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METHODOLOGY FOR CALCULATING THE TECHNICAL AND ECONOMIC INDICATORS OF A PHOTOVOLTAIC THERMAL INSTALLATION BASED ON A THIN-FILM CADMIUM TELLURIDE MODULE

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METHODOLOGY FOR CALCULATING THE TECHNICAL AND ECONOMIC INDICATORS OF A PHOTOVOLTAIC THERMAL INSTALLATION BASED ON A THIN-FILM CADMIUM TELLURIDE MODULE

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Abstract. *This article presents a methodology for calculating the technical, economic and environmental indicators of the developed design of a photovoltaic thermal installation with a nominal electric power of 1,2 kW and a thermal power of 2.17 kW for simultaneous production of electric energy and hot water for household needs of consumers. The capacity of the installation is 5.26 kWh of electricity and 30 liters/hour of heated water. The schemes of obtaining hot water by additional heating of the heated water produced by the installation in the cool seasons of the year are presented. This installation allows to receive total energy in the amount of 2,795.77 thousand UZS per year without consuming natural resources, save coal consumption in the amount of 2,236.5 thousand UZS per year, or natural gas in the amount of 1,745.45 thousand UZS. In addition, the installation avoids emissions of CO_2 carbon dioxide into the atmosphere for the production of annual energy based on the calculation, when using coal at thermal power plants, the output of CO_2 emissions in the amount of 17.3 tons or natural gas 2.15 tons of CO_2 per year and prevent environmental pollution.*

Keywords: *photovoltaic thermal installation, electrical energy, thermal energy, hot water, resources, emissions*

Аннотация. *Ушбу мақолада истеъмолчиларнинг маиший эҳтиёжлари учун бир вақтнинг ўзида электр энергияси ва иссиқ сув ишлаб чиқариш учун номинал электр қуввати 1,2 квт ва иссиқлик қуввати 2,17 квт бўлган ишлаб чиқилган фотоэлектрик иссиқлик қурилмаси конструкциясинининг техник, иқтисодий ва экологик кўрсаткичларини ҳисоблаш методологияси келтирилган. Қурилма унумдорлиги 5,26 квт·соат электр энергияси ва соатига 30 литр иситилган сувни ташкил қилади. Йилнинг салқин фаслларида қурилма ёрдамида ишлаб чиқариладиган иситилган сувни қўшимча иситиш орқали иссиқ сув олиш схемалари келтирилган. Ушбу қурилма табиий ресурсларни истеъмол қилмасдан йилига 2 795,77 минг сўм умумий энергия олиш ҳисобига йилига 2 236,5 минг сўм кўмир ёки 1 745,45 минг сўм табиий газ истеъмолини тежаш имконини беради. Бундан ташқари, иссиқлик электр станцияларида шунча миқдорда йиллик энергия ишлаб чиқариш учун кўмирдан фойдаланганда йилига 17,3 тонна CO_2 ёки табиий газдан фойдаланганда йилига 2,15 тонна CO_2 чиқинди гази ажралиб чиқишига ва атроф-муҳитнинг ифлосланишига йўл қўйилмайди.*

Калит сўзлар. *фотоэлектрик иссиқлик қурилмаси, электр энергияси, иссиқлик энергияси, иссиқ сув, ресурслар, чиқиндилар*

Аннотация. *В данной статье представлена методика расчета технико-экономических и экологических показателей разработанной конструкции фотоэлектрической тепловой установки номинальной электрической мощностью 1,2 кВт и тепловой мощностью 2,17 кВт для одновременного производства электрической энергии и горячей воды для бытовых нужд потребителей. Производительность установки составляет 5,26 кВт·час электроэнергии и 30 л/час нагретой воды. Приведены схемы получения горячей воды путем дополнительного нагрева выработанной установкой нагретой воды в прохладные сезоны года. Данная установка позволяет получать суммарную энергию в размере 2 795,77 тыс. сум в год без потребления природных ресурсов, экономить потребление угля в размере 2 236,5 тыс. сум в год или природного газа в размере 1 745,45 тыс. сум. Кроме того, установка позволяет избежать выбросов углекислого газа CO_2 в атмосферу для производства годовой энергии, исходя из расчета, что при использовании угля на тепловых электростанциях, выход выбросов CO2 составит 17,3 тонны или природного газа 2,15 тонны CO_2 в год и предотвратит загрязнение окружающей среды.*

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Ключевые слова: *фотоэлектрическая тепловая установка, электрическая энергия, тепловая энергия, горячая вода, ресурсы, выбросы*

Introduction

Currently, the main tasks of the global energy sector are to increase the share of renewable energy sources (RES) in the energy production process. The development strategy of Uzbekistan-2030 outlines the tasks of radically increasing the use of renewable energy, increasing the share of renewable energy in energy production to 25 MW, and in total energy consumption to 40% [1]. The development of energy based on renewable energy sources is one of the acceptable ways to ensure environmental cleanliness of the atmosphere, reduce the cost of centralized energy supply and a number of other related factors [2].

In order to ensure the fulfillment of the planned tasks, we have developed and created a photovoltaic thermal installation that allows increasing the efficiency of using solar energy and allowing simultaneous production of electricity and provide hot water supply.

Methods and Materials

In hot climates, photovoltaic modules (PVM) are heated above the operating temperature under the influence of solar radiation. Due to an increase in the heating temperature of the modules, their operating efficiency begins to decrease. In order to ensure stable efficiency and the use of accumulated heat for the production of hot water, we have developed a photovoltaic thermal installation (PVTI) of various designs.

Fig.1. Photo of the experimental installation of the PVTI and PVM

This installation allows you to cool the PVM by absorbing and transferring the accumulated heat to the coolant on the back of the module and simultaneously produce heated water. PVTI is a technological assembly of a thin-film photovoltaic module based on cadmium telluride and a thermal battery consisting of an aluminum sheet absorber and a copper tube heat exchanger inside which a coolant circulates in the form of water or other liquid. On the outside, the thermal battery is insulated with thermal insulation materials. During the spring-summer and autumn seasons of 2022-2023, we conducted field experimental studies to study the influence of environmental factors on the thermal and electrical characteristics of a photovoltaic module (PVM) and a photovoltaic thermal installation (PVTI) in comparison with the geographical conditions of Tashkent using a manufactured experimental installation (Fig.1).

The schematic diagram of the operation of the PVTI for the simultaneous production of electric energy and hot water is shown in Fig.2.

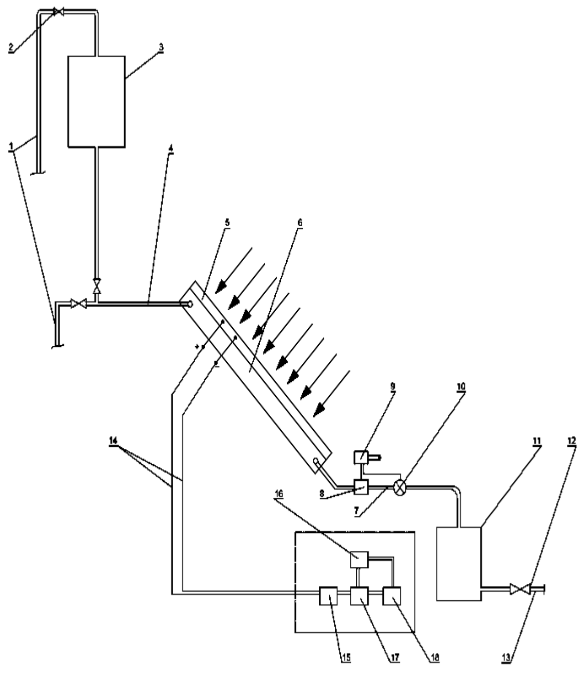

Fig.2. Schematic linear diagram of the PVTI for the production of electric energy and hot water

This PVTI consists of pipelines 1, valves 2 for supplying cold water to the storage tank 3, or direct supply of cold water from the water supply network to the pipeline 4, for supplying cold water to the thermal battery 6, which is attached to the back surface of the photovoltaic module 5, at the outlet of the heated water from the thermal battery into the pipeline 7, mounted a thermal sensor 8 with a thermocouple connected to a thermal controller 9, which are electrically connected to an electromagnetic valve 10, also mounted in a pipeline 7, a heated water storage tank 11, a valve 12 and a pipeline 13 for supplying heated water to the consumer, cables 14 connected to a voltage inverter

15, a charge-discharge controller 16, a battery 17, a voltage transmission node 18 to the consumer (Fig.2).

Experimental studies have shown an increase in PVM efficiency by an average of 2% and module power by 9.2-10.3% [3]. The developed PVTI by cooling the back of the module made it possible not only to increase energy performance, but also to produce electricity and heated water in combination for consumer household needs. Due to the use of automation elements, the technological process of working with the components of the PVTI is carried out in automatic mode.

The functional diagram of the operation of the hot water supply system is shown in Fig.3.

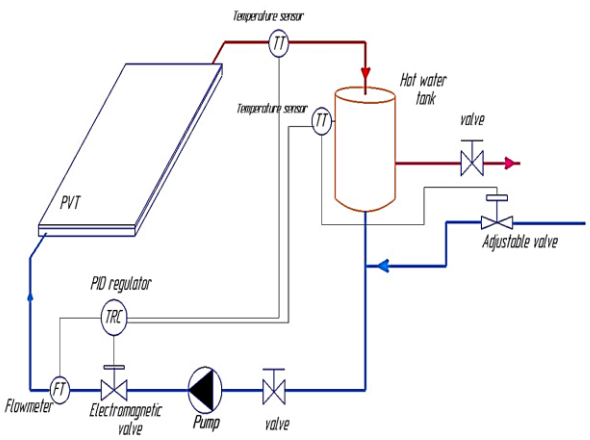

Fig.3. Functional diagram of the operation of the hot water supply system

Results and Discussion

To determine the required electrical power of a photovoltaic thermal (PVT) installation based on a thin-film module of the cadmium telluride type, first of all, it is necessary to proceed from the consumed load of electricity and heated water. For an individual household, we calculate the need for electricity for household and household needs (Table 1).

Table 1

Load calculation for household daily electricity consumption

Load	Unit	Qu-an-tity	Power, W	Operation, hour	Consump-tion, kWh/day
Electric lamp	pcs	4	20	2	0,16
TV	pcs	1	120	4	0,48
Refrigerator	pcs	1	100	6	0,60
Electric kettle	pcs	1	1000	0,2	0,20
Circulation pump	pcs	1	50	5	0,25
Computer	pcs	1	120	2	0,24
Washing machine	pcs	1	1200	1.5 hours per week	0,26
Electric iron	pcs	1	1200	0,5 hours per week	0,09
Vacuum cleaner	pcs	1	1200	1,5 hours per week	0,26
Total					**2,54**

According to the consumption mode, the average load is 2.54 kWh/day.

The amount of electricity produced by photovoltaic modules of the PVTI depends on the geographical latitude of the area, the angle of inclination of the station modules. The calculation of the intensity of solar radiation in a particular area can be carried out using empirical formulas and using information from the climate database [4].

The electricity generated by photovoltaic modules of the PVTI for a certain period of time is expressed as follows,

$$E_i = W_i \cdot P_n \cdot k_l / W_{stc} \, , \quad (1)$$

where, E_i – electricity for the i-period of time, kWh, W_i – total solar radiation for the i-time period, kWh/m^2, P_n - rated power of the modules specified by the manufacturer, kW, k_l – the coefficient taking into account the power loss is taken depending on the operating conditions of the modules within 0,8-0,9; W_{stc} – solar radiation equal to 1000 W/m^2, at which the manufacturer tested the module.

When designing and calculating the parameters of the PVTI for different geographical conditions of the area, it is more convenient to use the climatic databases METEONORM, NASA, Surface meteorology and Solar Energy, SARAH and a number of others [5, 6]. Will consider the definition of the technical and economic parameters of a PVTI based on thin-film modules of the cadmium telluride type, with an electric power of 1,2 kW and a thermal power of 2.17 kW. The optimal angle of the PV modules for this region is 41 degrees. The basic data of PVM power generation without cooling were calculated using the Technoline company's website, using the meteorological parameters of the NASA database for the geographical conditions of Tashkent [7, 8]. Table 2 shows for comparison the generated electricity of the PVM without cooling and the cooled modules of the PVTI during the year. The power generation of the cooled PVTI modules is calculated with an increase in power by 10.3% according to the data established by experimental studies.

Table 2

Power generation by PVM and modules of the PVTI

Months	Monthly electricity generation, kWh	
	PVM	PVTI
January	84.3	92.98
February	96.6	106.55
March	135.2	149.13
April	157.5	173.72
May	186.9	206.15
June	193.5	213.43
July	206.8	228.10
August	203.1	224.02
September	177.3	195.56
October	141.1	155.63
November	96.3	106.22
December	78.7	86.81
Total	**1757.3**	**1938.3**

The annual volume of electricity generated by the PVTI module is 1938.3 kWh, which is 181.0 kWh more than the generation of uncooled PV modules in the amount of 1757.3 kWh (Fig.4). The average daily productivity of the PVTI is 5.26 kWh of electricity, which covers the electrical load of the house with a reserve.

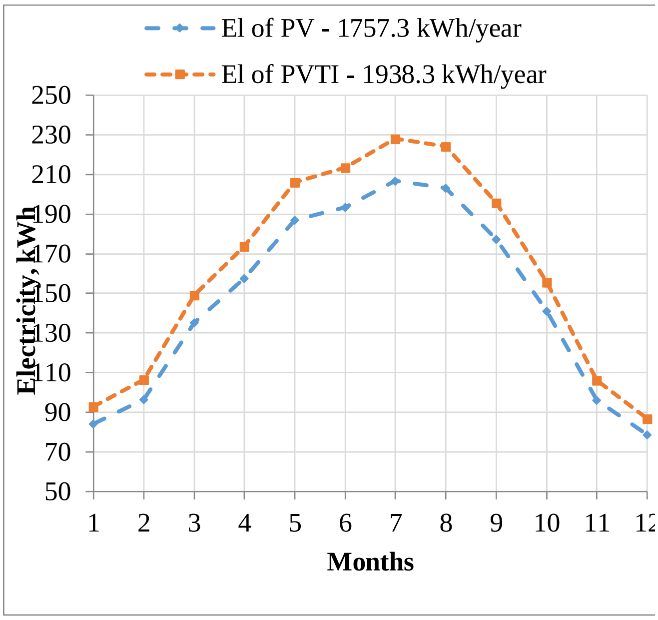

Fig.4. Schedule of electricity generation by month of the year

Calculations of the performance of the PVTI for the production of heated water are carried out based on the need to cover the load of hot water consumption. To calculate and cover the load on the consumption of residents of the house, we will use the average values of the standard consumption of hot water given in Table 3 [9].

Table 3

Consumption of hot water for everyday household needs at home

Types of consumption	Hot water consumption per day, l	Minimum supply of hot water, l	Total hot water, l	Hot water temperature
Washbasin	30	20	50	37°C
Bath	180	30	210	40°C
Shower	30	20	50	37°C
Kitchen sink, cleaning	30	20	50	43°C
Total	270	90	360	41°C

PVT installations in terms of hot water supply can be used all year round. In warm and hot seasons, water is used as a coolant in the thermal batteries of the installation according to a single-circuit operation scheme (Fig.5), in the winter season propylene glycol, ethylene glycol or other organic liquids are used according to a two-circuit operation scheme (Fig.6) [10, 11].

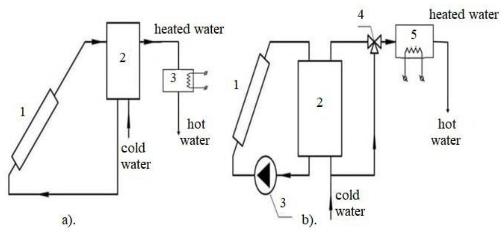

Fig.5. The basic single-circuit scheme of operation of the PVT for hot water supply, a) - with natural circulation; 1 –PVT; 2 – heated water storage tank; 3 –source of additional water heating; b) - with forced circulation; 1 –PVT; 2 – hot water storage tank; 3 – pump; 4 – mixing valve; 5 – source of additional water heating;

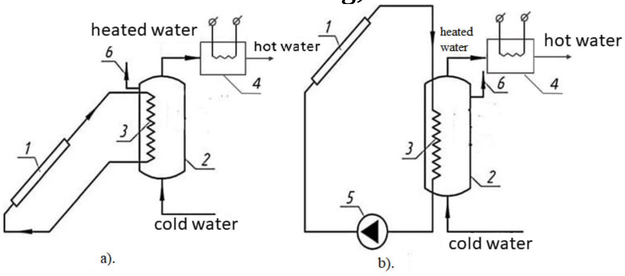

Fig.6. The basic two-circuit scheme of operation of the PVT for hot water supply, a) - with natural circulation; b) - with forced circulation; 1 –PVT; 2 – water storage tank; 3 – heat exchanger; 4 – backup water heating source; 5 – pump; 6 – safety valve

Taking into account the peak hours of sunshine [12] and based on data from experimental studies and tests of the PVTI in different seasons of the year, the volumes of hot water produced for the geographical conditions of Tashkent were calculated by month. The obtained values are shown in Fig.7.

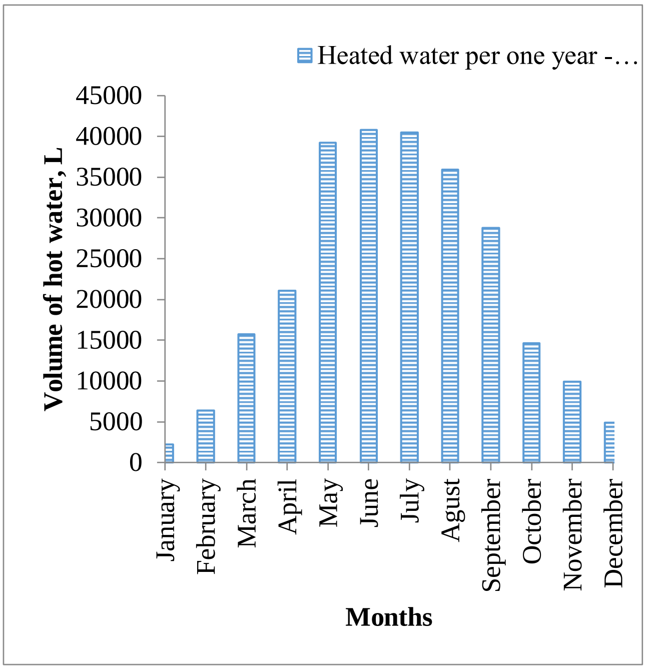

Fig.7. Diagram of hot water production by month of the year

Calculations show that the designed PVT produces 131,463 liters of hot water per year. The average daily capacity of the installation for the production of heated water is 360 liters/day, which fully covers the load of 270 liters of hot water.

To determine the useful thermal energy Q_{th}^{j}, obtained from the use of accumulated heat from the back of the module of several PVTs, for a certain time of sunshine, we use the following equation,

$$Q_{\text{th}}^{j} = \dot{m} \cdot C_{\text{w}} \cdot i \cdot N(\text{T}_{\text{out}} - \text{T}_{\text{in}}) \qquad (2)$$

$Q_{\text{th}}^{\text{tl}}$ - the annual amount of thermal energy of the PVT can be expressed in the following form,

$$Q_{\text{th}}^{\text{tl}} = \sum_{j=1}^{j=12} Q_{\text{th}}^{j} \qquad (3)$$

where, $\dot{m}$ – mass flow rate of water, depending on the season of the year for our installation, based on experimental measurements, the value of mass flow varies between 4.14-13.32 kg/hour, C_{w} is the specific heat capacity of water, 4180 J/kg•K, i –is the total amount of PVTs is 12, N-is the number of peak hours of sunshine, hour , T_{in} - the temperature of cold water, varies seasonally within the range of 18-20°C, T_{out} -is the temperature of the water at the outlet of the thermal battery, this installation provides automatic temperature control at the outlet of heated water from the thermal battery, depending on the weather conditions of the season within 40-43°C. The thermal energy of the PVT by month of the year was calculated using the above equations and listed in Table 4.

Table 4

Thermal energy of PVT

Months	Thermal energy, MJ	
	Day	Month
January	8.5	263.9
February	10.3	319.8
March	38.1	1181.4
April	52.8	1584.6
May	105.8	3279.4
June	113.6	3407.5
July	109.1	3383.0
August	96.9	3003.2
September	80.2	2405.3
October	35.5	1100.8
November	16.6	496.5
December	7.9	244.6
Total		**20670**

The average daily thermal energy received is 56.6 MJ, and the annual volume of thermal energy is 20670 MJ. This thermal energy was used to heat 131463 liters of water to a temperature of 38.5-43°C. The thermal energy obtained by the PVT installation, by month of the year, is shown in Fig.8.

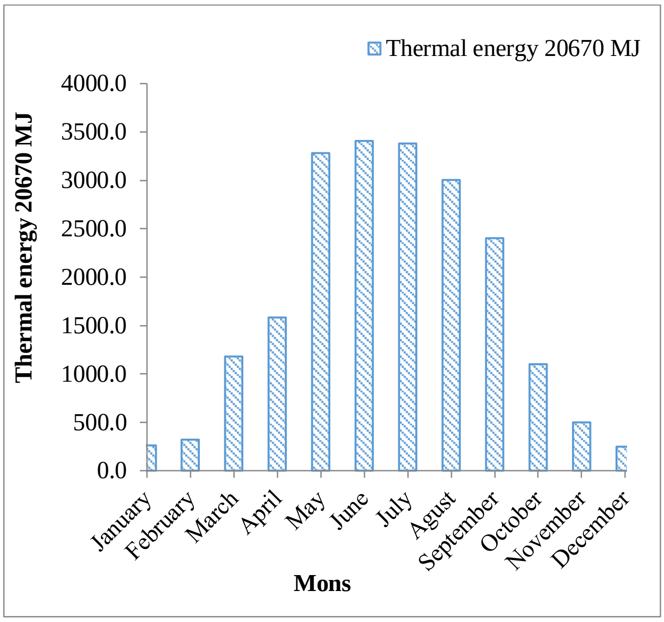

Fig.8. Diagram of the thermal energy of the PVT installation by month of the year

Since October 1, 2023, new rates have been established for fuel and energy resources [13], in particular for legal entities except budget organizations, the price for electricity is 900 UZS/ kWh, for natural gas 1500 UZS/m^3. Since November 9, 2023, 212606 UZS per 1 Gcal of heat or 50,863 UZS per 1 MJ have been installed for centralized thermal energy for Tashkent [14]. When calculating the cost of energy, we will use the new approved rates. Then, the annual cost of thermal energy in the amount of 20670 MJ is 1051338.21 UZS.

Calculation of economic indicators of PVTI

To compare the indicators of the PVT, we calculate the consumption and cost of resources in the production of these volumes of energy by traditional energy sources. To heat and produce hot water with an annual volume of 131.463 m^3, the thermal energy of 20670 MJ per year is used.

Will calculate the electricity consumption E_{el} for obtaining this thermal energy and heating water with an electric water heater using the following expression,

$$E_{el} = \frac{Q_{th}^{tl}}{\eta_{el\_h}} \tag{4}$$

where, η_{el_h} – efficiency of an electric water heater 0,95. E_{el}=20670/0,95/3,6=6043,8 kWh of electricity, which in value terms at a price of 900 UZS/ kWh is 5439,420 UZS.

Will calculate the required volume of natural gas V_g to produce thermal energy of 20670 MJ and heat 131.463 m^3 of water per year using a gas water heater using the following expression,

$$V_g = \frac{Q_{th}^{tl}}{\eta_{g\_h} \cdot C_g} \tag{5}$$

where V_g is the volume of gas, m^3, η_{g_h} is the efficiency of a gas water heater of 0.85, $C_г$ is the specific heat capacity of natural gas, according to GOST 5542-87 is 31.8 MJ/m^3 [15]. Will calculate the volume of gas required and its cost when heating water with a gas water heater,

V_g = 20670/31,8·0,85=764,7 м^3. In monetary terms, the cost of the annual volume of natural gas consumed is 764.7 m3 at a price of 1,500 UZS/m^3, which is 1147050 UZS.

To assess the economic efficiency of the PVT, we will conduct comparative calculations of the generated electric and used thermal energy.

The projected PVTI produces 1,938.3 kWh of electricity per year for the conditions of Tashkent, which in value terms at a price of 900 UZS/kWh is 1,744,470 UZS.

To produce this annual electricity of 1938.3 kWh using a thermal power plant (TPP) by burning natural gas, with an efficiency of 55%, it is required to consume the following volume of gas V_g = 6977,9/31,8•0,55 =398.9 m3, the cost of gas in monetary terms at a price of 1500 UZS/ m^3 is 598350 UZS.

To produce this annual electricity of 1938.3 kWh or 6977.9 MJ using a thermal power plant by burning coal with an efficiency of 47%, it is required to consume the following amount of coal V_c= 6977,9/9204,8·0,47=1.61 tons, the cost of coal in monetary terms at a price of 350000 UZS/ton is 563500 UZS. Will calculate the consumption of coal for produce of thermal energy of 20670 MJ. V_c= 20670/9204,8·0,47=4.78 tons, the cost of coal at the price of 350000 UZS/ton is 1673000 UZS.

Calculation of environmental indicators of PVTI

In the global energy sector, the dominant share in energy generation is occupied by production using coal and natural gas. When they are burned, greenhouse gases and pollutants are released into the atmosphere.

Will determine the amount of carbon dioxide emissions into the atmosphere during the combustion of natural gas for the production of electric and thermal energy. The amount of CO_2 emissions from the combustion of 1000 m^3 of natural gas is 1.85 tons, and when burning 1 ton of coal, CO_2 emissions average 2.7 tons [16].

In terms of producing an equivalent amount of energy per year when burning the required total volume of 1163.6 m^3 of gas, the amount of CO_2 emissions is 2.15 tons. To produce an equivalent amount of energy per year, 6.4 tons of coal is required, from the combustion of which CO_2 emissions amount to 17.3 tons. The calculated values of energy production are given in Table 5.

Table 5

Comparison of economic and environmental indicators of energy production

Electrical and thermal energy received from PVTI			
N	Indicators	PVTI	
		kWh	000' UZS
1	Electrical energy, kWh	1938.3	1744.47
2	Thermal energy, MJ	20670	1051.3
3	Total cost of energy produced		2795.77
4	CO_2 emissions, Tn	0.033	
The required volume of hydrocarbon fuel-energy resources for the production of equivalent energy at thermal power plants (TPP)			

Electrical and thermal energy received from PVTI					
N	Indicators	PVTI			
		kWh		000' UZS	
N-	Indicators	Fuel-energy resources (FER)			
		Coal		Gas	
		Tn	000' UZS	m^3	000' UZS
1	For the production of electricity 1938.3 kWh	1.61	563.5	398.9	598.35
2	For the production of thermal energy 20670 MJ	4.78	1673.0	764.7	1147.05
3	Total FER consumption	6.39	2236.5	1163.6	1745.4
4	CO_2 emissions, Tn	17.3		2.15	

Conclusion

Thus, the PVT installation allows you to receive total energy in the amount of 2,795.77 thousand soums without the consumption of natural resources, save coal consumption in the amount of 2,236.5 thousand UZS per year, or natural gas in the amount of 1,745.45 thousand UZS. In addition, the installation avoids CO_2 carbon dioxide emissions into the atmosphere based on the calculation of CO_2 emissions in the amount of 17,3 tons and natural gas 2.15 tons of CO_2 per year when using coal at thermal power plants and prevents environmental pollution.

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