Assessment of economic efficiency of combined power plants based on renewable energies

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Abstract. Energy plants based on renewable energy sources can be combined according to the type of energy source (hydro, solar, wind with or without hydro storage). Currently, not enough attention has been paid to assessing the economic efficiency of combined power plants incorporating a hydraulic accumulator. When designing combined power plants, it becomes necessary to choose the composition of such plants and evaluate their economic efficiency. The purpose of this study is to justify the possibility of applying the present value method to select the composition of combined heat and power plants and assess their economic efficiency. The research used the following methods: review, synthesis of existing literature on the subject, system analysis, collection of data on different types of power plants, and calculation of their economic efficiency. A computer program has been compiled with Turbo Pascal 7.0 for the calculations. The calculations have shown that a cost-effective option is a combined power plant based on a wind power plant and a hydropower plant with a hydro accumulator.

1 Introduction

There is a worldwide trend toward the widespread use of energy installations based on renewable energy sources [1-3]. Particular attention is paid to combined systems based on conventional and renewable energy sources [4,5], especially hybrid solar power-biomass power plants [6,7]. Although renewable energies are inexhaustible and environmentally friendly, they have some disadvantages. Such as their intermittent nature, variability, low energy density, etc. [1,2]. Combined power plants will make it possible to compensate for these shortcomings to some extent[8-10]. Using such installations leads to a reduction in the cost of fuel resources, a reduction in greenhouse gas emissions, a reduction in the cost of electricity received, and a reduction in the payback period of power plants. At the same time, one of the urgent tasks is to determine and evaluate climatic, energy-hydraulic, technical, electrical, energy, and regime parameters, as well as technical, economic, and

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environmental indicators of renewable energy installations in separate and combined use [11-14].

There have been many studies on the economic efficiency of energy installations based on renewable energy sources. It is worth mentioning the works on the assessment of the economic efficiency of solar installations [15-17], wind installations [18-20], and hydropower plants [21-23]. There are separate studies devoted to evaluating the efficiency of hybrid power plants [5, 7, 9]. No practical studies assess the economic efficiency of combined heat and power plants with a hydraulic energy storage device (accumulator).

Therefore, the research aims to evaluate the economic efficiency of various power plants in various combinations. Based on the comparison, the most optimal variant of the combined installation is selected. Using such installations leads to a reduction in the cost of fuel resources, a reduction in greenhouse gas emissions, a reduction in the cost of electricity received, and a reduction in the payback period of power plants.

The research was conducted at the Department of "Hydropower and Hydraulics" of Tashkent State Technical University (Uzbekistan). The main activities of the department are the calculation of improving the efficiency of hydraulic structures [24-27], especially pumping stations [28-31] and hydroelectric power plants [9,12], as well as power plants based on renewable energy sources [9] and especially combined with hydropower plants [9,12].

2 Methods

To assess the economic efficiency of various power plants, the method of estimated (reduced) costs was chosen [32]. The method of estimated costs (discounted costs) selects a rational option from alternatives that are identically equal in production effect or artificially reduced to identical conditions [33].

The essence of the method is as follows. Let's compare two options with identical consumer effect $P_1 = P_2$ (P-profit). To obtain this effect, certain costs (operational costs) are required even with mastered capital investments. There is almost always a relationship between these indicators; for example, if the capital investments of the two options under consideration differ as $K_2 > K_1$, then there is often a case with operational costs $OC_1 > OC_2$ [22, 32].

The criterion of efficiency is the minimum of the estimated (reduced) costs:

$$EC = OC + \lambda K \rightarrow min \tag{1}$$

Where *EC* is estimated (reduced) costs;

OC is operational costs;

K is capital investments;

The coefficient λ characterizes the conditions on the fulfillment of which the conditions for minimizing the estimated (reduced) costs *EC* completely depend. For different variants, λ may have different values with a not significant spread, i.e., $\lambda_{min} > \lambda > \lambda_{max}$. Determination of the minimum estimated costs within $\lambda_{min} > \lambda > \lambda_{max}$ with fixed values of *K* and *OC* ($K_{min} > K > K_{max}$, $OC_{min} > OC > OC_{max}$) [32].

The value of λ, which corresponds to the minimum estimated costs *EC*, is, therefore, an estimate of the economic efficiency of the investment, and it determines the most favorable discount factor at which the project can be invested.

The annual cost structure for a combined power plant (CPP) looks something like this:

$$OC_{CPP} = OC_{maint} + C_{depreciation} + C_{BI,} \tag{2}$$

where OC_{maint} is maintenance operating costs; $C_{depreciation}$ is depreciation deductions (charges); C_{BI} is bank interest (based on the discount rate) for the use of capital.

The interest payment for a bank loan or an investment significantly changes the share of components in the structure of annual costs; therefore, in our opinion, all annual expenses should be analyzed after determining the value of C_{BI}, followed by adjustments to the values of the components following the condition:

$$OC_{CPP}^{\min} \prec OC_{CPP} \prec OC_{CPP}^{\max} \quad (3)$$

Determining the cost-effectiveness of CPPs in comparison with other energy sources, for example, central power supply or a diesel power plant should be carried out taking into account the costs not only for electricity production but also for environmental and social needs for laying power lines [32,33].

In addition, in the world practice of determining the effectiveness of costs, the method of accounting for damage due to the deviation of the established parameters (quantitative and qualitative) of manufactured products is widely used [32,33]. So, for example, in one of the options, less energy and power will be produced (due to energy restrictions, etc.), then it is necessary to add the costs of compensating for this damage to the estimated costs. In this case, the total costs are determined by the formula:

$$\Sigma EC = ECCPP + ECcompensation + ECsocial + ECenvironment + ECunaccount \quad (4)$$

where EC_{CPP} is estimated costs for CPP; $EC_{compensation}$ is estimated costs for compensation of undelivered electricity; EC_{social} is estimated costs for social needs; $EC_{environment}$ is estimated costs for environmental measures; $EC_{unaccount}$ is other, unaccounted estimated costs.

When comparing CPPs based on RE with thermal power plants, the power of thermal power plants (TPPs) is assumed to be 10–15%. The generated electricity is 5% more than the power and energy of CPPs, considering energy consumption for own needs and the difference in energy losses in power transmission lines [32,33].

$$\begin{cases} P_{TPP} = (1.1 \div 1.15) P_{CPP} \\ E_{TPP} = 1.05 E_{CPP} \end{cases} \quad (5)$$

where P_{CPP} is power of thermal power plants (TPPs); P_{CPP} is power of CPPs; E_{TPP} is electricity generated at TPP; E_{CPP} is electricity generated at CPP.

When calculating the costs of TPP, it is necessary to consider the additional investments in fuel and transport, as replacing the capacity of CPP requires additional fuel and transport costs.

In general, the construction of a CPP plant is considered cost-effective if the condition is fulfilled

$$\Sigma\, EC_{CPP} \leq \Sigma\, EC_{TPP} \quad (6)$$

$\Sigma\, EC_{TPP}$ is total estimated costs for the TPP.

$$\Sigma\, EC_{TPP} = EC_{TPP} + EC_{maint} + EC_{fuel} + EC_{compensation} + EC_{transport} + EC_{\text{power line}} \quad (7)$$

where,
EC_{TPP} is the estimated operating cost of the TPP;
EC_{maint} is operation costs of make 4.4 ÷ 4.7 % of TPP's capital investments [22].
EC_{fuel} is estimated fuel costs and is determined by the following expression:

$$EC_{fuel}=c_{fuel}\,b\,E_{TPP} \tag{8}$$

c_{fuel} is cost of fuel, sum/tef (tef – tonnes of equivalent fuel); b - specific fuel consumption, kg ef/kWh.

The estimated cost of compensating for damage due to underdelivered energy is difficult to estimate. According to long-term observations in agriculture and continuous manufacturing industries, the damage from undersupply of electricity is 25–30 times higher than its cost. According to various estimates, the amount of under-delivered energy is 10-30% of the total amount of energy consumed [9,33]. In foreign practice, it is customary to consider the damage from the failure to supply electricity of 1.5 ÷ 4 dollars per kWh [31].

$EC_{transport}$ is transportation costs for transportation of fuel. Transportation costs for transportation of fuel are minimal (10% of the fuel cost), and specific costs for environmental measures can be taken as 10% of capital investments at TPPs [32,33].

Connecting new consumers to the central power supply network is inevitably associated with connecting a power line to them. Therefore, in the estimated costs, it is necessary to consider the cost of power transmission lines $EC_{\text{power line}}$. The cost of low-voltage power lines is 12,000÷ 25,000 dollars per 1 km [31].

The structure of the discounted costs for the combined power plant (consisting of wind turbines, power plants, and hydraulic accumulators) consists of the following components,

$$\sum EC_{CPP} = EC_{CPP} + EC_{environment} + EC_{depreciation} + \lambda\, K_{CPP} \tag{9}$$

EC_{CPP} is operating estimated costs for CPP;
$EC_{environment}$ is estimated costs for environmental activities;
$EC_{depreciation}$ is estimated depreciation charges for CPP;
λ is the discount rate (rate);
K_{CPP} is the number of capital investments for CPP.
The components of annual operating costs are as follows.

$$EC_{CPP} = EC_{unsurace} + EC_{staff} + EC_{repair} + EC_{rent} \tag{10}$$

$EC_{unsurace}$ is installation insurance costs; EC_{staff} is the service's wages (staff salary); EC_{repair} is estimated costs for current repairs; EC_{rent} is land rent.

The annual operating costs of the CPP can be taken in the amount of 10–20% (without depreciation) of the total annual costs by analogy with a hydroelectric power station (HPP)[31]. Depreciation deductions for HPP structures made of reinforced concrete are accepted at 1.7%, and for hydroelectric units, 2.9% of the cost of the structure [31]. When calculating the total cost of CPP, it is necessary to consider that the factory cost of equipment is only 75% of capital investments.

The discount rate depends on many factors, mainly its value based on the investment of fuel and energy facilities can be taken within the range of 0.1 - 0.25.

Calculations to determine the economic efficiency when taking diesel generators as a compared option are also performed according to the above method.

To determine the efficiency of CPP as compared to options, consider the following types of CPP:

1. CPP based on wind turbines, power plants, and solar power plants with a hydraulic accumulator (HA).
2. CPP based on wind turbines, solar power plants, and power plants in natural flow without a hydraulic accumulator.
3. CPP based on wind turbines and power plants with a hydraulic accumulator.
4. CPP based on wind turbines and power plants in natural flow without hydraulic accumulator
5. CPP based on solar power plant (SPP) and hydropower plant (HPP) with a hydraulic accumulator
6. CPP based on SPP and HPP in natural flow without hydraulic accumulator
7. CPP based on wind turbines, SPP without hydraulic accumulator
8. Diesel electrical installations (DEI).
9. Increasing the capacity of thermal power plants (TPPs).

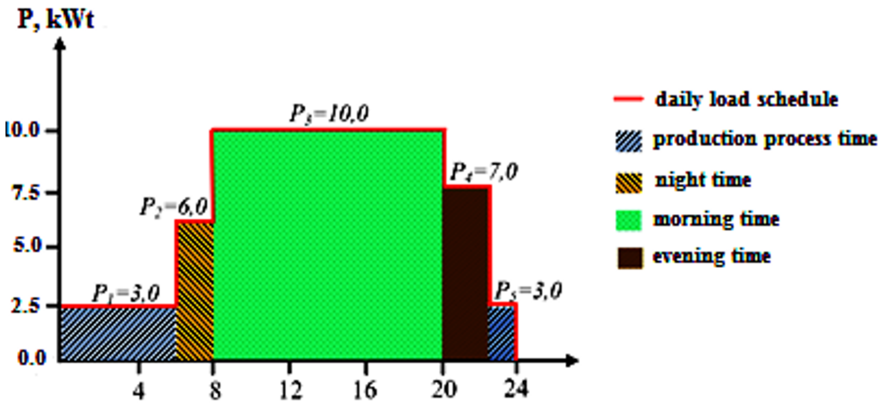

Fig. 1. Daily load schedule of consumers with individual production.

Calculations are made for CPP with a capacity of 10 kW, the most typical for consumers - individual farms. Calculations will be carried out based on the loading schedule shown in Fig. 1. The version with DEU was adopted as the basic option.

3 Results and discussions

Based on the above methods, a computer program was developed in the Turbo Pascal environment. The results of determining the economic indicators of CPP are shown in Table 1.

The results of calculating the economic efficiency of various combinations of hybrid power plants according to the proposed methodology are presented in Table 1. An analysis of the economic indicators of the CPP given in this table shows the lowest indicators (minimum annual costs, energy cost (8.8 cents / kW), and payback period (0, 5 years) for the variant of the CPP based on wind turbines and hydraulic accumulator power plants. Economic indicators increase significantly for the variants of the combined CPP based on wind turbines, solar power plants, and hydraulic accumulator-based power plants,

Table 1. Economic indicators of CPP.

Indicators	WPP SPP HPP	WPP SPP HPP HA	WPP HPP	WPP HPP HA	SPP HPP	SPP HPP HA	WPP SPP	DEI	TPPs
power, kWt	44123	18813	41873	13441	60155	20375	50813	10000	17000
capital investments, $	882	376	837	269	1203	408	1016	640	1700
depreciation charges, $	-	-	-	-	-	-	-	25480	6439
fuel cost, $	-	-	-	-	-	-	-	2548	644
fuel transportation costs, $	-	-	-	-	-	-	-	1000	1700
costs for environmental activities, $	1078	460	1024	329	1470	498	1242	460	493
operating costs, $	8824	3762	8375	2688	12031	4075	10163	2000	-
discounted costs, $	10785	4598	10236	3286	14704	4981	12421	32128	10976
total annual cost $	29.0	12.4	27.5	8.8	39.5	13.4	33.4	86.4	-
working cost of electricity, cent/kWh	2.06	0.68	1.91	0.47	3.45	0.75	2.58	-	0.80
payback period, years	44123	18813	41873	13441	60155	20375	50813	10000	17000

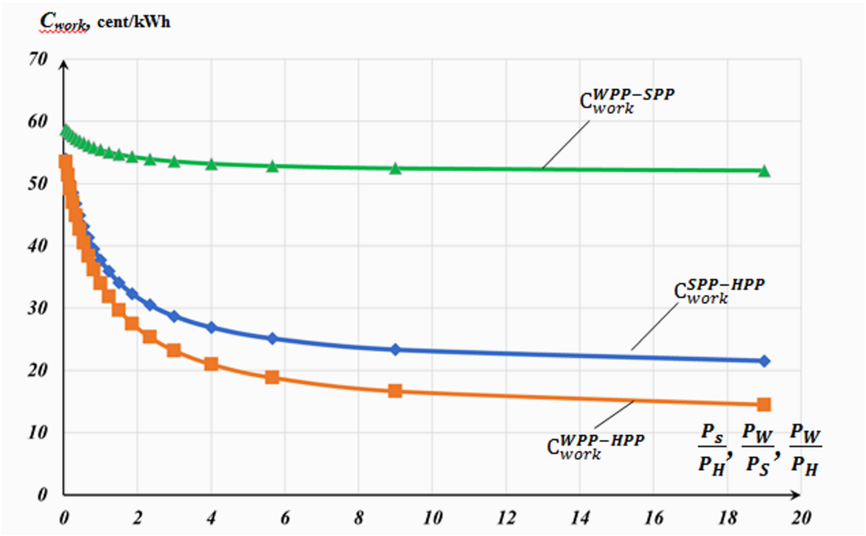

Fig. 2. Dependence of cost of generated electricity on power ratio of two types of power plants with storage in their combined use

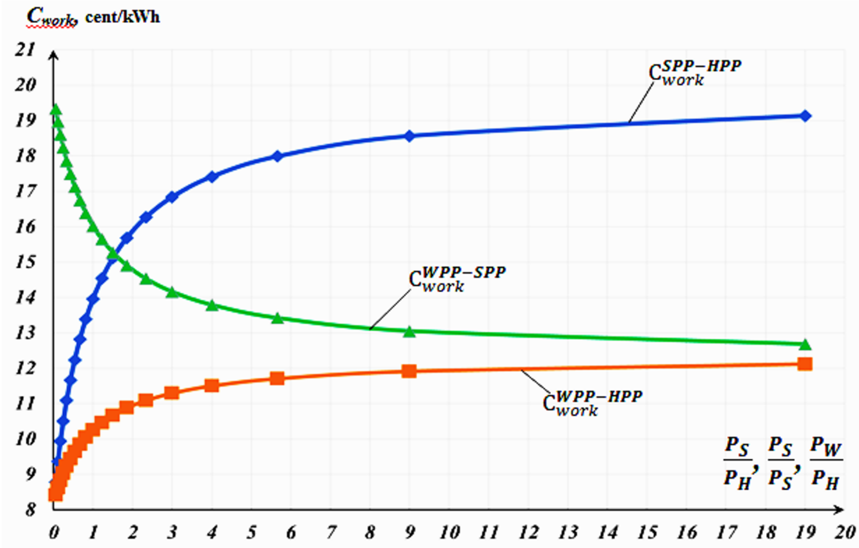

Fig. 3. Dependence of cost of generated electricity on power ratio of two types of power plants without storage in their combined use

Based on the results of the developed methodology and program, various options for the economic efficiency of combined power plants based on renewable energy sources were studied at various power ratios (Fig. 2 and Fig. 3).

An analysis of the graphs of the dependence of the cost of electricity generated for various combined plants on the ratio of the capacities of the plants shows that the cost is minimal for a combined plant consisting of a wind turbine and a hydropower plant. Moreover, the graph of the dependence of the cost on the ratio of capacities has a sharply steep character up to the values of $P_W/P_H \approx 4 \div 6$ and then becomes more gentle. From this, it follows that to reduce the cost, it is advisable to combine the installations in such a way that the power of the hydropower plant is less than the power of the wind power plant by at least 4-6 times.

4 Conclusions

1. The results of economic calculations showed that a cost-effective option is a CPP based on a wind turbine and a hydroelectric power plant since it is in this variant that the minimum annual costs, the cost of energy (8.8 cents / kW), and the payback period (0.5 years). When using a combined power plant based on wind turbines, solar power plants, and power plants with a hydraulic accumulator, the annual costs increase by almost 1.4 times, and this is due to the high cost of the power plant and the costs associated with it.
2. Comparison of economic indicators of CPP without hydraulic accumulation and with it clearly shows the latter's effectiveness since using a hydraulic accumulator leads to a decrease in annual costs and energy costs up to 3 times. This is since in the absence of a hydraulic accumulator, the power of existing installations (wind turbines and power plants) increases, which leads to a significant increase in costs leads to a significant increase in costs

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