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Technical-Economic Analysis of a Hybrid Thermal Energy Supply System Based on Renewable Energy Sources †

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Abstract: The technical-economic analysis represents a decisional factor in the implementation of a new thermal energy supply system and is a key part of the feasibility study. In the present paper, the economic performance indicators, used as evaluation instruments within the analysis, highlight the economic efficiency of each proposed scenario and offer an establishment of hierarchy for them. Based on this analysis, the optimal scenario can be recommended, such that the benefits are maximized. The sensibility analysis, performed for the optimal scenario at the end of the paper, shows an estimation of the effects throughout the lifespan of the new system. This is beneficial to pre-empt negative effects or to stimulate the factors that can increase the efficiency of the system throughout the entire lifespan.

Keywords: renewable energy sources; thermal energy supply; technical-economic efficiency; performance indicators; optimisation

1. Introduction

Mainly, through a technical-economic analysis, the effects of an investment project are assessed together with the implementation profitability of the project throughout the entire lifetime. The analysis within the feasibility study is holistically performed, combining technical and economic aspects, on which the optimal solution is determined. The economic performance indicators are strictly dependent on the equipment of the technical solution and its characteristics. The calculations performed within the economic analysis, throughout a relatively long period of time, take into account considerations, premises, and a set of hypotheses compatible with the analysed project, which are lowering the uncertainty degree of the analysis.

In the present paper, a comparative analysis from an economical perspective is performed for a hybrid thermal energy supply system with different operating scenarios, in order to identify the optimal solution.

Defining and determining the financial-economic performance indicators associated with the proposed scenarios for the hybrid thermal energy supply system offers the possibility to identify the optimal operating scenario. For given conditions, this scenario will minimize the financial effort and risks while increasing the benefits.

The main purpose of the project that will be implemented is to cover the thermal energy demand of a building from the campus of University Politehnica of Bucharest (UPB) using a hybrid thermal energy supply system based on renewable energy sources, and to inject the overproduction of heat into UPB's district heating network. Therefore, the following objectives are proposed:

- Generate three forms of energy (electricity, heat, and cold) based on a hybrid renewable energy source (geothermal and solar), in which the electricity produced will cover at least the consumption of the thermal energy generation unit (on a yearly basis).
- Fully cover the heating and cooling demand for the target building (TB) using thermal energy produced from 100% renewable energy sources [1].
- The reintegration of the TB into the UPB heat distribution network (UPB DH) to inject the overproduction of heat.
- Develop a modular concept that will ease the process of replication and scaling.

2. Description of Hybrid Thermal Energy Supply System

The energy audit of the target building (TB) and the UPB DH led to the development of a new solution for the thermal supply of the building, which ensures heating, cooling, and domestic hot water. It integrates technologies based on renewable sources, namely a ground-to-water heat pump (HP), solar hybrid photovoltaic panels (PVT), and photovoltaic panels (to cover the power consumption of the thermal installation). The proposed solution also involves the replacement of the heat and cold distribution system of the building, as well as the implementation of a new internal hot/cold water distribution system (pipelines, appliances, and final consumers). The structure of the hybrid system is presented in Figure 1 [2].

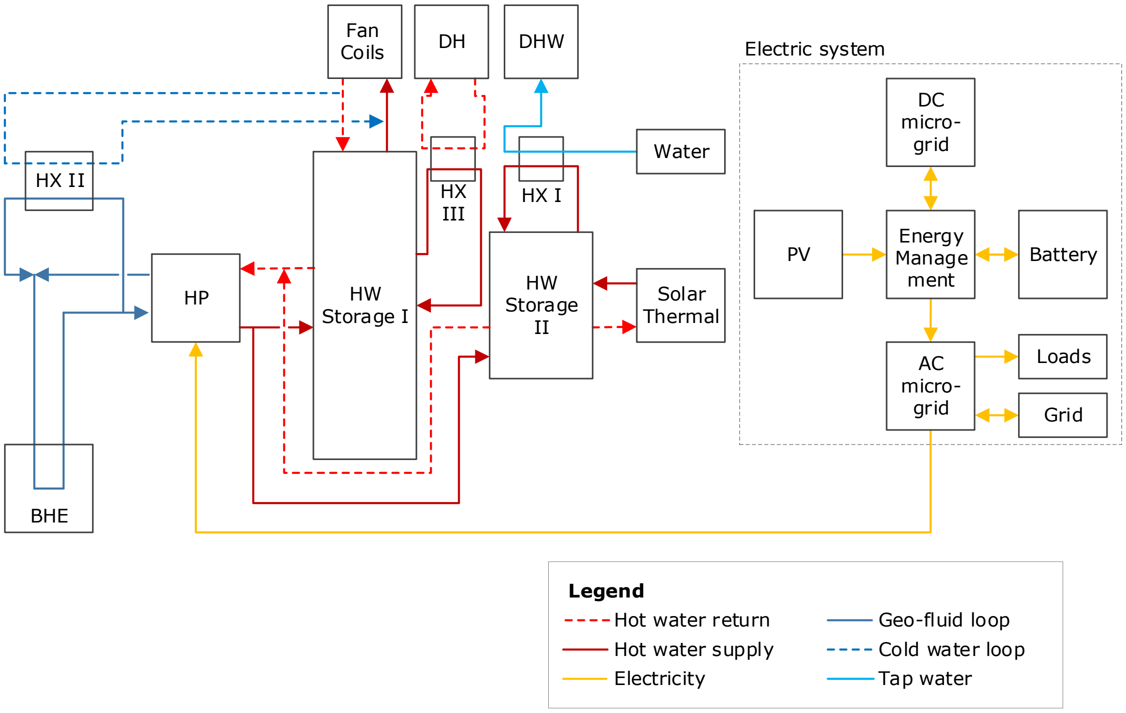

Figure 1. Structure of hybrid thermal energy supply system. BHE—borehole heat exchanger; HX—heat exchanger; DH—district heating; HP—heat pump; HW—hot water; DHW—domestic hot water; PV—photovoltaic panels; DC—direct current.

The energy capacity of the proposed solution will allow ensuring the indoor comfort in the target building's spaces, safety, and flexibility in the supply of thermal energy, as well as the delivery in the DH system of UPB of a share of thermal energy produced from renewable sources.

The design of the hybrid system and sizing of the equipment is based on the thermal energy demand of the analysed building. An oversize of about 30–40% was considered in order to achieve the injection of heat into the local district heating network. In Table 1, the consumption of thermal and electrical energy of the target building and the production ensured by the proposed hybrid solution are summarized.

Table 1. Consumption of thermal and electrical energy of target building and the productions related to the hybrid solution.

Energy Consumption/Energy Production	UM	Value
- thermal energy production—heating	MWh	281.00
- thermal energy consumption—heating	MWh	127.00
- thermal energy consumption injection—DH	MWh	154.00
- electricity consumption for cold production	MWh	4.43
- electricity consumption for production—DHW	MWh	0.69
- electricity production from PV + PVT	MWh	50.00
- electricity consumption for building heating (related to GT-S scheme)	MWh	42.33
- electricity consumption for heat injection (related to GT-S scheme)	MWh	51.33
- total electricity consumption (related to GT-S scheme)	MWh	93.67
- reduced CO_2 through the GT-S scheme for the building	t/year	31.88
- reduced CO_2 through the GT-S scheme for the network	t/year	32.00
- building heating gas consumption	MWh/year	138.00
- combined heat power plant heating gas consumption (equivalent to injection)	MWh/year	192.50
- total gas consumption	MWh/year	330.50

3. Definitions of Scenarios, Characteristics, and Considerations

The technical-economic analysis was performed for three scenarios, in which functioning, economical, and marketing aspects were considered.

In the definitions of the scenarios the followings were considered:

- The thermal energy demand of the building
- Its reintegration into the centralized heat supply system of UPB by injecting a quantity of heat [3,4].

The aspects considered in the technical-economic analysis, valid for all scenarios, were the following:

- As a reference, the current heat supply of the building from a local thermal power plant, which uses natural gas, was considered.
- The production of electricity resulting from photovoltaic panels, as well as from PVT, covers a part of the electrical consumption of the thermal scheme, namely the one related to ensuring the necessary heat and cold of the building [5].
- By implementing the new solution, based on renewable sources, the CO_2 emissions were reduced both at the level of the building frame and the analysed system, this reduction being directly proportional to the reduction of the consumption of primary resources (saved natural gas) [6].
- The value of CO_2 certificates related to reducing the amount of CO_2 by implementing the new energy supply solution were considered as revenues, or *virtual receipts*.
- The share provided by UPB was considered as the value of the investment from its own funds. The difference up to the total value of the investment that the analysed solution implies is considered non-reimbursable from European funds (grants).
- The calculations were performed in two ways:

    1. The value of the investment was equal to the insured quota from the UPB budget.
    2. The value of the investment was equal to the total investment costs assumed by the implementation of the new solution.

Characteristic aspects of Scenario 1:

- By implementing the thermal energy supply solution of the building based on the integration of geothermal-solar systems, it is considered that natural gas saving is achieved both for the building and the centralized heat supply system of UPB (corresponding to the production of heat injected into the system). This economy is quantified economically by the *annual saving of expenses with the fuel (natural gas) saved*.

- The total annual expenses include both the maintenance and operation expenses related to the solution, as well as the expenses related to the annual electricity consumption, in addition to the production provided by the photovoltaic panels.

Characteristic aspects of Scenario 2:

- The virtual receipts of "virtual sales" of the entire amount of heat produced by the implementation of the proposed scheme were considered as income.
- The price of the "sold" heat was considered equal to the price in the UPB invoice.

Characteristic aspects of Scenario 3:

- The virtual receipts of "virtual sales" of the share of the heat produced by the new system, related to the injection into the centralized UPB system, were considered as income.
- It was considered that a natural gas saving is achieved at the level of the building, corresponding to the coverage of the heat demand for its heating. This economy was quantified economically by the *annual saving of expenses with the fuel (natural gas) saved.*

4. Methodology of Technical-Economic Analysis

The technical-economic analysis of the proposed scenarios was mainly based on three economic efficiency indicators with present values, which were determined for each described scenario considering the above-mentioned conditions and maintaining, at the same time, the hypothesis and general considerations [7,8].

4.1. Net Present Value (NPV)

The NPV represents the algebraic amount of annual net income updated over the entire period of activity considered (lifetime). The analytical form of the indicator depends essentially on the reference point considered for the update.

In the case of the present economic analysis, the moment of starting the investment project was considered as a reference moment.

The net present value is given by the following equation:

$$NPV = \sum_{i=1}^{n} \frac{IN_i - C_i - I_i}{(1+a)^i} \tag{1}$$

where

IN_i are the receipts made in the year "i";
C_i are the operating expenses for the year "i", excluding depreciation;
I_i are the investments made from European non-reimbursable funds (grant) in the year "i" (the investment is made in one year, in the year "1")
a is the discount rate considered, and n is the duration of the study. The time period for which the discounted net income was calculated was n = 20 years.

An analysed solution is economically efficient if NPV $\geq$ 0, and in the case of comparing several solutions, the optimal solution corresponds to the condition NPV = max [9,10].

4.2. Internal Rate of Return

The internal rate of return (IRR) of an investment is the discount rate (a_0) for which the net present value is cancelled, respectively:

$$NPV = \sum_{i=1}^{n} \frac{IN_i - C_i - I_i}{(1 + a_0)^i} = 0 \tag{2}$$

$$IRR = a_0 \tag{3}$$

The solution of Equation (2) results from attempts of an iterative calculation, due to the fact that the equation cannot be solved analytically.

The IRR value was interpreted as the percentage interest that could be accepted for both the investment and the working capital so that the proposed investment project does not produce losses.

It is worth noting the following:

- The internal rate of return (IRR) was used to estimate the economic efficiency of each solution proposed and analysed individually. The IRR cannot be used to compare several solutions as it may lead to false conclusions.
- The profitability of a project (solutions) was interpreted in relation to the IRR value, as follows: if the IRR has a unique value (in this analysis, only this situation is taken into account), the project is profitable if $a \geq IRR$ (the comparison was made with values of the discount rate in the range of 5–10%).

4.3. Payback Period

The payback period (PP) is defined as the number of years (n_r) for which the condition is met:

$$NPV = \sum_{i=1}^{n_r} \frac{IN_i - C_i - I_i}{(1 + a)^i} = 0 \tag{4}$$

$$PP = n_r \tag{5}$$

where PP represents the objective duration of exploitation, at the end of which the initial investment can be covered and an additional income corresponding to the considered discount rate can be achieved [9,10].

Defining the payback period requires establishing an origin of time. The accepted convention is to calculate this duration starting from the moment of implementation of the respective objective.

The decision to accept or eliminate an investment project should be taken by comparing the recovery period of the capital "n_r" with the lifetime of the objective "n" (in the analysed case, 20 years). Theoretically, if $n_r \leq n$, the investment project can be accepted, bringing net updated incomes, and if $n_r > n$, the project must be rejected; it will not bring net incomes over the lifetime of the proposed solution.

In practice, the project is considered economically efficient based on this indicator, if the value calculated for the PP is compared with a reference value (T_r), called the standard return of investment. From the literature, it results that the standard term is in the following range:

$$T_r \leq \left(\frac{1}{2} \div \frac{1}{3}\right) \cdot n \tag{6}$$

A particular case is the gross value of the payback period (GPP), which does not take into account the discount rate (a). The value for the GPP is determined at the beginning of the investment and is defined as the following:

$$GPP = \frac{I}{IN - C} \tag{7}$$

5. Results of the Analysis

The technical-economic comparison of the proposed solutions was made over a study period equal to a lifetime of 20 years for both proposed solutions, based on the calculation of economic performance indicators with updated values: the net present value (NPV), the internal rate of return (IRR), and the payback period (PP) [11,12]. The considerations and hypotheses mentioned in the previous paragraphs were taken into account.

The components of the income and expenditure flows related to the analysed solutions are presented in Table 2.

Table 2. Income and expenditure flows for the analysed scenarios.

Type of Cost [EUR]	Scenario 1		Scenario 2		Scenario 3	
	UPB Investment Share	Total Investment	UPB Investment Share	Total Investment	UPB Investment Share	Total Investment
Total investment [EUR]	52,000	279,747	52,000	279,747	52,000	279,747
Specific investment [EUR/kW]	812.5	4371	812.5	4371	812.5	4371
Total annual expenses [EUR/year]	−5992	−5992	5609	5609	765	765
Specific expenses [EUR/kW year]	93.7	93.7	87.7	87.7	12	12
Sales receipts [EUR/year]	1916	1916	19,801	19,801	11,718	11,718
Annual revenue [EUR/year]	7909	7909	14,192	14,192	10,953	10,953

Note: Negative values indicate cost savings.

The values of the economic performance indicators calculated for the analysed solutions, in the "University Politehnica of Bucharest (UPB) Investment option", are summarized in Table 3.

Table 3. Performance indicators values.

Economic Performance Indicator	Scenario 1	Scenario 2	Scenario 3
NPV [EUR]	55,482	140,877	96,857
PP [years]	7.80	4	5.2
GPP [years]	6.58	3.66	4.75
IRR [%]	14.13%	27.07%	20.56%

The optimal solution is one in which the following occurs:

- Virtual receipts of annual costs related to "virtual sales" of the entire amount of heat produced by the implementation of the proposed scheme are considered as income.
- The price of the "sold" heat is considered equal to the price in the UPB invoice.
- The value of the investment is equal to the quota provided by the UPB budget.

The summary of the results of the technical-economic analysis is presented in Table 4, while in Figure 2, the evolution curve of the payback period for all analysed scenarios is shown.

Table 4. Technical-economic analysis results.

Economic Performance Indicator	Scenario 1		Scenario 2		Scenario 3	
	UPB Investment Share	Total Investment	UPB Investment Share	Total Investment	UPB Investment Share	Total Investment
NPV [EUR]	55,482	−172,265	140,877	−86,870	96,857	−130,890
PP [years]	7.80	>lifetime	4	>lifetime	5.2	>lifetime
GPP [years]	6.58	35.37	3.66	19.71	4.75	25.54
IRR [%]	14.13%	−5.57%	27.07%	0.14%	20.56%	−2.22%

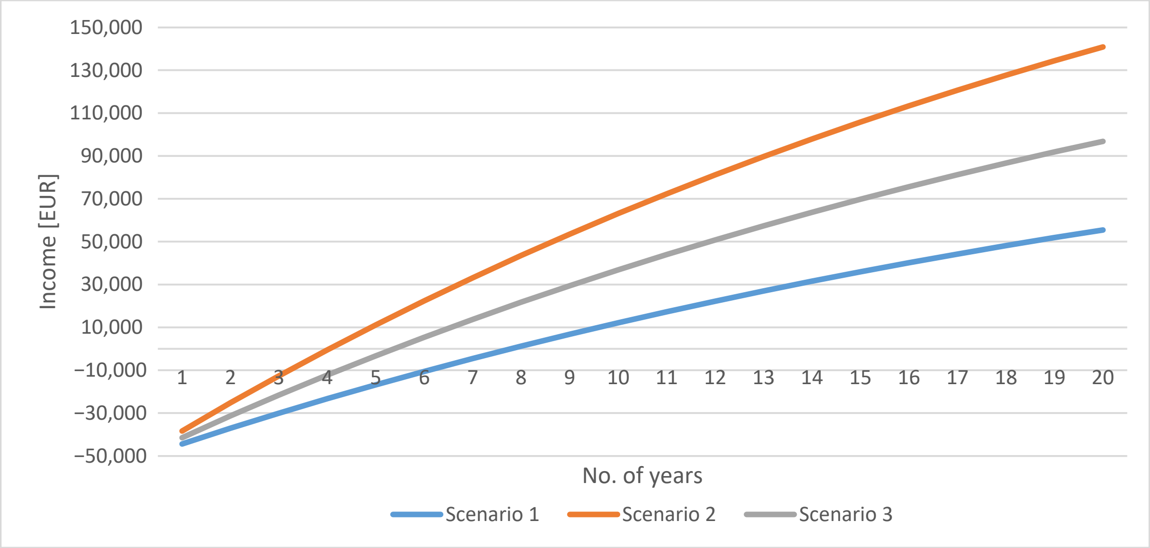

Figure 2. Payback period evolution for all scenarios.

6. Conclusions and Sensibility Analysis for Optimal Scenario

In all the analysed scenarios, when the integral value of the investment related to the new heat supply system is considered, the economic performance indicators are below the profitability limit [13]. This conclusion is highlighted by all the calculated indicators:

- NPV < 0
- GPP and PP > analysed system lifetime (20 years)
- IRR < 4%

This aspect was predictable due to the current high investment cost of the new technologies, but also due to small installed capacities, which do not allow significant compensation from high investments, with savings in energy costs and/or revenues resulting from "selling" the heat injected into the UPB centralized heat supply system.

To financially support the implementation of projects through which new technologies are implemented, which use renewable sources, the application of financial levers, such as non-reimbursable grants, are practised at the European level that allows the amortization of the investment in an acceptable period of time during the life of the objective. Considering this fact, the technical-economic calculation was used the share of the investment that returns as the investment effort of UPB, while the difference (up to the value of the total investment) being ensured by the WEDISTRICT H2020 project, Grant agreement ID: 857801, which aims to demonstrate that District Heating and Cooling systems can be built on a combination of renewable energy sources and waste heat recovery solutions.

Under these conditions, in all three analysed scenarios, the proposed solution is efficient from the technical-economic point of view, a conclusion resulting from the determined values of the economic performance indicators.

- NPV > 0
- GPP and PP < analysed system lifetime (20 years)
- IRR > 4%

The scenario in which the maximum values of the technical-economic indicators are obtained is Scenario 2, namely income, the "virtual receipts" of annual costs, related to "virtual sales" of the entire amount of heat produced by the implementation of the proposed scheme (Table 5).

Table 5. Results of the sensibility analysis.

Variable Factor	**Solution 1**			
	NPV [EUR]	**DR [years]**	**PP [years]**	**IRR [%]**
a [%]				
4	140,877	3.66	4	27.07
5	124,867	3.66	4	27.07
6	110,784	3.66	4	27.07
e_p [EUR/MWh]				
100	150,966	3.48	4	28.53
117	140,877	3.66	4	27.07
140	127,228	3.94	4.1	25.07
q_p [EUR/MWh]				
55	107,854	4.42	5	22.21
63.65	140,877	3.66	4	27.07
75	184,231	2.99	3.2	33.32
CO_{2p} [EUR]				
25	136,537	3.75	4.1	26.43
30	140,877	3.66	4	27.07
35	145,218	3.58	4	27.70

To eliminate the degree of uncertainty of the prediction of certain quantities that intervene in the calculation of economic indicators for the entire analysed period (20 years), it is opportune to conduct a sensitivity analysis on the economic efficiency indicators to the variation of quantities that are relatively difficult to predict [14]. In this sense, the variation of NPV, IRR, PP were analysed for the optimal solution from a technical-economic point of view, depending on the following:

- discounting rate (4, 6, 8%)
- fuel price (natural gas), (±5, ±10%): to determine the extent to which the decrease in fuel price no longer allows recovery of the investment (pessimistic scenario—the limit of economic profitability of the proposed solution)
- electricity price: e_p (±5, ±10%)
- the price of the delivered heat: q_p (±5, ±10%)
- the value of CO_2 certificates: CO_{2p} (30–35 EUR)
- annual maintenance expenses (biannual growth of ±1%)

Only one size varied, the others remaining constant, at a value equal to that of the reference option. The sensitivity analysis was done only for the selected solution as the optimal one.

The increase in the discounted net revenue of the optimal solution was influenced by the increase in the annual revenue, depending on the following:

- the amount of heat injected into the centralized system
- the fluctuation of the related thermal energy price
- the value of carbon certificates

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