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APPLICATION OF PV/T TECHNOLOGY IN LITHUANIA

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Abstract. PVT technology combines solar PV and solar thermal energy in the same PVT panel. In this way, the PVT panel produces both electricity and heat. Compared to PV technology and solar heating technology, PVT technology is in the early stages of the market, but the demand for panels has grown rapidly in the past two years.

This paper summarizes best practices for PVT technology, which is still in rapid development. Commercial systems with different types of PVT panels, different types of PVT systems with different components for different applications are reviewed. Possible advantages and disadvantages of PVT systems in Lithuanian market conditions are presented.

Keywords: solar energy, PVT system, PVT training module, Renewable energy technologies

INTRODUCTION

PV/T hybrid modules combine photovoltaic and solar collector modules in the same component, which allows the simultaneous production of heat and electricity, similar to combined heat and power (CHP) plant. Photovoltaic (PV) modules made from semiconductor cells have one drawback: a decrease in work efficiency due to temperature. At noon on a sunny day, when the PV would be expected to work at full capacity, the module temperature can reach more than 80° C. The manufactured modules are tested under STC (Standard Test Conditions). Those conditions correspond to a module temperature of 25°C and an illumination of 1000 (kWh/m^2)/year. Therefore, at a temperature of 80°C, the optimal efficiency of an average PV module drops to as much as 20% (S. Navakrishnan et al., 2021).

PV/T collectors extract the excess thermal energy generated by the PV cells by using a coolant, which is a mixture of water and antifreeze, for heat transfer (Abora data sheet, 2023). The coolant circulating in the PV/T collectors reduces the temperature of the PV module while increasing the overall efficiency of the PV cell as the module temperature approaches STC conditions. Reducing the temperature can increase the efficiency of PV modules by 10-25% (S. Navakrishnan et al., 2021, Herrando et al., 2023, Dual sun Wave data sheet, 2023, Solink heat pump collector data sheet, 2023). PV/T technology is particularly important and attractive when roof space is limited. The PV/T market is gaining momentum in various European countries. In recent years, more and more specialized PV/T technology suppliers have entered the European markets.

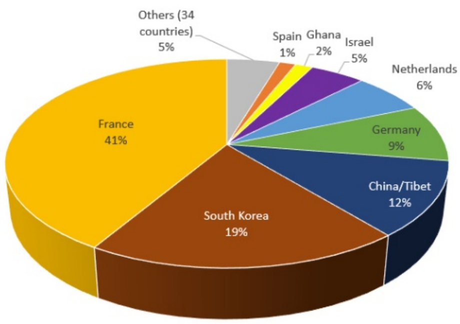

Figure 1. **Global PV/T Market Development 2021 (**IEA 60 systems overview)

Demand for PV/T collectors has grown rapidly over the past two years. In 2020, 1,235,176 m^2 of PV/T modules were installed in the world. Annual sales of PV/T modules in 2021 increased by 16.8% and 207,420 m^2 were installed per year. Total PV/T installed area in 2021 reached 1.4 million m^2, most of which were installed in Europe (0.8 million m^2). The world's largest markets for new PV/T modules in 2021 were France, South Korea, China, Germany, Holland, Israel, and Spain. France achieved its highest annual growth rate in 2021, almost six times more PV/T modules were installed (97,165 m^2) than in 2020 (Application of PV/T collectors, IEA 60 systems overview). Global PV/T Market Development 2021 shown in Figure 1.

BEST PRACTICES FOR PV/T TECHNOLOGY

Although PV/T collectors have emerged recently, they have been improved every year and now PV/T collectors can be classified according to various characteristics (Herrando et al., 2023, Diwania et al., 2019, Evangelisti et al., 2019), but the main ones can be arranged by PV elements type, the type of thermal solar collector, what kind and how the working fluid is being used in PV/T collector, whether there is additional glazing, and last but not least, they can be sorted by what kind of heat absorber is being used (Figure 2).

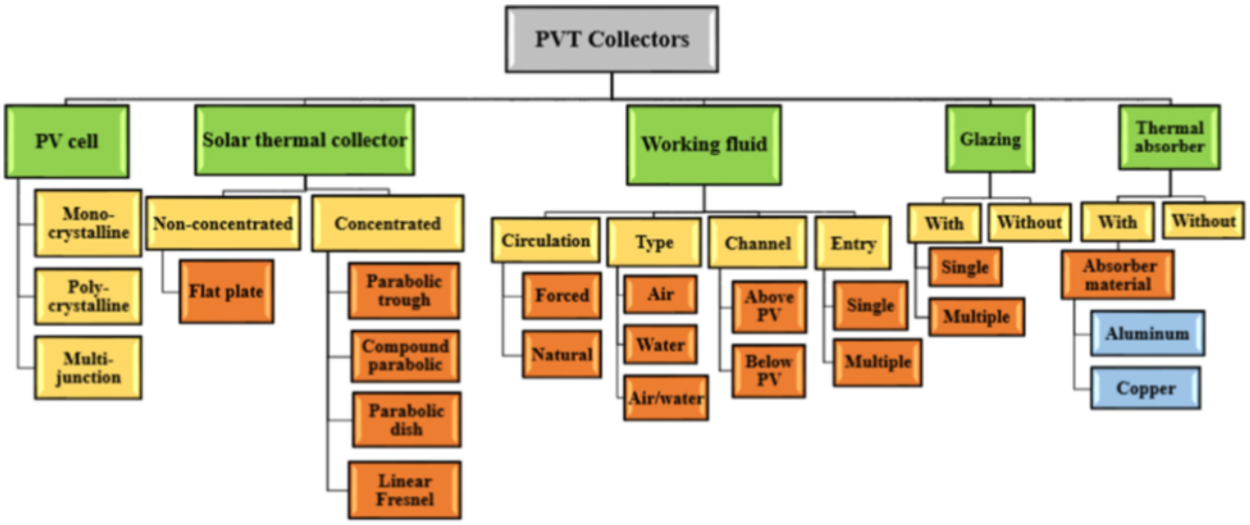

Figure 2. **Classification of PV/T solar collectors** (Herez et al., 2020)

Depending on how the PV/T modules are assembled thermal, electrical, and total efficiencies may be in the range 35-75%, 7-20% and 36-85% respectively (Herez et al., 2020).

PV/T systems can be used for many different applications and many different PV/T system designs are possible. Figure 3 gives an overview of PV/T panel technologies and PV/T applications for different temperature levels.

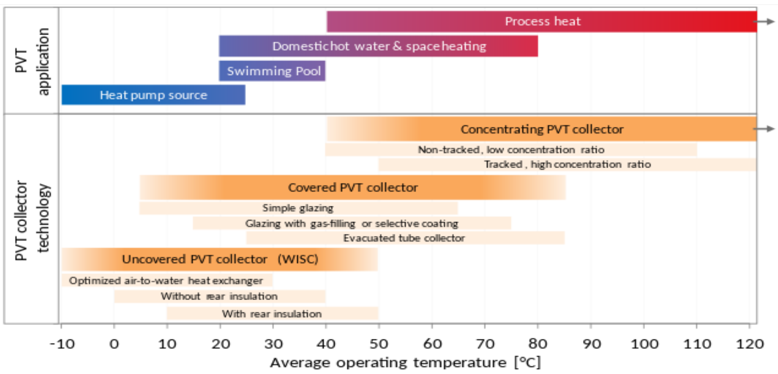

Figure 3. **PV/T technology and applications for different temperature levels** (Lämmle et al, 2020)

Currently, approximately half of the installed PV/T area of all operating PV/T systems consists of air-cooled PVT panels (IEA 60 systems overview). Air-cooled PV/T panels are suitable for buildings where air is used for heating. In these systems, air flow is the key factor in reducing the temperature of the solar cells, thereby increasing the overall energy efficiency of the system. The thermal efficiency of such PV/T panels is usually between 20% and 40% (Furbo et al., 2021).

Unfortunately, according to the report submitted by the IEA agency, in the table 1, we do not see either Lithuania or any other Baltic country. Currently, only a few flat PV/T modules are offered on the Lithuanian market. However, when we asked the suppliers if even one module was sold, the answer was negative. The leader in terms of the area of the PV/T installed collectors is France, where air-cooled PV/T systems prevail. And the leaders of liquid-cooled PV/T systems in Europe are Germany and the Netherlands.

Below we present the distribution of installed capacity per 1 m^2 of area by the type of PV/T collector (Figure 4). From this graph, we can see that the leader in terms of installed power is uncovered PV/T collectors, whose installed power per 1 m^2 of area is 0.72 kW/m^2, of which 74% is heat power. The installed capacity of covered PV/T collectors per 1 m^2 of area is 0.68 kW/m2, of which 75% is for heat capacity. In air-cooled PV/T collectors, the situation is similar, as the installed capacity per 1 m^2 of area is 0.66 kW/m^2, of which 75% is heat capacity.

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Table 1

Cumulated installed collector area by PVT collector type and country, at the end of 2021

Country	Water Collectors [m²]			Air Collectors [m²]	Concentrators [m²]	TOTAL [m²]
	uncovered	covered	evacuated tube			
Albania	148	12	0	0	0	160
Australia	3,477	0	0	99	0	3,576
Austria	1,234	1,731	0	0	0	2,965
Belgium	2,314	0	32	290	15	2,651
Brazil	26	0	0	0	0	26
Bulgaria	517	43	0	0	0	560
Canada	0	32	0	0	0	32
Chile	213	113	0	0	10	337
China	141,721	1,034	0	0	171	142,926
Croatia	907	125	0	0	0	1,032
Denmark	109	0	0	0	0	109
Dubai	43	9	0	0	0	52
Ecuador	0	138	0	0	0	139
Egypt	0	0	0	0	21	21
France	49,633	949	0	547,575	0	598,157
Germany	122,738	4,196	0	512	195	127,640
Ghana	22,000	0	0	0	0	22,000
Iraq	0	16	0	0	0	16
Guadeloupe	0	4	0	0	0	4
Hungary	525	53	0	0	0	578
India	0	801	0	0	255	1,056
Iraq	0	30	0	0	0	30
Israel	68,575	0	0	0	0	68,575
Italy	13,793	2,334	0	0	0	16,127
Korea, South	280,814	0	0	0	0	280,814
Lesotho	0	48	0	0	0	48
Luxembourg	635	0	0	145	0	780
Macedonia	629	147	0	0	0	776
Maldives	0	0	0	0	21	21
Martinique	0	63	0	0	0	63
Netherlands	80,898	9,034	0	0	1,822	91,754
Norway	646	0	0	0	0	646
Pakistan	0	7	0	0	0	7
Paraguey	0	0	0	0	51	51
Peru	0	16	0	0	0	16
Poland	413	61	0	0	0	474
Portugal	335	338	0	0	0	672
Peru	0	50	0	0	0	50
Singapur	875	0	0	0	0	875
Slovakia	0	250	0	0	0	250
Slovenia	60	12	0	0	0	72
South Africa	0	79	32	0	767	878
Spain	1,552	18,946	0	0	0	20,498
Sweden	1,200	20	0	0	31	1,251
Sri Lanka	692	24	0	0	0	716
Switzerland	11,365	112	0	3,530	0	15,007
Tibet	24,000	0	0	0	0	24,000
Turkey	0	25	0	0	30	55
United Kingdom	891	426	252	348	135	2,051
United States	8,093	0	0	0	0	8,093
Uruguay	0	2	0	0	0	2
Other	629	3,250	16	0	15	3,910
Total	841,699	4,4527	332	552,499	3,538	1,442,596

Meanwhile, the share of thermal power installed in concentrated and vacuum PV/T collectors is higher than in other PV/T collectors and is 79% - in vacuum and 83% - in concentrated ones. This is because in them, due to the design features, the area of the PV cells is smaller than in other collectors.

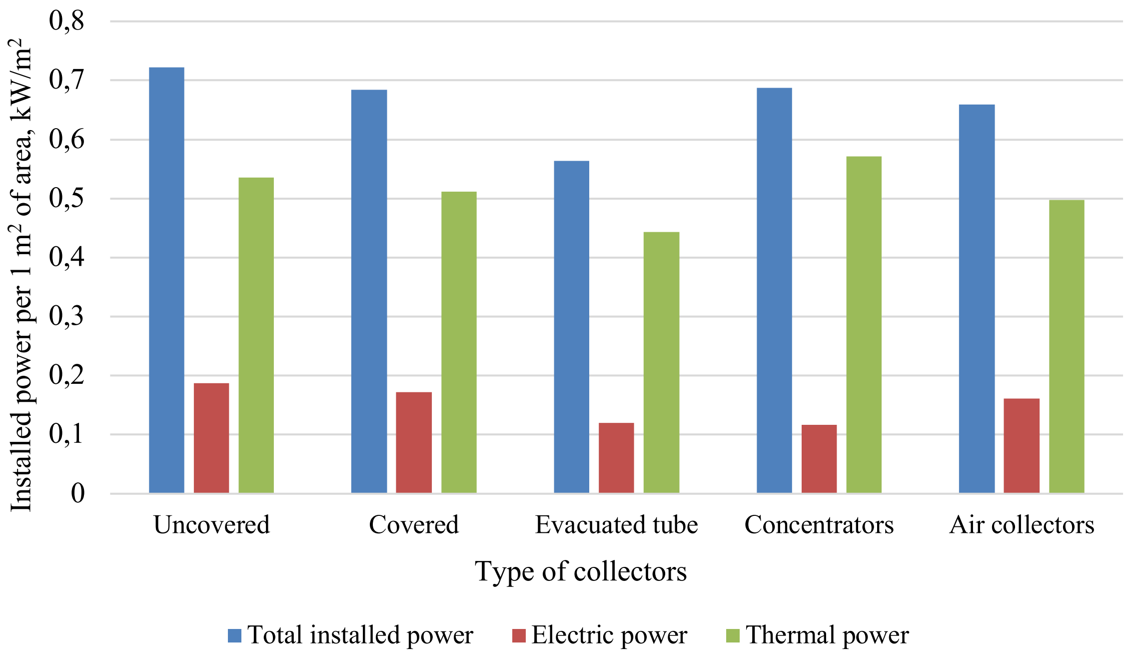

Figure 4. **Distribution of installed capacity per 1 m² of area by type of PV/T collector**

It should be noted that the most popular PV/T collectors are uncovered and air-cooled, the installed area of the all other collectors is ten times smaller. In addition, air-cooled PV/T collectors are common in only one country - France. Suppose the installed capacity of covered PV/T collectors in 1 m² is distributed similarly to uncovered ones, but the installed area is about 20 times smaller than that of uncovered PV/T collectors. In addition, based on the installed power, it is very difficult to judge the efficiency or the amount of energy per 1 m² of area. We will try to answer this question in the next chapter by modeling with Polysun and Abora programs, and presenting the prices of the expected project.

PERFORMANCE OF PV/T COLLECTORS

Solar radiation reaches the module at a solar irradiance of G where a fraction is lost to the ambient as Q_{loss} and the remaining portion empowers the PV module (Q_{el}) with a given electric efficiency (η_{el}). The accumulation of solar energy increases the temperature of the PV module and generates the thermal power of Q_{th}, depending on the fluid medium and module design which is transferred to the thermal module through a heat transfer mechanism with a thermal efficiency of η_{th}. Finally, thermal insulation obtained by reducing and eliminating the back and sides heat losses and makes the entire system more efficient. The general energy equation in a simple PVT module and overall efficiency (η_{PVT}) can be defined by equation Equation (1), Equation (2), Equation (3) (Ramos et al., 2019, Shakouri et al., 2020).

$$\eta_{el} = \frac{Q_{el}}{GA}, \quad (1)$$

$$\eta_{th} = \frac{Q_{th}}{GA}, \quad (2)$$

$$\eta_{PVT} = \eta_{el} + \eta_{th}. \quad (3)$$

Where G (W/m²) is the solar radiation and A (m²) is the aperture area of the module.

Electrical Efficiency

PV/T systems are two separate systems that consist of a single solar thermal collector and a PV module. They are attached together and work simultaneously to generate electricity and thermal energy. The performance of a PVT collector is reduced when the temperature of the system rises (Zondag et al., 2002).

For the separate PV module, electrical efficiency η_{el} is given by equation Equation (4).

$$\eta_{el} = \frac{I_m V_m}{G A_c}, \quad (4)$$

I_m stands for the maximum power point current, V_m for the maximum power point voltage, G for total solar irradiance in W/m² and A_c for the collector gross area in m² (Zondag et al., 2002). A special maximum power point tracking controller in the system assures that the PV modules operate at the best working point (I_m, V_m)

The reduction of the PV module performance with increasing temperature, is given by Equation (5), which represents the traditional linear expression for the PV electrical efficiency.

$$\eta_{el} = \eta_{0,el}\left(1 - \beta\left(T_c - T_{ref}\right)\right), \tag{5}$$

where T_c is PV cell temperature, T_{ref} is reference temperature and β is the coefficient of temperature. Typically, the value of β is 0.0045 °C^{-1}. $\eta_{0,el}$ and β are normally given by the PV manufacturer. However, they can be obtained from flash tests in which the module's electrical output is measured at two different temperatures for a given solar radiation flux.

Thermal Efficiency

Based on ISO 9806:2017 at steady-state condition for glazed liquid heating collectors, the instantaneous efficiency η_{th} shall be calculated by statistical curve fitting, using the least squares method, to obtain an instantaneous efficiency curve of the form presented in Equation (6).

$$\eta_{th} = \eta_{0,th} - a_1\frac{T_m - T_a}{G} - a_2\frac{(T_m - T_a)^2}{G}, \tag{6}$$

where T_m is average temperature of heat transfer fluid (°C), T_a is ambient air temperature (°C), $\eta_{0,th}$ is peak collector efficiency (η_{th} at T_m-T_a = 0), G is hemispherical irradiance, a_1 is heat loss coefficient (W/m^2·K) and the temperature dependence of the heat loss coefficient comes as a_2 (W/m^2·K^2) (ISO9806:2017 ISO 9806). Figure 5 shows thermal efficiency of Abora aH72 PV/T.

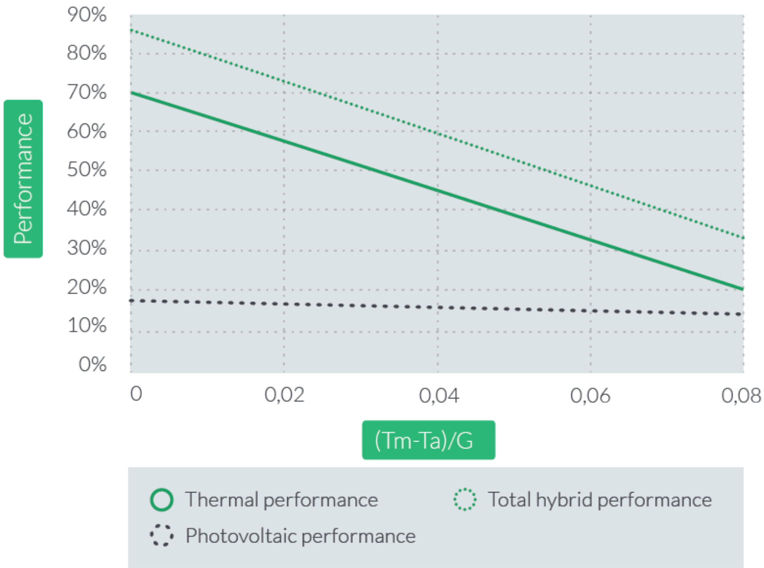

Figure 5. **Abora aH72 PV/T collector efficiency dependence on fluid temperature** (Abora aH72 data sheet)

Suppose the ambient temperature is 25°C and solar radiation G=1000 m^2. We will consider two cases: 1) the temperature of the liquid entering the collector is 25°C, leaving 45°C; 2) the temperature of the liquid entering the collector is 45°C, the outgoing liquid is 65°C. In the first case, the efficiency of the collector will be 65%, because the difference (T_m-T_a) will be 10°C, and in the second case, this difference will already reach 30°C and the efficiency factor will be 50%. In other words, the efficiency will be the highest if we will be able to immediately use all the heat produced in the collector, i.e. the temperature of the fluid entering the collector must be as low as possible.

PV/T TECHNICAL ASSESSMENT

The area of the roof to be built is 1100 m^2. We predict that the collectors will cover an area of 400 m2. The modeling of the solar PV/T power plant and the forecasting of the amount of energy produced were carried out with the help of Polysun 2023 Simulation and Abora 2023 Simulation software, choosing the coordinates of a specific object. Preliminary project prices were obtained from manufacturers.

The diagram below was used for the simulation, in which the liquid heated in the PV/T collector circulates in a closed circle with the help of a pump, heating the storage tank. Water is taken from the storage tank for further heating and supplied to the user.

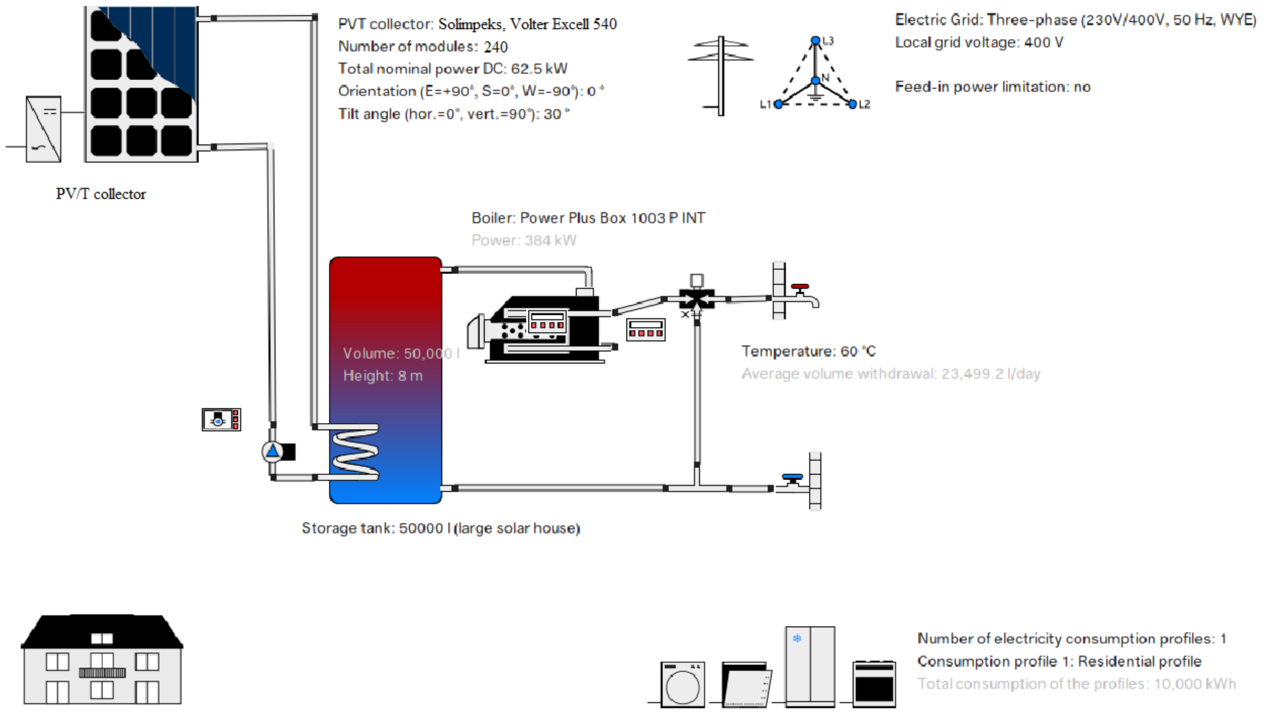

Figure 6. **Scheme of domestic hot water preparation using PVT collectors**

The table below shows the amounts of energy produced by flat covered PV/T, flat uncovered PV/T, monocrystalline PV, vacuum ST and vacuum PV/T solar collectors, the preliminary cost of the project, and CO_2 savings. These solar collectors were not chosen by chance, it was for them that the manufacturers sent the preliminary prices of the project.

Table 2

Summary of economic and ecological calculations of PV/T power plant

Name of the module	Abora, aH72, PV/T	Solimpeks, Volter Excell 540	Solet TSA-370M2	Naked energy, Virtu^{HOT}	Naked energy, Virtu^{PVT}
Collector type	Flat covered, PV/T	Flat uncovered, PV/T	Monocrysta-lline PV	Evacuated tube ST	Evacuated tube PV/T
Installed electric power of the PV/T power plant, kW	70,7	78	77,7	0	34,7
Installed thermal power of the PV/T power plant, kW	277,14	173,6	0	246	173,4
The active surface area of a solar power plant, m^2	379,76	401	388	400	400
Number of modules, pcs.	202	240	210	615	615
Investment in PVT power plant, without VAT, Eur	370942	269464	80130	313384	359420
The amount of energy produced, DC, kWh/year	69262	74490	66822	0	34691
Electricity consumption for power plant purposes (DC to AC conversion, water pump*), kWh/year	8035	8245	2673	5265	6653
The amount of energy produced, AC (minus the electricity consumption for power plant needs), kWh/year	61227	66245	64149	-5265	28038
The amount of thermal energy produced, kWh/year	189116	121520	0	200315	125501
Amount of energy per 1 m^2, efficiency, kWh/m^2	659	468	165	488	384

Name of the module	Abora, aH72, PV/T	Solimpeks, Volter Excell 540	Solet TSA-370M2	Naked energy, Virtu^{HOT}	Naked energy, Virtu^{PVT}
Electricity price component for 2022, excluding VAT (Nordpool), Eur/MWh	184,83	184,83	184,83	184,83	184,83
Variable heat price component for 2022, excluding VAT (pe.lt), Eur/MWh	33,69	33,69	33,69	33,69	33,69
Annual economic savings, Eur/year	17687,8	16338,1	11856,7	5775,5	9410,5
Reduce CO_2 emissions **, t/year	78,67	61,85	26,94	53,88	46,92
Discount rate, %	5	5	5	5	5
Net present value, NPV, Eur	-143345	-62719	64410	-229913	-230614
Internal rate of return IRR, %	0	2	14	-8	-6
Payback period (PBP), year	21,0	16,5	6,8	54,3	38,2
Discounted payback period (DPBP), year	over 30	over 30	8,4	over 30	over 30

* It is planned that the system will use a 1.5 kW water pump, estimating the pump time per year (3510h), the electricity consumption for the pump is 5265 kWh/year, inverters, with an efficiency of 96%, are used to convert DC electricity to AC. Then the electricity consumption for the PV/T system will be:

electricity consumption for PV/T system = amount of DC electricity produced * 0.04 + 5265, kWh/year.

** The reduction of the amount of CO2 equivalent emitted is calculated according to the methodology approved by the Lithuanian Environmental Protection Investment Fund, when the pollution coefficient of electricity is 0.42 t CO_2e/MWh, and heat is 0.28 t CO2e/MWh (Order No. D1-275) according to the formula:

Amount of GHG emissions = activity data * pollution factor.

CONCLUSIONS

The performed calculations showed that the most efficient are the flat-covered PV/T collectors. Their efficiency is 659 kWh/m^2. The efficiency of flat-uncovered PV/T and evacuated tube ST is similar, 468 kWh/m^2 and 488 kWh/m^2, respectively. Meanwhile, monocrystalline PV efficiency is the lowest and reaches only 165 kWh/m^2.

The amount of CO_2 emitted into the atmosphere would be reduced the most by choosing flat-covered PV/T collectors, which would amount to 78.7 tons per year. The smallest CO_2 reduction would occur if we chose a system of monocrystalline PV modules, which would be 27 tons per year. Other collector systems would save from 47 to 62 tons per year.

After evaluating the preliminary cost of the project, the amount of energy produced and the annual savings for 20 years, monocrystalline PV modules would have the highest NPV and IRR indicators, i.e. 64410 Eur and 14% respectively. When at that time the NPV and IRR indicators of flat-uncovered PV/T modules would be -62719 Eur and 2%, respectively, the NPV and IRR indicators of flat-covered PV/T modules would be -143345 Eur and 0%, respectively. Meanwhile, both indicators of evacuated tube ST and PV/T systems are negative.

The lowest payback period (PBP) of the PV/T modules was flat-uncovered modules i.e. 16.5 years, while the PBP of flat-covered and evacuated tube PV/T modules were 21 and 38 years, respectively. The discounted payback period (DPBP) of all modules except monocrystalline was over 30 years.

Considering the NPV and IRR indicators, as well as the simple and discounted payback period, it is uneconomical to install PV/T systems at current energy prices and PV/T technologies. The NPV and IRR indicators show that a monocrystalline PV module system would be a better investment for today.

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