules will produce different amounts of power. To figure out what type they are, you need to understand the peak load, both overall and by hour. The peak load produced depends on the size of the battery, the climate, the location. It takes into account the "panel generation factor", which is different in each location.

The calculation of the number of photovoltaic panels results in their minimum number. If more modules are installed, the station will work better and the autonomous operation time will increase. If fewer modules are used, it may not work at all during cloudy periods and the service life of the panel will be reduced.

The nominal input power of the inverter cannot be lower than the total power of the appliances. The inverter has a nominal voltage equal to the battery. For stand-alone stations, it must be large enough to handle the total amount of energy used at one time. The size should be 25-30% larger than the total power. In case the device type is a motor or compressor, the size is at least 3 times larger and is added to the inverter power to handle the surge current during startup. For grid-connected systems, the rated power should be the same as the PV array to ensure safe and efficient operation [13], [14].

The type of panel recommended for use is a deep cycle, high cyclic battery. A deep cycle battery should be specifically designed to discharge to a low energy level and recharge quickly, or to cycle and discharge day after day for many years. The battery needs to store enough electricity to operate the devices at night and on cloudy days.

For a solar power plant to work at 100%, all calculations must be accurate. Even minor errors can lead to a drop in performance.

A computer model that calculates all the options for the station's operation allows the following parameters to be taken into account [15], [16].

Shading indicators allow us to answer what impact nearby objects (structures, trees, pipes) will have.

Climatic features take into account the amount of sunlight typical for the area, weather conditions, and other factors (Fig. 3).

Figure 3: Solar panels operating in shaded conditions.

Determining the optimal angle of inclination of the modules allows to receive maximum solar radiation.

The calculations made allow to understand what distance between modules is optimal for efficient use of available space, excluding the shading effect.

Direct conversion of solar radiation into electrical energy is carried out by solar photovoltaic cells (batteries, installations). The most widespread solar photovoltaic installations (SPPU) are based on three types of silicon: monocrystalline, polycrystalline and amorphous. In industrial production there are SPPUs with the following efficiency:

1) monocrystalline: 15 – 16% (up to 24% on test samples);

2) polycrystalline: 12 – 13% (up to 16% on test samples);
3) amorphous: 8 – 10% (up to 14% on test samples).

All these data correspond to the so-called single-layer elements [17], [18]. Currently, two- and three-layer photocells are being studied, which allow us to study a large part of the solar spectrum by the wavelength of solar radiation. For a two-layer solar cell, an efficiency of 30% was obtained on experimental samples, and for a three-layer cell, up to 40%. In recent years, a promising competitor for silicon in solar power plants has appeared - gallium arsenide. Installations based on it, even in a single-layer design, have an efficiency of up to 30% with a much weaker dependence of its efficiency on temperature, since during the operation of the solar photovoltaic power plant, their surfaces heat up strongly, which leads to a decrease in the energy performance of the installation. Water is used to cool such installations. An important circumstance is the fact that solar photovoltaic power plants are characterized by a relatively simple design, low metal consumption, and can operate with the same efficiency in any power range and at any latitude.

Structurally, the solar power plant contains: solar batteries (SP), containing photocells; an inverter (I), made on semiconductor devices, as a rule, containing a transformer in its design; storage batteries (SB); – a control and protection system (CPS) (Fig. 4).

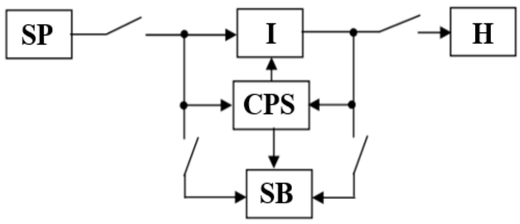

Figure 4: Structural diagram of the solar power plant with the connected load of the pump head H.

Solar panels SP convert solar radiation energy into direct current electrical energy. The inverter converts direct current voltage into alternating current voltage, and its transformer matches the voltage of solar panels SP with the load voltage H. The batteries are a backup power source. The control and protection system of the control and protection system ensures voltage stabilization, transfer of power supply to the load from the backup source and protection of the device from emergency operating modes. Currently, new technical solutions for inverters are known, made using transformers with a rotating magnetic field and intermediate high-frequency conversion, which will significantly improve their operational and technical characteristics [19], [20]. The peculiarity of the work is that the current of the solar photovoltaic power plant can be increased by parallel connection of solar batteries (Figure 5a). Solar batteries must have the same number of elements providing the same voltage. Due to the different illumination of the solar cells shown in Figure 5a, the voltages generated by them will differ slightly from each other. Therefore, only one solar cell will work effectively. When solar cells are connected according to the scheme shown in Figure 5b, the voltages generated by them are distributed more evenly across the solar battery. As a result, partial shading of the cells will not cause much harm to the operation of the solar battery.

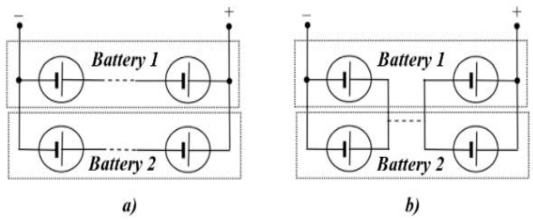

Figure 5: Solar cell connection diagrams.

To increase the voltage of the solar power plant, it is necessary to connect the solar battery elements in series. The voltage in this case will be equal to the sum of the voltages on all the components of the solar elements. The current given by the solar power plant will be limited by the current of the worst element.

For solar power plants with a large area of solar panels consisting of many series-parallel connected cells, it is necessary to take into account the shadow effect that occurs when the panel is partially darkened. If a cell in a series circuit is completely darkened, then it turns from an energy source into a consumer. Due to the series connection with the illuminated cells, a current flows in the circuit, heating the shaded cell with the power loss released on its internal resistance. Thus, the electric power of the SP decreases. In order to reduce the influence of the shadow effect on the energy characteristics of the solar battery, the series circuit of photovoltaic modules is divided into several sections using bypass diodes (Fig. 6).

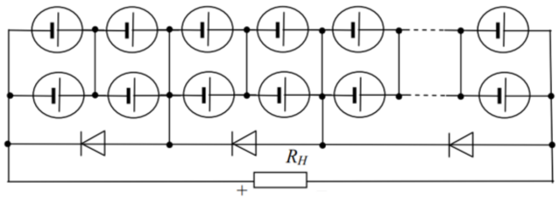

Figure 6: Schematic diagram of bypass diodes between solar cells of the SP.

It is known that the power generated by the solar battery increases at lower temperatures. However, the maximum power at different temperatures corresponds to different voltages. To address this shortcoming, a solar power plant must be equipped with a cooling system [21]-[25]

The value of the SP load significantly affects the value of the power removed from it. The operating point of the photovoltaic panel can be defined as the point of intersection of its volt-ampere characteristic (VAC) with the VAC of the load. This determines the operating point at the intersection of the energy characteristics of the photoconverter and the load (Fig. 7).

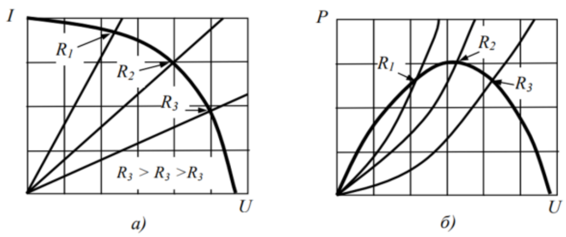

Figure 7: VAC characteristics of a photoconverter with different load resistances (R_1, R_2, R_3)

The maximum power can be removed from the solar battery on a load with resistance R_2.

Silicon-based solar cells have an efficiency of 12–23% [3], [14]. The efficiency of laboratory samples currently reaches 28%. The global production of solar cells exceeds 50 MW per year and increases annually by 30%. Cascade connection of photoconverters allows to build solar power plants with a capacity of up to hundreds of kW. The total area of the solar panel required to obtain the required power of the power plant is determined taking into account the efficiency of photoconversion and the specific level of illumination of the solar panel surface, which depends on the time of day, latitude, weather conditions, and the location of the surface of the solar converter relative to solar radiation.

Solar power plants are planned to be used in the devices for sealing the foundations of solar panels to eliminate water leaks through defective butt joints between elements during their cleaning. Research is being conducted on the energy patterns of direct cooling and cleaning modes of solar panels [26,27].

3 CONCLUSIONS

The present study demonstrates the significant potential and advantages of solar energy as a sustainable solution for electricity generation.

1) Solar panels provide numerous benefits as a renewable energy technology. They operate autonomously, require no fuel, and produce electricity silently. Solar energy is environmentally safe, consistent, and renewable, making it a "green" technology. Panels can be installed across different latitudes and climates, and individual units can be easily replaced or maintained. Regular monitoring and cleaning are recommended to ensure optimal performance. Solar power plants can supply electricity to various devices and can be selected according to required power, type, and functionality.
2) The use of solar energy allows electricity generation without carbon dioxide emissions. The cost-effectiveness of solar systems depends on technology efficiency, system design, and operational management, which can significantly influence the cost per kilowatt-hour. By 2050, renewable energy is expected to supply approximately half of the global energy demand, with production levels potentially exceeding 140 times current annual global consumption.
3) Increasing the efficiency of pumping stations and related machinery is crucial for energy and resource conservation. Many pumps in operation for 25–50 years exhibit reduced efficiency due to physical and technological wear. Modernization and reconstruction of these facilities using renewable energy sources can significantly improve performance, reduce energy losses, and enhance sustainability.

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