COMPLEX ANALYSIS OF INTEGRATION OF HYBRID PHOTOVOLTAIC THERMAL PANELS INTO A DISTRICT HEATING SUBSTATION

Diana TUTICA[1], Mihaela NORISOR[2], Roxana PATRASCU[3], Eduard MINCIUC[4]

In Bucharest, heat is supplied to consumers through a district heating system based on fossil fuel sources. The paper is underlining the technical, economic, and environmental benefits of integrating solar renewable energy into the district heating system of the city. The analyze is performed for the case of a substation, where photovoltaic-thermal panels (PVT) are proposed to be installed to ensure domestic hot water supply to consumers. The study of 3 different technologies and two scenarios, showed that the proposal is economically feasible and replicable for most Bucharest's district heating substations.

Keywords: PVT panels, Renewable Energy, District Heating, Economic Efficiency

1. Introduction

In the current context of rising prices of electricity, but even worse, of fuels consumed in conventional energy production systems, it becomes even more important to focus on inexhaustible renewable sources of energy, such as solar energy. For economic, social, political, and technological reasons, the transition to an energy mix in which renewable energies occupy a higher share can be achieved slowly and should begin by interconnecting these energy sources within the current structures.

A concrete case that is discussed in this paper is that of the district heating system of the city of Bucharest. The local operator of the public service of heat supply in the Bucharest-Ilfov area is the Municipal Company "Termoenergetica Bucuresti" SA, hereinafter referred to as CMTEB. It has in operation: the transmission and distribution system composed of 954 km of pipes for the primary district heating network and almost 3000 km of pipes for the secondary district

[1] Prof., Dept. of Energy Generation and Use, University POLITEHNICA of Bucharest, Romania, e-mail: dianatutica@gmail.com
[2] Prof., Dept. of Energy Generation and Use, University POLITEHNICA of Bucharest, Romania, e-mail: norishor_mihaela@yahoo.com
[3] Prof., Dept. of Energy Generation and Use, University POLITEHNICA of Bucharest, Romania, e-mail: op3003@yahoo.com
[4] Prof., Dept. of Energy Generation and Use, University POLITEHNICA of Bucharest, Romania, e-mail: eduard.minciuc@upb.ro

heating network, 1027 heat substations and modules, and 48 boiler plants [1]. Although the era of disconnection of consumers is coming to an end, due to the decrease in the economic attractiveness of individual methods of heat production, like most district heating systems in Romania, the CMTEB district heating network is experiencing advanced wear and tear. This directly affects the quality of the parameters of the thermal agent supplied to consumers and creates economic and social shortcomings [2, 3]. In addition to these shortcomings, the rapid development of the real estate sector by introducing new consumers into the current system, has made the heat substations at the ends of the district heating network, to have even bigger problems related to the flow, temperature or pressure of the hot water supplied to costumers.

The complex analysis within this study was carried out for the implementation of an energy production system based on solar energy, namely hybrid photovoltaic thermal panels (PVT) for the simultaneous production of heat and electricity. The analysis was based on data obtained from transient simulations generated to evaluate and size the capacity installed in hybrid solar photovoltaic thermal panels to cover heat consumption for hot water preparation for a selected heat substation. The methodology is presented in the paper [4].

Therefore, the sizing of the PVT panel system was done to cover the need for hot water consumption, outside the heating period (May, June, July, August and September).

2. Methodology

The heat substation that has been chosen for this study, is Aviatiei 5, and is a substation located at the end of a primary district heating network branch. Due to its location, there are a series of disadvantages: neither in terms of quantity nor quality, the consumers requirements are sometimes difficult to be achieved. The problem is even more complex, because of the bad condition of the primary network that is connecting the substation to the heat source. Therefore, the proposed solution is to integrate locally hybrid photovoltaic-thermal panels, which will allow heat and power generation on site.

Below there are presented data/solutions that were the basis for the complex analysis (from a technical, economic, and environmental point of view):

I. PVT panel system with accumulation of both heat in hot water tank (TES), and electricity in batteries, and respectively

II. PVT panel system provided only with thermal energy storage (TES) for hot water consumption.

The analysis was performed for 3 different constructive variants of hybrid photovoltaic thermal solar panels systems available on the market. The constructive variants used will be generically called PVT1, PVT2, PVT3.

The 3 constructive types of PVT used in the realization of the analyzed systems have the following technical-constructive characteristics [4].

- PVT1. This panel measures 1650 x 995 mm. The thermal collector is made of aluminum. On the electrical side are photovoltaic cells of 290 Wp, with an electrical efficiency of 17.66% tested at STC (AM 1.5, radiation 1000 W / m2 and ambient temperature of 25ºC). The temperature coefficient (which is the decrease in electrical efficiency at each degree above the STC temperature) is 0.38%. The equipment weighs 43 kg. Price for one PVT is 780 Euros.
- PVT2. On the electrical side there are 375 Wp photovoltaic cells, with an electrical efficiency of 20% tested at STC. The temperature coefficient is 0.34%. The equipment is thermally insulated, and the total weight is 27.1 kg. Price for one PVT is 540 Euros.
- PVT3. The thermal collector is made of copper, with a liquid volume of 1.2 l. On the electrical side, there is a 260 Wp cell, with an electrical efficiency of 15.95% tested at STC. The temperature coefficient is 0.47%. Price for one PVT is 500 Euros.

In all the 3 constructive variants analyzed for sizing, the following general considerations were taken into account:

- the inlet temperature in the panels is 15°C;
- heat loss on pipes is negligible;
- shading and accumulation of dust on the panels are not considered (it is assumed that they are correctly positioned in relation to the adjacent buildings and that there is regular maintenance);
- it is considered an orientation to the south with a degree of inclination of 35°;
- the mass flow is kept constant.

Sizing was done in two main steps, using TRNSYS software [4].

A. for a single panel (for each construction type) - daily, monthly simulations were performed during the heating period (table 1).

Table 1

Monthly and total energy produced by a single PVT panel

Month	PVT1		PVT2		PVT3	
	E_{th} (kWh)	E_{el} (kWh)	E_{th} (kWh)	E_{el} (kWh)	E_{th} (kWh)	E_{el} (kWh)
May	121,58	40,08	95,58	56,24	114,36	39,92
June	161,69	46,19	135,43	64,8	149,16	46,01
July	180,68	47,04	156,83	66	164,78	46,86
August	162,57	42,43	141,07	59,53	148,23	42,26
September	91,93	29,07	73,48	40,78	85,97	28,94
Total	718,44	204,81	591,25	287,35	666,88	203,98

B. for the number of panels necessary to cover the domestic hot water consumption (for each constructive type) - daily, monthly simulations were made during the heating period (table 2).

Table 2

Annual heat and power production and number of panels resulting from sizing

Heat substation / data	Constructive solution (PVT)		
5 Aviatiei	PVT1	PVT1	PVT1
Number of panels	1494	1815	1609
E_th (MWh)	1073.355	1073.116	1073.008
E_el (MWh)	305.985	521.738	328.176

3. Economic quantification of environmental impact analysis

The implementation of the energy production system composed of PVT (producing simultaneously heat and electricity) leads to the increase of the energy efficiency of the heat substation and the centralized system. Energy efficiency is quantified by fuel savings determined as the difference between the consumption of fuel (natural gas) related to the heat substation in the initial situation and the consumption of fuel related to the heat substation when the heat production for the preparation of domestic hot water is produced by PVT.

Energy savings - the amount of energy saved determined by measuring and / or estimating consumption before and after the implementation of any type of measure, including a measure to improve energy efficiency, while ensuring the normalization of external conditions affecting energy consumption.

According to the statistical analysis performed in the paper [5], heat losses in the transmission, distribution and supply network of thermal energy are very important, totaling approximately 68.45% of the energy purchased from producers. Losses can be divided into heat loss due to the heat carrier loss and heat loss to the environment. Of these, the last category represents the largest share, namely 76.33% of the total losses. In summer the situation is even worse, and losses can reach 90% of production. The study also shows that on average only 31% of the heat delivered from producers ends up being billed to final consumers.

Based on these data, the fuel economy (primary thermal energy savings – $EETP_{Thermal\ station}$) can be defined as the difference between the thermal energy consumed to produce hot water consumption required by the consumers (ETP_{source}), in conventional plants of centralized heat supply system and thermal energy produced by new PVT systems (ET_{PVT}):

$$EETP_{Heat\ substation} = ETP_{source} - ET_{PVT} \quad [\text{MWh}] \qquad (1)$$

Where ETP_{source} can be determined for the hypothesis that heat (ET_{PVT}) is generated by burning natural gas, in installations with an estimated conversion efficiency (η_{source}) of 90%, and with a transmission and distribution efficiency ($\eta_{T\&D}$) of 31 %:

$$ETP_{source} = \frac{ET_{PVT}}{\eta_{source} \cdot \eta_{T\&D}} \cdot 100 \qquad [MWh] \qquad (2)$$

Ton of oil equivalent (TOE) is an internationally agreed unit of measurement as an energy equivalent. TOE measures the energy produced by burning one ton of oil.

Not all oil has the same chemical composition, so an average is proposed by the International Energy Agency.

The recommended value by the International Energy Agency (IEA) for one ton of oil equivalent (TOE) is 11.63 MWh. As a result, we have [6, 7]: 1 TOE = 11.63 MWh = 1.4285714285714 tons of coal.

The following table shows the energy quantities of the heat substation, expressed in Tons of oil equivalent, according to the report:

$$ET_{PVT,[TOE]} = ET_{PVT,[MWh]}/11{,}63 \qquad [TEP] \qquad (3)$$

Table 3

Equivalence of thermal energy quantities in TOE

Heat substation	Heat demand [MWh]	Total Energy [TEP]	Primary energy savings [TOE]
5 Aviatiei	1073	92,26	238,42

The primary energy saving would be 72% compared to the production of heat required from current sources operating on natural gas. This can be determined by equation 4.

$$EETP_{Heat\ substation} = \frac{ETP_{source} - ET_{PVT}}{ETP_{source}} \cdot 100 \qquad [\%] \qquad (4)$$

If we take into account that for 1 MWh of heat produced on natural gas in an installation with an average efficiency of 90%, a quantity of 185 kg CO_2 is obtained, then by multiplying it with the heat produced with the help of PVT to cover the demand for heat in the form of domestic hot water, and respectively with the electricity produced from the PVT system and consumed by the heat substation analyzed in the two scenarios, the total amount of CO_2 avoided can be obtained.

The values are centralized for each case, in table 4.

Table 4

The amounts of CO_2 avoided by implementing the new PVT system

Case	Own services [MWh/year]	CO_2 avoided own services [Tons/year]	Heat from PVT [MWh/year]	CO_2 avoided heat [Tons/year]	Total CO_2 avoided per case study [Tons/year]
I.1	87,084	16,11	1073	198,505	215
II.1	27,72	5,13			204

It can be said that from the point of view of the positive impact on the environment, both solutions are very good, the decisive factor in choosing the optimal variants remaining the technical-economic analysis presented in the next chapter. The positive economic impact of reducing the amount of CO_2 can be better underlined if we look at this at the level of the city's district heating system. Thus, for the over 1000 heat substations, a reduction of at least 200 tons of CO_2 / year, for a price of carbon certificates that tends to 100 Euro / ton, can bring an annual saving of over 20.000.000 Euros.

4. Economic analysis of the proposed scenarios

For all the analyzed cases, considering the value of the investment, it was assumed that 50% of it will be supported from own funds, the remaining 50% being covered from non-reimbursable funds. A slightly pessimistic scenario was chosen compared to the real situation of investments through the Large Infrastructure Programme in which the share borne from European Union funds was 65% [8].

The investment costs, with the operation and maintenance of both the panels and the heat and electricity storage equipment, were estimated based on the specialized literature [9, 10], but also from the market prices at the time of the study.

The present analysis aims at the technical and economic study of the solutions to replace in a proportion of 100% the current production of heat with energy coming from renewable sources. In a further analysis, starting from the optimal solutions, it will also be verified its application within the limits imposed by the available space located around each analyzed heat substation, as well as in different configurations that ensure the best technical and economic efficiency.

Regarding the price chosen for the sale or purchase of electricity produced by PVTs, it was considered that after choosing the optimal variant, it will also be taken into account the space limitations, at which point the installed power on each heat substation will fall below 100 kW of installed power, this complying with the category of prosumers. For this category of producers, the price of electricity sold on the market is regulated and is equal to the weighted average price of the Day-Ahead Market in the previous year. For this reason, the estimated value of the sale price in the system of the electricity produced through PVTs is 108 Euro/MWh. The price of electricity purchased from NPS during periods when there is no self-production, as an average between the prices existing in the current year on the different energy markets, namely 196 Euro/MWh [11, 12]. Thus, the common input data for all cases are presented in Table 5.

Table 5

Common economic data for all studied cases

Data	Value
-discount rate, a [%]	6
-lifetime period [years]	25
-heat price, [€/MWh$_e$], [13]	66
-price of electricity purchased from the market [€/MWh$_e$], [11]	195,8
-price of electricity sold on the market [€/MWh$_e$], [12]	107,8
-medium price for a tone of CO2, [€/t], [14]	70
-duration of the investment, [years]	1
-share of investments made from own funds [%]	50

The following will be presented in detail the results obtained from the economic and environmental analysis and will be interpreted starting from the values of the main indicators (GPP, NPV, IRR), for the heat substation ST5 Aviatiei.

GPP- Gross Payback Period, is the total investment (*Inv*, Euros) related to the annual cashflow (the difference between total income (*IN,* Euros) and total expenditure (*Ex*, Euros)). The solution is economically efficient if $GPP \leq n$, where n is the operation time and life span of the equipment.

$$GPP = \frac{Inv}{IN - Ex}\ [years] \tag{5}$$

NPV – Net Present Value, represents the algebraic sum of annual net present value over the lifetime (n- number of years), where (a) is the discount rate. One solution is cost-effective if $NPV \geq 0$, and in the case of comparing several solutions, the optimal solution corresponds to the condition $NPV = max$.

$$NPV = \sum_{k=1}^{n} \frac{(IN - Ex)_k - Inv_k}{(1+a)^k},\ [Euros] \tag{6}$$

IRR- Internal Rate of Return, can be defined as the discount rate which, when applied to the cash flows of a project, will generate a net present value (NPV) equal to 0 ($IRR=a_0$). A solution is cost-effective if $IRR \geq a$.

$$NPV = \sum_{k=1}^{n} \frac{(IN - Ex)_k - Inv_k}{(1+a_0)^k} = 0 \tag{7}$$

The results obtained from the calculations will be presented for each of the 2 operating scenarios I and II, for each of the 3 hybrid panels. All monetary values are in constant currency, euro, at an exchange rate of 5 lei for 1 euro.

Case I. Use of PVT type 1, 2 or 3, in configuration with tank for storing heat and with batteries for storing electricity to cover 100% of the own consumption of the heat substation. The data from which the analysis was started, are presented below, in table 6:

Table 6

Input economic data for the first case study and for the 3 types of PVT

Economic data	PVT1	PVT2	PVT3
-heat production PVT, [MWh]	537		
-total number of PVT, [pieces]	1.494	1.815	1.609
-price PVT, [Euro/piece]	780	540	500
-total price PVT, [Euro]	1.165.320	980.100	804.500
-total price storage batteries, [Euro]	208.525		
-electricity production, [MWh]	306	522	328
-heat substation power consumption, [MWh]	87		
-electricity sold on the market, [MWh]	219	435	241
-HS maintenance costs, [Euro/year]	2.468		
-PVT maintenance costs, [Euro/year]	9.532	14.974	9.203
-HS investment, [Euro]	49.350		
-total investment [Euro]	1.423.195	1.237.975	1.062.375
-CO_2 avoided by the system, [t/year]	199		
-CO_2 avoided by the heat substation, [t/year]	16		

This solution is an economically efficient one, in all 3 proposed technological variants. It is noticed, however, that the best results are brought by the variant in which the PVT2 system is used, a system that although it would involve the largest number of PVT to cover the heat needs, comes with two major advantages: the specific price is about 30% lower than the first variant of studied PVT, and the annual produced electricity is almost 40% higher compared to the other two variants of PVT.

Table 7

Economic indicators for the first case study and for the 3 types of PVT

Economic indicator	PVT1	PVT2	PVT3
-Gross Payback Period (GPP), [years]	9	6,39	6,49
-Net present value (NPV), [€]	299329	619688	514515
-Internal Rate of Return (IRR), [%]	10,11	15,2	14,92

Case II. The use of PVT type 1, 2 or 3, in configuration with a tank for storing heat and with partial coverage of the own consumption of the heat substation. The uncovered share electricity of the production of the panels will be bought from the NPS. The surplus produced will be sold in the NPS. The data from which the analysis was started, are presented below, in table 8:

Table 8

Input economic data for the second case study and for the 3 types of PVT

Economic data	PVT1	PVT2	PVT3
-heat production PVT, [MWh]	537		
-total number of PVT, [pieces]	1.494	1.815	1.609
-price PVT, [Euro/piece]	780	540	500
-total price PVT, [Euro]	1.165.320	980.100	804.500
-electricity production, [MWh]	306	522	328
- heat substation power consumption, [MWh]	57		
- electricity TS consumption savings, [MWh]	30		
-electricity sold on the market, [MWh]	276	491	298
-HS maintenance costs, [Euro/year]	2.468		
-PVT maintenance costs, [Euro/year]	9.532	14.974	9.203
-HS investment, [Euro]	49.350		
-total investment [Euro]	1.214.670	1.029.450	853.850
-CO2 avoided by the system, [t/year]	199		
-CO2 avoided by the heat substation, [t/year]	5		

This solution is also an economically efficient one, in all the 3 proposed technological variants.

As in case I, it can be seen that the best results are brought by the variant in which the PVT2 system is used, a system even if it would involve the largest number of PVT to cover the heat needs, will bring the same two major advantages: a specific price about 30% lower than the one of the PVT1 variant, and a quantity of electricity almost 40% higher than the one generated with PVT1 or PVT3.

Table 9

Economic indicators for the first case study and for the 3 types of PVT

Economic indicator	PVT1	PVT2	PVT3
-Gross Payback Period (GPP), [years]	9,76	6,43	6,8
-Net present value (NPV), [€]	187888	508247	376096
-Internal Rate of Return (IRR), [%]	9,08	15,08	14,18

6. Conclusions

From the data presented above, and from the graph below (fig.1), it can be noted that the solution with the best economic indicators is that of using hybrid solar panels of PVT2 type, together with the storage in batteries of the electricity necessary to cover the own consumptions of the heat substation. This is followed in the hierarchy, almost equally, by the solutions using PVT3 panels together with electric storage batteries, and respectively the solution of using PVT2 panels, without storing the electricity. Although the investment in the solution analyzed for case 2, with PVT2, seems interesting from the point of view of the rapid recovery (6,5 years), it can be seen from the graph that it has a slow increase in cashflow, bringing at the end of the lifetime, an NPV lower than the one that the first 3 ranked solutions can generate.

On the last two positions are the variants of using PVT1 panels, whose specific large investment compared to the other two types of PVT, leads both to a late return of the investment, as well as to an unattractive net present value at the end of the operating lifetime (NPV is less than 1/2 of the initial investment value).

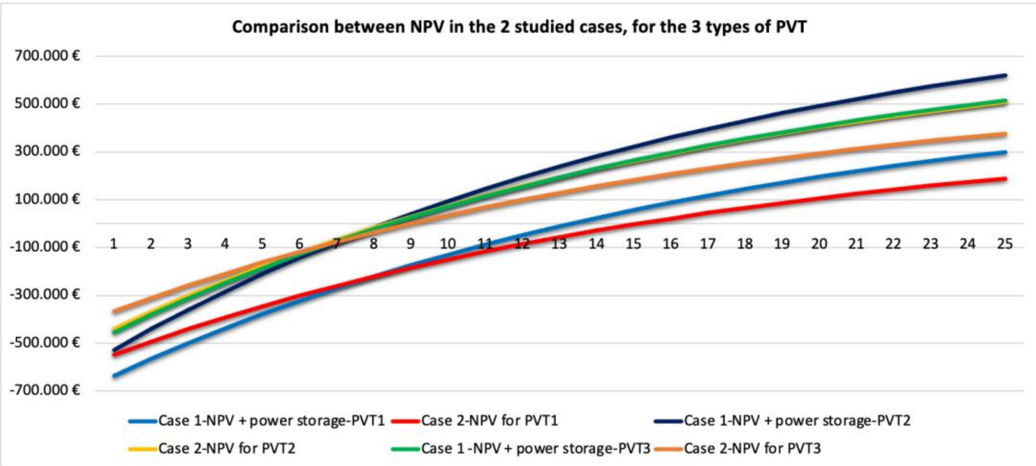

Fig 1. Comparison between NPV values for the studied scenarios in the case of TS5 AVIATIEI, with economic data from 2021-2022

However, things change if the investment is made 100% from own funds. In this case, the cumulated NPV is double in the case of using PVT3 type equipment compared to that brought by using PVT2. As well as the updated return on investment, it is 17 years for PVT3 compared to 20 years for using PVT2. In conclusion, in order to choose the optimal solution, a multicriterial sensitivity analysis of these two variants of panels must be performed.

From the comparative analysis of the proposed solutions presented in the previous paragraphs, the following resulted: for both case I and case II, the optimal variant of panels resulted in PVT2, with an installed electric power of 375 W, a thermal power of 629 W and an average unit price (540 Euro). Their economic efficiency being the highest of the 3 solutions, and the electricity production is higher and therefore the amount of electricity sold on the market is more important and generates an increase in revenues, especially in the current conditions in which in recent months, there has been a significant increase in prices of both electricity and carbon certificates.

It becomes interesting to compare the period 2020-2021 (before the increase in prices on the energy market) with the current one. Thus, in Figure 2, it can be seen that a decrease in the price of electricity by 50% on average, as well as in the price of certificates for the ton of CO2, would lead to a slightly different classification of the analyzed solutions. The best solution in such a scenario would be the use of PVT3 panels together with electricity storage batteries. In case I, the problem with the investment, is the fact that electricity storage batteries have a lifespan of no more than 10 years, and they must be replaced three times during the 25-year period of study. Because one of the economic calculation assumptions was that the entire investment is made before the commissioning of the system (year 0), automatically its total value was very high. Consequently, the unit price of the panels plays the decisive role in determining the optimal variant.

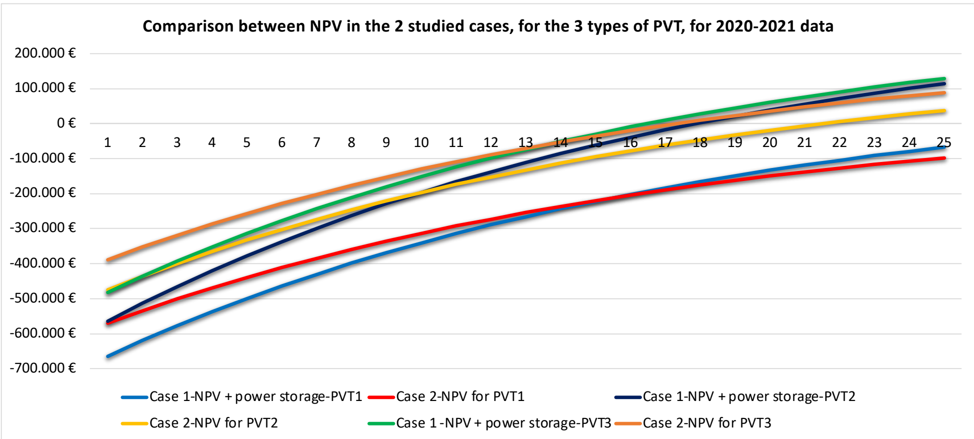

Fig 2. Comparison between NPV values for the studied scenarios in the case of TS5 AVIATIEI, with economic data from 2020-2021

A general conclusion that can be drawn from the obtained economic results is that in the current context of rising electricity, carbon certificates, but also primary energy prices, the refurbishment of conventional district heating systems, by integrating renewable sources, is an attractive solution, if there is the possibility of partial non-reimbursable financing. In order to find an economically efficient solution in the case of 100% use of own funds too, the next stage of the study will be to identify the optimal number of PVT that can be used both depending on the surface available at the heat substation, as well as in the case of forming a hybrid system of PVT and solar panels for the preparation of domestic hot water.

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