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Hybrid Power Supply System for Pumping Stations Based on Thermal, Photovoltaic and Hydroelectric Stations

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Abstract. Information is provided on the work carried out in the Republic of Uzbekistan for the development and transformation of energy infrastructure. A diagram of the proposed Talimarjan hydropower complex is proposed, consisting of a cascade of pumping stations, a reservoir, thermal electric, photovoltaic and hydroelectric stations, which is a decentralized hybrid energy system connected to a centralized energy system. A method for determining the operating mode of the parameters of a hybrid power system on a daily load schedule is presented. The results of calculations to determine the efficiency of the proposed energy system, obtained due to the difference in the cost of electricity compared to a centralized energy system and the reduction of carbon dioxide emissions, are presented.

Keywords: photovoltaic power plants, hydro power plants, decentralized energy system, cascade of pumping stations, daily load schedule.

INTRODUCTION

Currently, large-scale changes are being carried out in the electric power industry of the Republic of Uzbekistan to modernize old thermal power stations (TPS) and build new hydro, solar and wind power plants, the main goal of which is to achieve a sustainable energy supply to the country's economy and improve the living conditions of the population based on the most efficient use energy resources. The "Concept for Providing the Republic of Uzbekistan with Electric Energy for 2020-2030" sets a goal to increase electricity generation to 120.8 billion kWh by 2030, which is 1.76 times more than electricity generation in 2020 [1]. At the same time, the annual growth in electricity consumption in the republic will be 6-7 percent, and the total electrical load during peak consumption hours will reach more than 20.9 GW by 2030 versus 10.4 GW in the winter of 2019, as a result of which by 2030 an increase in generating capacity by almost 2 times is required [1]. Achieving these milestones in the energy sector will be difficult and ineffective without energy transformation based on diversification, decarbonization, decentralization and digitalization of the process of energy production and consumption.

In matters of diversification and decarbonization of energy processes in the Republic, certain goals have been outlined, which include reducing specific greenhouse gas emissions per unit of gross domestic product by 35% by 2030 from the 2010 level, developing renewable energy sources (RES) with increasing their share to more than 25 % of the total volume of electrical energy generation [2].

In the Republic, energy supply to consumers is carried out by a centralized energy system, which has significant disadvantages, such as significant energy losses due to the remoteness of some consumers, insufficient flexibility of the production process due to the low share of highly maneuverable power plants in it, and the lack of highly effective mechanisms for regulating consumption and energy tariffication. All these shortcomings ultimately lead to increased fuel consumption and the cost of energy produced.

Currently, these shortcomings of the centralized energy system have created the conditions for the transition to other, more efficient energy systems, such as decentralized energy systems (DES). DES are relatively small energy systems that serve to cover the energy needs of consumers located within a certain boundary and having all the necessary conditions for the generation, accumulation, transmission and distribution of energy. In most cases, DES are created on the basis of renewable energy sources, and they can be connected to a centralized energy network to purchase and sell energy depending on the prevailing climatic conditions.

The International Energy Agency states that by 2030, DES will be the most cost-effective way to access energy and can be used by more than 70% of the population in rural areas of the planet [3].

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Bloomberg New Energy Finance researchers believe that Australia's DES will account for 44% of the energy generated by 2050, and 33% in Japan [4].

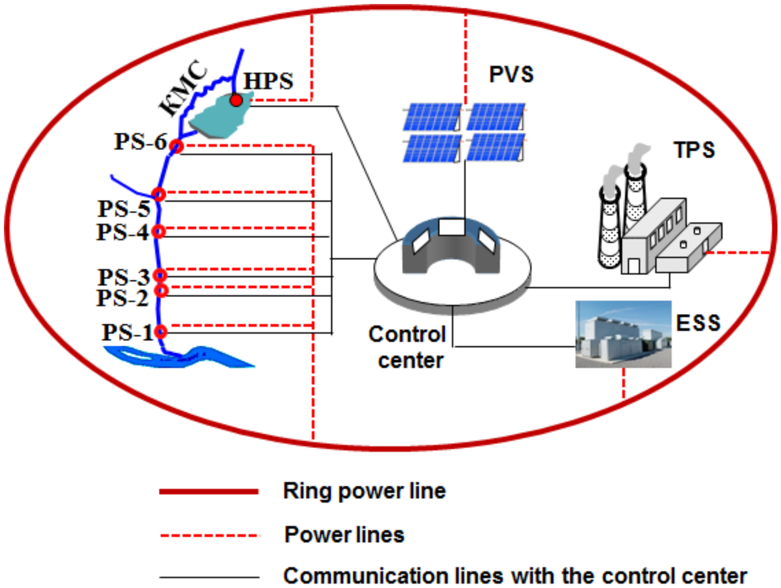

FIGURE 1. Power supply diagram for pumping stations. Karshi main canal based on the DES, consisting of TPP, PVS, HPS and energy storage system (ESS)

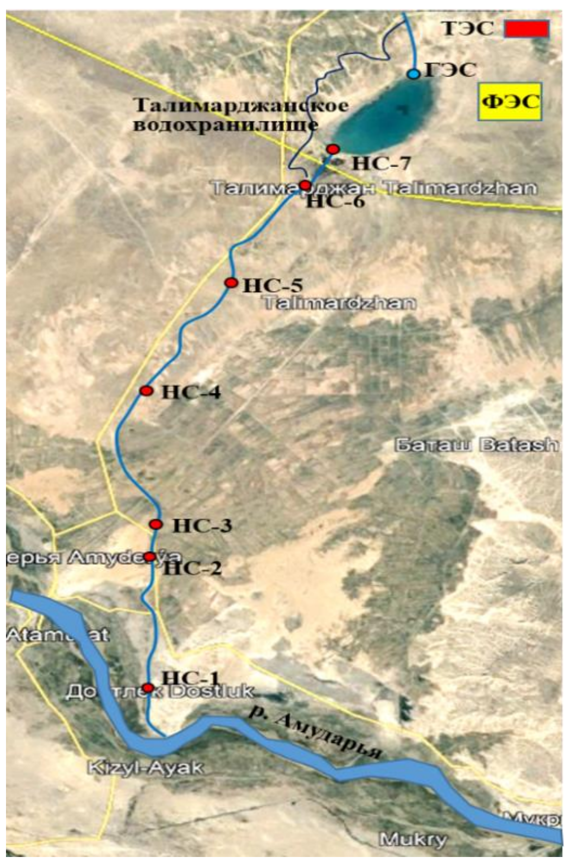

FIGURE 2. Layout plan for the cascade of pumping stations of the Karshi main canal and the Talimarjan reservoir.

In our opinion, one of the possible effective DES can be created on the basis of the Talimarjan energy and water management zone, located in the south of the Republic of Uzbekistan and including the Talimarjan TPS with an installed capacity of 1700 MW, a cascade of pumping stations of the Karshi Main Canal (PS KMC) with an installed capacity of 450 MW, Talimarjan bulk reservoir with a design volume of 1.5 billion m^3 (Fig. 1). The main prerequisites for the creation of this DES are the following:

- in the DES zone there is the largest consumer of electricity - the PS KMC, which has six stages of mechanical water lifting, with annual consumption in the range of 2.0-2.2 billion kWh, which is about 3% of the total energy consumption in the Republic (Fig. 2.). Supplying water to irrigated areas with such electricity consumption almost doubles the cost of production, which requires making specific decisions to reduce energy costs;
- the presence of the Talimarjan reservoir creates conditions for generating electricity using a hydroelectric power station (HPP) installed in the water outlet structure [5];
- due to the known advantages of RES compared to thermal power plants, for the energy supply of the PS cascade, it is beneficial to maximize the use of energy from photovoltaic stations (PVS) within the framework of the proposed DES;
- Talimarjan TPS, as an object of the centralized energy system, can participate in the DES as a guaranteed source of energy in periods of insufficient energy generated by PVS and HPP. Participation of the Talimarjan TPS in this scheme is beneficial in that the use of energy from HPP and PVS partially relieves tension when providing peak loads with turbine units, and the energy consumption of the PS cascade at night low loads allows reducing changes in equipment operating modes, which has a positive effect on fuel economy and increased reliability station operation [6];
- all objects of the proposed DES are located in close mutual proximity within a radius of no more than 45 km, which allows reducing costs associated with energy transportation.

METHODS AND MATERIALS

The energy balance in the above energy system is obviously determined by the following relationship

$$E_{PS} = E_{TPS} + E_{HPS} + E_{PVS} - \Delta E \quad (1)$$

where ΔE are losses in switching, during energy transportation, as well as its volumes spent on own needs.

The capacity of power plants used in DES is determined based on the cost of electricity offered by producers at the moment and the restrictions imposed on the use of power resources. The tariff for electricity of the centralized energy system of the Republic (generated by TPS and HPS) is currently in dollar equivalent 0.0265 $\$(kWh)^{-1}$, however, to ensure the profitability of energy organizations, it is planned in the near future to switch to a tariff of 0.072-0.073 $\$ (kWh)^{-1}$ [7]. It should be noted that the cost of hydroelectric power will be lower than indicated, but so far a separate tariff for hydroelectric power has not been established in the Republic, so it can be taken according to international data, equal to 0.061 $\$ (kWh)^{-1}$ [8]. The cost of electricity from PVS built in the Republic of Uzbekistan ranges from 0.02679 $\$(kWh)^{-1}$ (Masdar Clean Energy company) to 0.04273 $\$(kWh)^{-1}$ (Total Eren company) [9].

Based on the above, it can be noted that in terms of electricity tariffs, an attractive option is the use of solar energy to power the PS KMC, moreover, in the nearby territory of the Talimarjan reservoir, the construction of a solar power plant with a capacity of 500 MW has begun by the China Gezhouba Group Overseas Investment Co. LTD [10].

The HPS, which will be included in the DES, can be built on the water outlet structure of the Talimarjan reservoir, operating for 3.0...6.0 months in the summer. A HPS, depending on the accumulated volume of water in the reservoir, can generate up to 50,000 MW·hours of electricity per year with an average power of 60 MW [5].

Thus, the most suitable power plants that can participate in the DES to supply energy to the PS KMC are the Talimarjan TPS, the FVS and the HPS.

Approximate operating modes of TPS, PVS, and HPS can be characterized on the basis of the annual load schedule of the PS cascade for 2021 with a total volume of 2,173,000 MWh, constructed according to data from the management of the operation of the Karshi main canal and pumping stations (Fig. 3)

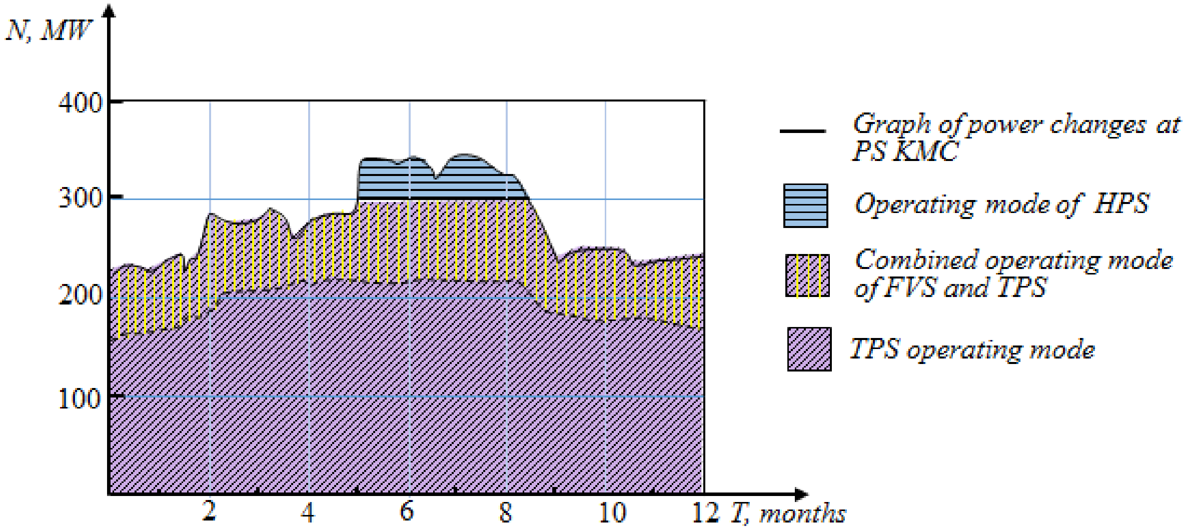

FIGURE 3. Operating schedule of the PS KMC and DES power plants.

The operating mode of the HPS is characterized by power values depending on the flow rate of the water outlet in the period from May to August with a maximum value of 60 MW.

Of all the operating modes of the DES shown in Fig. 3, the joint operating mode of the PVS and TPS is of interest, determined on the basis of the integration of the PVS operation into the operating mode of the centralized energy system and taking into account the duration of the period of solar activity. In order to better understand this process, let us consider the graph of the daily operating mode of the DES, shown in Fig. 4.

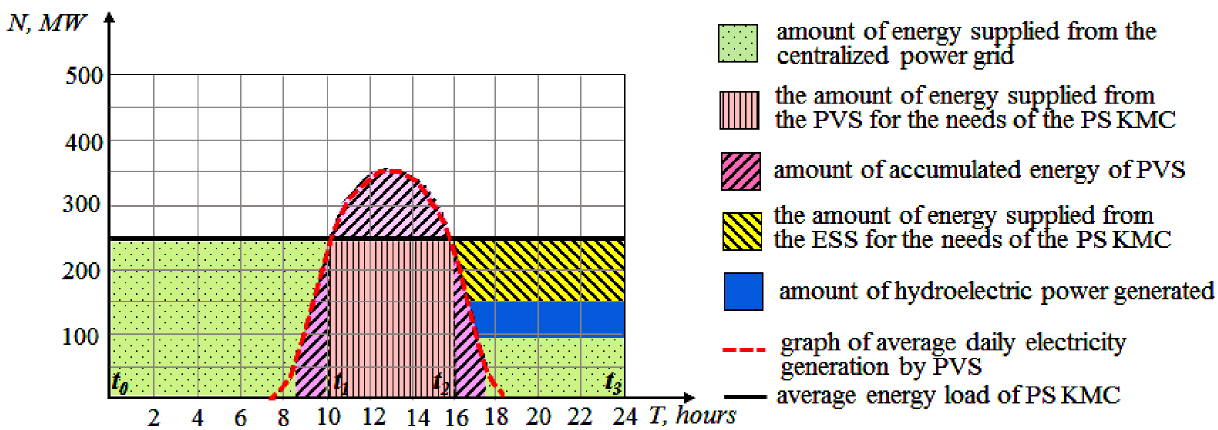

FIGURE 4. Daily schedule of the DCES operation mode.

The graph illustrates the possibility of covering the average energy load of a KMC PS with a capacity of 250 MW (installed capacity 450 MW), which, as a rule, remains almost unchanged in stationary operating modes of the PS for a certain period. At the same time, the main participant in the DES is the TPS, and during periods of solar activity from 10^{00} to 16^{00}, some excess energy from the PVS with a rated power of 350 MW (installed capacity of 500 MW), exceeding the consumption of the PS KMC, is accumulated in the energy storage system (ESS). The graph shows that in the period from 16^{00} to 24^{00}, to cover part of the consumption of the PS KMC, the energy accumulated in the storage tank is used, as well as the energy of the HPS operating during those periods when water is released from the Talimarjan reservoir.

The amount of annual energy consumed by the PS KMC cascade during the period T_{year} can be expressed by the following dependence

$$E_{PS}\ (T_{year}) = \sum_{i=1}^{n} E_{PSi}(T_{day}) = \int_{t_0}^{t_\kappa} N_{PS}(t)dt \tag{2}$$

where, E_{PSi} (T_{day}) is the amount of energy consumed by the PS KMC during the day, $N_{PS}(t)$ is the power of the NS KMC at time t, n is the number of days during the time T_{year}.

Daily energy consumption by the PS KMC cascade based on the graph shown in Fig. 4 is determined by the following equation

$$E_{PS}(T_{day}) = N_{TPS}T_{t_1-t_0} + \int_{t_1}^{t_2}(N_{PVS} - N_{PVS}^{str}\ )(t)dt + N_{TPS}T_{t_3-t_2} - \int_{t_2}^{t_3}(N_{str} + N_{HPS})(t)dt \tag{3}$$

where, $N_{TPS}(t)$, $N_{FVS}(t)$, $N_{HPS}(t)$ is the power of TPS, PVS and HPS supplied for consumption by PS KMC at time t, $N_{PVS}^{str}(t)$ is the power of the accumulated energy of the PVS, $N_{str}(t)$ is the power of the ESS at the time t.

The amount of electricity supplied from the TPS can be determined as follows

$$E_{TPS}(T_{TPS}) = \int_{t_0}^{t_1} N_{TPS}\ (t)dt + \int_{t_2}^{t_3} N_{TPS}(t)dt\ = N_{PS}T_{t_1-t_0} + N_{PS}T_{t_3-t_2} - \int_{t_2}^{t_3} N_{str}(t)dt - \int_{t_2}^{t_3} N_{HPS}(t)dt \tag{4}$$

where, T_{TEC}, $T_{t_1-t_0}$, $T_{t_3-t_2}$ – duration of operation of thermal power plants per day, as well as in time intervals per day t_1 - t_0 and $t_3 - t_2$.

The volume of accumulated energy of the PVS in the time interval t_2 - t_1 can be calculated by the following dependence

$$\int_{t_2}^{t_3} N_{str}\ (t)dt\ \ = \int_{t_{C1}}^{t_{C2}}(N_{PVS} - \Delta N_{str})(t)dt - N_{PS}T_{t_2-t_1} \tag{5}$$

where $\Delta N_{str}(t)dt$ – the amount of energy lost during its accumulation, $t_{c2} - t_{c1}$ - duration of solar radiation during the day.

The power of the generated energy of the HPS can be determined by the following dependence

$$N_{HPS}(t)=9.81\cdot Q_{HPS}(t)\cdot H(t)\cdot \eta_{HPS} \tag{6}$$

The water flow in the HPS $Q_{HPS}(t)$ depends on the time of supply of the volume ΔV, and in this regard it can be determined as follows

$$Q_{HPS}(t)=dV/dt \tag{7}$$

Using dependencies (6) and (7) you can calculate the power as follows

$$\int_{t_2}^{t_3} N_{\mathrm{HPS}}(t)dt = 9.81\int_{t_1}^{t_2} dV \cdot \eta_{HPS} H(t) \tag{8}$$

In this case, the pressure of the HPS is determined by the known dependence

$$H(t)=H^S(t) - \Delta H(t)= \nabla UR(t) - \nabla LR(t) - \Delta H(t) \tag{9}$$

where ∇UR, ∇LR – are water surface marks in the reservoir and downstream, $H^S(t)$ – is the static head, ΔH – is the pressure loss in the water supply path of the HPS, η_{HPS} is the efficiency factor of the HPS.

Typically, the release of water from a reservoir is carried out according to a predetermined schedule, and from it is possible to determine the value of $Q_{HPS}(t)$, and from the data of the elevations of the upper and lower pools, the value of $H(t)$.

RESULTS

Based on the results of calculations performed using the above methodology for powering the PS KMC, the following annual electricity generation indicators were obtained:

1. Currently, the energy needs of the PS KMC are covered from the centralized energy system, based on this we assume that at a tariff of 0.073 $ (kWh)^{-1}$ the cost of 2,173,000 MWh of electricity will be $158,629 thousand.

2. The amount of electricity produced by the PVS can be determined based on the research results presented in [11,12,13], which show that in the Kashkadarya region, where the solar power plant under construction with a capacity of 500 MW is located, the average annual electricity generation by the PVS with a peak power of 0.1 MW, installed with a reference point to the south at an angle equal to the geographic latitude of the area, calculated taking into account all types of losses according to the Sankey diagram, is 114.97 ≈ 115.0 MWh. Hence, the annual electricity generation received by a PVS with a maximum power of 500 MW is equal to 575,000 MWh. With an average tariff for electricity from PVS in Uzbekistan of 0.03 $ (kWh)^{-1}$, the cost of such an amount of energy will be $17,250 thousand.

3. Based on the analysis of the annual electricity production of the FVS and the consumption of the PS KMC, it can be concluded that 20...40% of the FVS's electricity must be accumulated in a special energy storage system. Taking into account this circumstance, we can take the average amount of accumulated energy equal to 172500 MWh, which will be used to cover the needs of the PS KMK in the period 16^{00} - 24^{00}. The levelized cost of energy storage (LCOS) according to Lazard for 2023 is 178 $ (MWh)^{-1}$ [14]. At the same time, the cost of accumulating electricity in the EAC is $30,705 thousand.

2. The results of calculations of the energy indicators of HPS showed that the amount of electricity generated by HPS is 20,000....50,000 MWh [5]. Taking this volume equal to 30,000 MW hours and taking into account the hydroelectric power tariff of 0.061 $ (kWh)^{-1}$, we obtain the cost of energy at $1,830 thousand.

3. The main part of the load of the PS KMC in electricity is covered by the Talimardzhan TPS with an annual volume of 1162160 MW·h, which requires costs at a planned electricity tariff of 0.073 $ (kWh)^{-1}$ in the amount of $84840 thousand. The total cost of energy for HPS, PVS, TPC and ESS is $134,625 thousand.

The resulting effect from the difference in electricity tariffs when using the proposed power supply system of the PS KMC is $24,004 thousand (without taking into account the loss of electricity).

DISCUSSION

The main advantages of the proposed power supply scheme for the PS KMC are the following:

- power supply of the PS KMC using energy from PVS and HPS, compared to the option from TPS, significantly reduces energy costs, since currently the specific cost of energy, according to the Lazard company for 2023, for combined cycle combined cycle plants is up to $0.108 $(kWh)^{-1}$ [14]. It is worth noting that in modern energy there is a clear trend towards a decrease in the cost of the main types of renewable energy, and an increase in the cost of fossil fuels due to the rise in price of hydrocarbons;
- the use of renewable energy sources in the energy supply of the PS KMC makes it possible to reduce the cost of cleaning harmful emissions from the combustion of fossil fuels, primarily carbon dioxide. According to the US Environmental Protection Agency, the estimated cost of environmental measures to remove CO_2 is 42 dollars/ton [15], and according to calculations by the International Monetary Fund, 75 dollars/ton [16]. If we take the data of the International Energy Agency on the possible amount of CO_2 emitted equal to 0.48 kg/kWh [17], then when replacing the volume of energy production with the capacities of HPS and PVS in the energy system under consideration, the reduction in CO_2 emissions amounts to 290,400 tons, which at specific prices of wastewater treatment plants work 42 dollars/ton will be no less than 12.2 million dollars per year;
- the proposed DES makes it possible to improve the daily operating mode of TPS by reducing its load in hours with increased energy consumption through the use of the capacities of PVS and HPS;
- the proposed DES is designed to supply energy to a large consumer, whose energy load varies little on a daily, even weekly basis, which creates favorable conditions for the use of a high-tech control system consisting of intelligent electricity metering systems, excellent communication, special software products that will ensure power

balance connected energy sources and power consumption, leading to minimizing costs, improving the quality of electricity and the reliability of its supply [18].

CONCLUSION

1. Results of calculations of the main parameters of the energy supply of the PS KMK with an annual electricity consumption of 2,173,000 MW h based on the DES, consisting of a TPS with an annual electricity supply of 1,162,160 MWh, a PVS with an electricity generation of 575,000 MWh per year, a HPS with annual output of 30,000 MWh, as well as an ESS with the accumulation of 172,500 MWh of electricity showed that the use of this energy system allows achieving cost savings in the amount of $24,004 thousand per year due to the difference in the cost of electricity compared to TPS.

2. The possibility of reducing the cost of purifying CO_2 emissions using the proposed DES in the amount of $12,200 thousand per year has been shown.

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