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Life Cycle Assessment and Economic Energy Efficiency of a Solar Thermal Installation in a Family House

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Abstract: Designing solar strategies is a powerful step forward to set up an adequate residential house in terms of energy. Many types of research have simulated the energy needs for residential buildings. Designing an improper installation can contribute to a growth in the overall energy expenditure in ensuring thermal comfort. The use of solar thermal processes in Slovakia is on a rise as compared to recent years. This study models twelve solar water heating systems created on the roof of the household. Solar energy techniques are carried out to comply with the demands of heating and domestic hot water. The analysis deals with the most efficient alternative for the arranged solar systems of the building. Considering these installations and the corresponding overall prices of machinery, the best workable alternative is selected. The potential energy performance of auxiliary heating and the energy output of the solar thermal installation are examined. The required amounts of the different energy contributions are modelled and simulated in specific software for a family house in Kosice, Slovakia. We determine the limits of the design for an apartment and analyse which procedure is used to provide the typical average water expenditure and heating need, covering a multi-criteria analysis considering costs, energy, and life cycle analysis of every installation. This approach can support professionals to decide the best scheme considering these criteria, and this method can be satisfactorily applied. In these conditions, converting a conventional gas boiler into a solar thermal system involves monthly economic savings of around EUR 140–250, with payback periods of 2.5–7 years. The energy requirements are fully covered by the solar thermal schemes and the life cycle assessment resulted in reasonable impacts on the environment.

Keywords: solar thermal; domestic hot water; T*SOL; life cycle assessment; OneClickLCA; multi-criteria analysis; flat-plate collector; Slovakia

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1. Introduction

The latest data stated that world energy production has continued to grow (+1.5%) in recent years and is close to reaching 15,000 Mtoe, but remains below its real trend (2%/year) [1]. The energy demand is projected to rise by 1.3% each year until 2040 [2], and the population forecast highlights that the population will be 70% higher in the year 2050 [3]. The overall energy expenditure in 2035 will amount to around 32,922 TWh, twice that in 2008 [4] (with 75% of the overall energy used being produced by fossil fuels). The European Commission points out as one of its primary purposes curtailing emissions by 2050; such contraction can be achieved with monetary, industrial, and civil transformation measures [5]. In 2018, the European Union (EU) fulfilled 55% of its energy demand using gas and oil sources, and encourages diminishing this value by up to 20% by the year 2050.

The construction sector uses 40% of the overall energy consumption within the European Union. Energy management to reduce carbon emissions was revealed as a hot topic, as 12% of the literature produced is focused on this [6], and the concept of a post-carbon city [7] appeared as a result of meeting the European targets regarding emissions. This industry handles a significant part of the overall greenhouse gas emissions. The European Union is trying to improve the environment in households by means of new ideas. One project is run by the Slovak Innovation Energetic Agency (SIEA), in which the state can support households (up to half of the cost) to perform any installations using renewable sources. The massive consumption of fossil fuels could likewise lead to important environmental concerns, such as air pollution and global warming [8]. To promote energy self-sufficiency, the European Parliament has encouraged policies supporting energy efficiency in the construction industry. Regulations include energy certification of houses and economic motivations for reducing energy usage in residential buildings. Houses and the construction industry consume 33% of the overall final energy use and produce 40% of the total CO_2 emissions [2]. These figures justify the attempts to diminish energy use through envelopes [9,10], warming and cooling (60% of the overall consumption [11]), demand response, etc. In accordance with Directive 2010/31/EU, all EU Member States are obligated to perform energy analysis to diminish energy needs. The concept of net-zero energy buildings [12] comes out as a solution for houses with an excellent energy performance and diminished energy need [13], where renewable sources feed energy demands. In this regulation, the cost-optimal method was proposed—this means dealing with the global costs applied to the building lifespan [14]. Researchers and practitioners have investigated many techniques to exploit solar power for cooling and heating [15,16], photovoltaic energy for electricity [17], and hybrid solar collector thermal and photovoltaic systems [18]. Many approaches have dealt with energy storage [19,20], with wind energy production [21,22], and with modelling energy demand in buildings [23,24].

The energy retrofitting of existing buildings is also a challenge for diminishing energy consumption [25,26]. Many studies have highlighted solar thermal (ST) installations as a promising and ecological technique [27,28], as they contributes to hot water management [29] in several regions with changing solar irradiance [30]. Despite systematic campaigns, the full-scale adoption of solar panels has not materialised yet, because of a lack of confidence in power savings [31,32]. Solar energy usage is needed to face urgent dilemmas posed to our civilization, such as fossil fuel depletion, excessive CO_2 emissions, and the increasing electricity demand [33]. The life cycle analysis of solar technologies has been investigated [34], dealing with renovation materials in family houses [35,36], buildings [37,38], and commercial building [39]. The studies found the most sensitive parameter is daily hot water consumption [34,40] when designing a solar thermal system [41].

Solar thermal energy generation can be used over a small scale [42] or in the industrial sector [43]. The researchers analysed the successful installation of solar concentrator systems [44,45] because of the exorbitant amount of energy savings (40% [46]). Some approaches optimized solar thermal installations [47], considering the key components—the solar collector, the pump, and the storage tank. The auxiliary energy requirements were estimated [48] and the tank for hot water storage was dimensioned to reduce its size [49].

Solar power conversion systems need greater expenditures than conventional energy conversion apparatuses. However, they still provide future monetary savings (users will not pay for warming their houses and for obtaining domestic hot water (DHW)). The future costs or revenues (annual charges and/or future savings) incorporate a discount rate [50] that accounts for inflation to obtain their present value.

This work deals with assessing the overall cost throughout the system. First, for the best hypothesis of a lifetime period, it is compulsory to obtain the input data of energy needs for all installations. To follow these conditions, we simulate using the program "T*SOL" (Valentin Software) [51]. The T*SOL software reports auxiliary heating energy requirements, the solar contribution to heating and for DWH for every alternative. Twelve

ST schemes were analysed, and their net present value throughout their lifespan was calculated [52]. These cases were selected as they are the most common schemes (I-IV) and incorporate different auxiliary heat sources. The energy savings were calculated by comparing each alternative with a zero-case (no renewable energies), covering a tank and a gas boiler for heating and DHW. We rank alternatives for the best alternative solar energy system in buildings after the machinery lifespan. In brief, higher revenues achieved after the installation lifespan indicate a better choice. In these cases, the climate conditions for Košice (Slovakia) were used. Without any doubt, choosing the appropriate solar thermal system in a cold climate condition represents a challenge due to the large amounts of energy needed and the irradiance limitation because of the latitude [41]. A life cycle analysis (LCA) covering the whole installation (buffer tanks, ST panels, etc.) was performed for every alternative analysed. This research was carried out using software "OneClickLCA", attaining the impact on the environment in several categories. Bionova Ltd. developed OneClickLCA software compliant with EN 15978 standard [53,54]. Afterwards, a multi-criteria analysis (using MCA7 software) was performed based on proportion share for each of these categories. This analysis provides us with results for our decision.

We set up the work as follows. Section 2.1 selects the input data required for the method, Section 2.2 shows the program, and we present the obtained output data in Section 2.3. Section 2.4 illustrates how to estimate the net present value, Section 2.5 shows the life cycle analysis of this installation, and Section 2.6 presents the multi-criteria analysis. Section 2.7 depicts the process. Section 3 shows a true case study. The results and the discussion are shown in Sections 4 and 5, while Section 6 features key conclusions.

2. Materials and Methods

2.1. Input Data for the Simulation

The input data required for the procedure can be classified into building location, thermal installation, and economic data. Building location data cover longitude, latitude, diffuse radiation percentage, total annual global irradiation (kWh/m^2), average outside temperature (°C), and the lowest outside temperature.

The thermal installation data are gross collector area (m^2), active solar surface (m^2), active collector area (m^2), inclination (degrees), orientation, and azimuth angles (degrees).

The economic data are the equipment to buy, the costs of the energy, and the discount rate.

*2.2. T*SOL Software Characteristic*

T*SOL is a software for modelling ST installations in buildings. This program can reproduce solar thermal schemes for various households, comprising installation presentation of competent solar thermal systems and yield and assumption of profit. There are 80% of common solar installation variations in the database for such buildings in the USA and Europe. By implementing an alternative relation, the software detects the effect of solo pieces on the behaviour of a system. The variant study also presents the effects of global radiation, DHW, space heating, collector performance, auxiliary for heating, and total simulation outcomes.

Software results show the scheme of behaviour in other outdoor conditions (the installation's location area, the value of heat loss of a building, etc.). Concerning the results achieved, a specific correlation between the variations and their costs was determined.

2.3. Output Data for the Annual Simulation

T*SOL ® program calculates the following results for every case:

- Energy delivered by collectors (kWh). The software shows the energy produced by the solar thermal installation. It also divides this energy into solar energy increase to DHW (kWh) and heating (kWh).

- Auxiliary heating energy (kWh). This value showed that our installation cannot offer the total energy demanded by our building. This energy can be achieved by different sources such as gas boilers, heat pumps, wood pellet boilers, and many others. In this work, the method is described, and practitioners can incorporate any other energy sources.

The software highlights the wood pellet economic savings obtained by wood fire boilers (kg), natural gas savings by gas fire boilers (m^3), and the CO_2 emissions avoided by heat pumps (kg).

2.4. Life Cycle Cost of ST Installation

Maintenance may increase the lifespan of solar thermal systems (30 years). The ST modules need to be regularly cleaned. However, maintenance considers components such as thermostatic valves, pumps, solar circuit pumps, and storages for solar accumulation.

This procedure intends to bring knowledge to professionals when they analyse which alternative technique is better. The upcoming incomes and savings in present-day money are considered here. Because the cost of capital is time-dependent, future costs and revenues must consider inflation to compare with today's money [55,56]. The "Net present value" shows current investments and future earnings using the equivalent discount rate. This indicator must be maximised from the present time to the lifespan (Equation (1)). We express this as the net present value (NPV) from the current year (0) to the installation lifespan (T*):

$$NPV = -\sum I_i e^{-rt} + \int_0^{T^*} S_i e^{-rt}\, dt \quad (1)$$

I_i is the investment performed, and S_i is the monetary savings for the *i*th year. The maintenance costs should be incorporated into this analysis as a cumulative investment per year.

2.5. Life Cycle Assessment

Utilizing the LCA assessment process, the environmental performance of a family house based on "cradle to the gate with options" is calculated. LCA is a methodical technique for determining the possible environmental effects associated with the lifespan of a product [57,58]. The LCA method comprises all steps, which start from natural materials to industrial productions, and incorporates material extraction, energy expenditure, production, transport, usage, recycling, and ultimate removal or end-of-life. It is an overall process that specifies the influence a device can have on climate change, non-renewable resources, and the environment as an entity. As already mentioned, this LCA was performed using OneClickLCA software, which generates impact complying with standards of ISO 14040, ISO 14044, EN 15804+A1+A2, and ISO 21930 and ISO 14025. It complies with the CML-IA method. This software is a standardised program to run LCA with a good opportunity to cut down costs, incorporating environmental effects. The software OneClickLCA uses elements in management and construction stage through the use-step until end-of-life, i.e., the "grave" stage.

2.6. Multicriteria Analysis

To determine which alternative is the best, according to environmental, economic, and energy aspects, we used the multi-criteria analysis (MCA). MCA is a family of well-known methods implemented by decision support systems to compare different alternatives based on multiple factors, and to find the best performing solution [59]. Due to various objectives considered in the analysis, the hierarchy approach [60] was applied. For the calculation, the MCA7 software was used, which performs calculations using several specific methods with the so-called "Cardinal information on the criteria". This means that to use these methods, it is necessary to know (i) the criteria according to which the decision will be made (number of criteria, names of criteria, weights of criteria, and distinction between maximization and minimization criteria); and (ii) variants, or alternatives, between which decisions are made and which are arranged from best to worst using some multicriteria methods (number of variants, names of variants, values of all criteria for a given variant).

For the multi-criteria analysis, MCA7 software was chosen, and the Concordance Discordance Analysis (CDA) method was used. CDA includes a comparison of alternatives for pair choice. It measures the degree by which the alternatives of choice and the weights of factors prove or disprove the ratio between the alternatives. The discrepancies in the weights of factors and the evaluations of criteria are analysed through the procedures of concordance and discordance [61], which the software calculates by itself from input data.

2.7. Calculation Process

Figure 1 reflects the computation process in 10 stages. The irradiance inputs are gathered in step 1. The cases for solar thermal installation are depicted in step 2. The cases include supplementary heating provided by a gas boiler, a heat pump, and a wood pellet boiler. Calculations are performed using the software in Step 3 to obtain the energy results described before (Section 2.3). We consider the economic input data (step 4) and calculate the investment and savings for every case (Step 5). The economic analysis for every installation lifespan is calculated in step 6 to obtain the best alternative for this economic standpoint. The LCA is performed in step 7 using the parameters calculated in steps 2 and 3, obtaining the results shown in stage 8. Finally, results from stages 3, 6, and 8 are included in the MCA software to achieve a priority ranking in step 10.

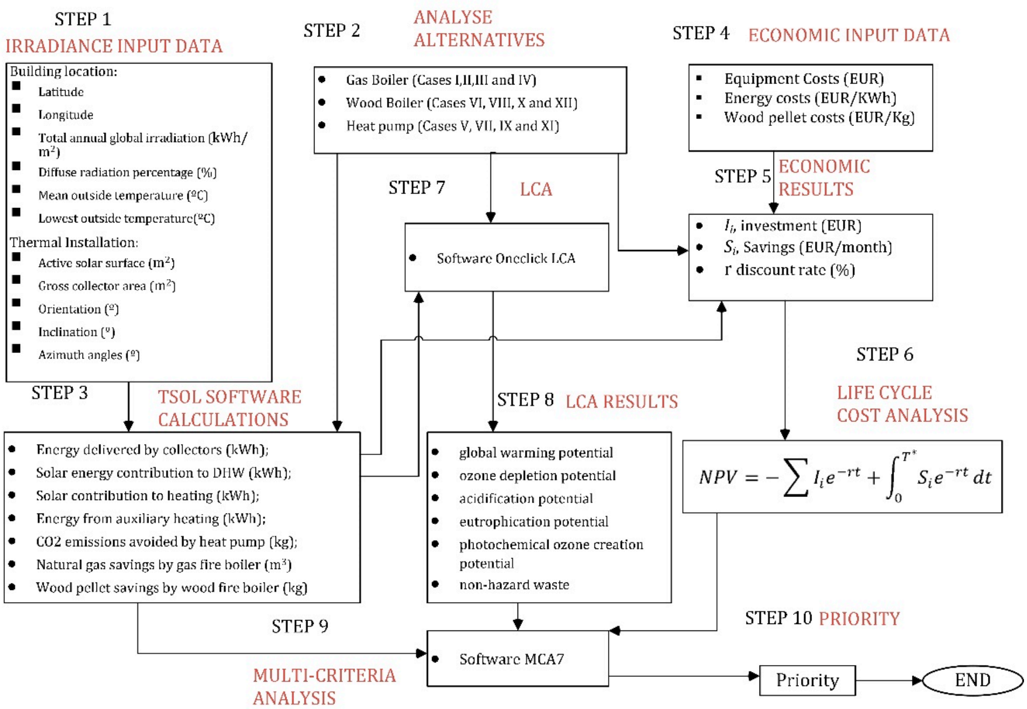

Figure 1. Workflow for the process to calculate the lifespan of the alternatives.

3. Case Study

3.1. Input Data for the Simulation

Table 1 shows the input climate and solar thermal installation data. Twelve opportunities to size solar thermal panels and other machinery were analysed (Table 2). The following step calculates the investment cost for every installation and every device of the installation. Another step of this analysis is to obtain midterm energy results from the software and compare them with measured values on a real house. For comparison, energy needs for an auxiliary source for heating were used, such as a gas boiler, heat pump, or wood boiler. After comparing the heating energy, it is also necessary to compare the domestic hot water (DHW) heating energy supply. CO_2 emissions per year were also compared among alternatives. The last step calculates total lifespan for every situation. The designed one-floored apartment (usable area 53 m^2) is located in Košice (Slovakia). The heat load was 5 kW, the indoor temperature was 20 °C, the specific head load was 94.34 W/m^3, and the specific annual energy supply was equal to 163.585 W/m^3

Table 1. Input climate data for a house and solar thermal installation.

Building Location		Thermal Installation	
Location	**Košice, Slovakia**		
Latitude	48.7°	Active solar surface	1.78 m^2
Longitude	–21.3°	Gross collector area	2.03 m^2
Overall global irradiation (tilt angle 45°)	1144.4 kWh/m^2	Orientation	180 °C
Diffuse radiation	53.90%	Lowest outside temperature	–13 °C
Average outside temperature	9.8 °C	Azimuth angles	0°

3.2. Cases Simulation

We describe the cases analysed here in Figure 2.

Case 0 does not have any solar thermal collector. It includes only a 15kW gas-fired boiler. Every case has five Thermosolar Žiar TS 300 solar collectors (with efficiency η_{col} = 57%), and the components are described here.

Case I has a 200 litre preheating tank, a space-heating buffer tank of 500 litres, one tank for DHW with 120 litres, and a gas-fired boiler with 15 kW performance and floor heating.

Case II has a gas-fired boiler (15 kW), a 500 litre tank for floor heating, and a dual coil indirect water tank of 300 litres.

Case III has a 1000 litre tank for DHW and floor heating and a gas-fired boiler with 15 kW performance.

Case IV contains a gas-fired boiler with 15 kW performance and a 500 litre tank for floor heating and a heat exchanger.

The following cases repeat the features in Cases I-IV but consider a heat pump (Cases V, VII, IX, and XI) or wood-fired boiler (Cases VI, VIII, X, and XII). To clarify this, the auxiliary source in Case I is a heat pump with 14 kW performance and floor heating (Case V), and this is compared to a wood-fired boiler with 14 kW performance and floor heating (Case VI).

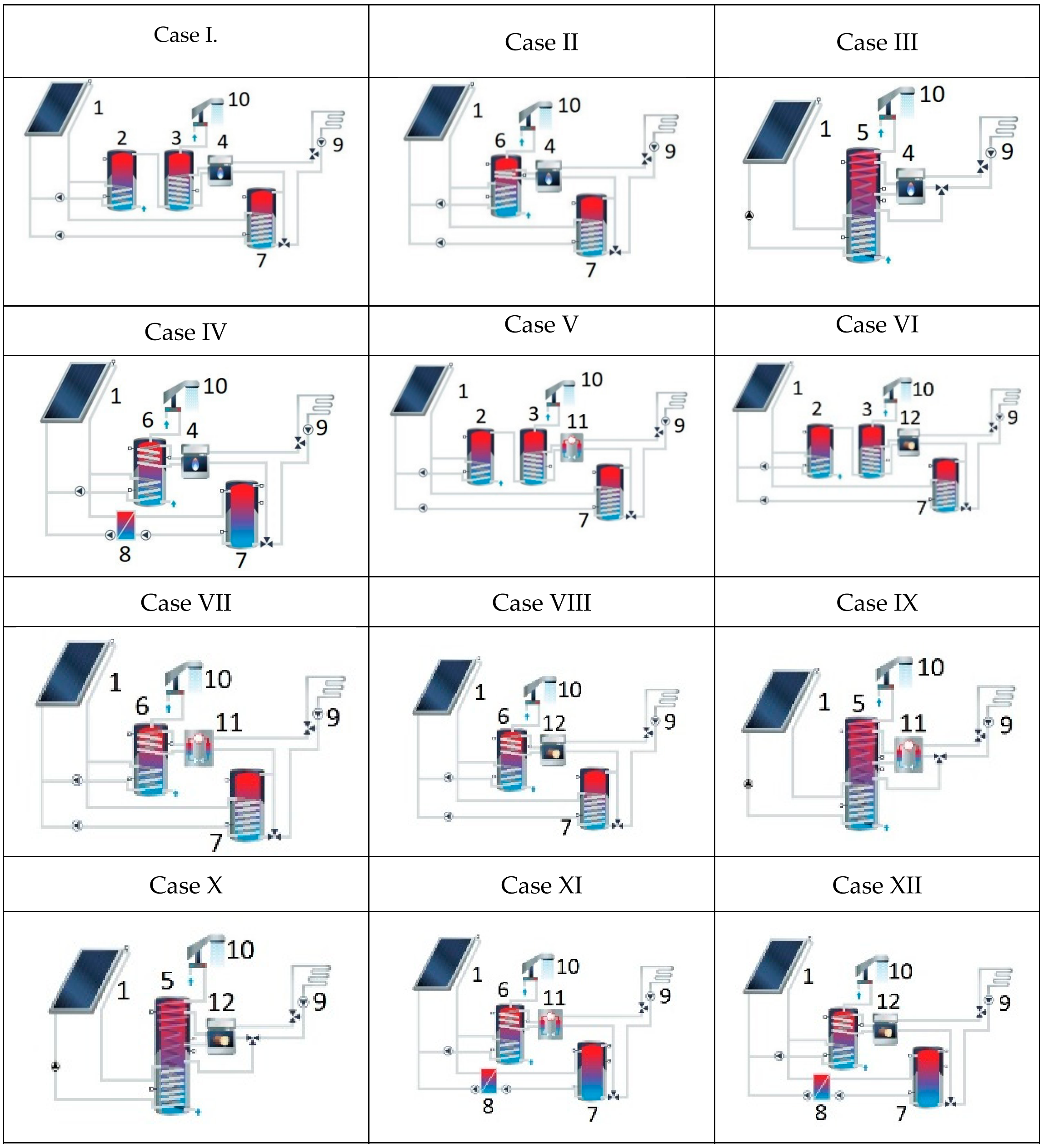

Figure 2. Numbers represent the following: 1—solar collector Thermosolar Žiar TS 300; 2—solar preheating tank, 200 litres; 3—DHW (domestic hot water) standby tank, 120 litres; 4—gas boiler, 15 kW; 5—combination tank, 1000 litres; 6—dual coil indirect water tank, 300 litres; 7—space-heating buffer tank, 500 litres; 8—heat exchanger; 9—floor heating; 10—DHW consumption; 11—heat pump, 14 kW; 12—wood fired-boiler 14 kW.

3.3. Economic Data

The financial character of input data collected from the T*SOL simulation software is summed up in the following paragraph:

- Five solar collectors = 2128.8 € (this cost applies to all cases), type Thermosolar Žiar TS 300 flat plate collector, gross surface 2.03 m^2, active solar surface 1.78 m^2, gross collector area 10.15 m^2, active collector area 8.9 m^2, orientation 180°, inclination 45°, and azimuth angles 0°;
- Gas boiler = 1169 € (cases I, II, III, and IV), nominal output 15 kW;
- Solar preheating tank 200 litres = 401.41 € (cases I, V, and VI), volume 200 litres, height 1.8 m, insulation thickness 100 mm, effective thermal conductivity 0.065 W/(mK), and losses 2.31 kWh/day;

- Buffer tank 500 litres = 906 € (cases I, II, V, VI, VII, and VIII), volume 500 litres, height 2.93 m, insulation thickness 45 mm, effective thermal conductivity 0.03 W/(mK), and losses 3.46 kWh/day;
- DHW standby tank 120 litres = 376 € (cases I, V, and VI), volume 120 litres, height 1.8 m, insulation thickness 100 mm, effective thermal conductivity 0.065 W/(mK), and losses 1.95 kWh/day;
- Dual coil indirect water tank 300 litres = 1944.76 € (cases II, IV, VII, VIII, XI, and XII), volume 300 litres, height 1.8 m, insulation thickness 100 mm, effective thermal conductivity 0.065 W/(mK), and losses 3.23 kWh/day;
- Collector loop heat exchanger = 100 € (cases IV, XI, and XII), maximum heat transfer rate 4.45 kW;
- Combination tank = 3956.09 € (cases III, IX, and X), volume 1000 litres, height 2 m, insulation thickness 100 mm, effective thermal conductivity 0.065 W/(mK), and losses 4.75 kWh/day;
- Heat pump = 14,744.0 € (cases V, VII, IX, and XI), nominal output 14 kW;
- Woodfire boiler = 852.0 € (cases VI, VIII, X, and XII), nominal output 14 kW.

Table 2 shows all economic costs and their lifespans [62]. Replacement costs are considered as investments in future time (they appear when the lifespan of every component ends). As replacement costs represent future expenses, their value is discounted by the equivalent continuous rate. Residual values of the replaced elements are considered as zero.

As it can be observed in Table 2, the best investment cost was case VI (4664.2 EUR), and the most expensive was case IX (20,828.89 EUR). The values for midterm energy calculations were determined from auxiliary heating, a gas boiler with 15 kW performance, heat pump 14 kW, and wood fire boiler with 14 kW. Gas boiler cases ranged from 7253 to 4981.2 EUR (cases III and I), heat pump cases ranged from 20,828.89 to 18,556.2 EUR (cases IX and V). Wood pellets boiler oscillated among 6936.89 and 4664.2 EUR (cases X and VI).

Energy cost of natural gas (assuming 228 g per kWh [63]) for all alternatives was 1.32 EUR/kg. Other energy sources were wood pellet alternatives (0.18 EUR/kWh) and heat pump (0.08 EUR/kWh).

Table 2. Investment cost of equipment for cases I–IV.

Equipment	Case I	Case II	Case III	Case IV	Lifespan
Solar collector TS 300 5x	2128.8	2128.8	2128.8	2128.8	30
Solar Preheating tank 200 litres	401.4	-	-	-	20
DHW standby tank 120 litres	376.0	-	-		15
Gas Boiler 15 kW	1169.0	1169.0	1169.0	1169.0	15
Combination tank	-	-	3956.1	-	15
Dual coil indirect water tank 300 litres	-	1944.8	-	1944.8	25
Space-heating buffer tank 500 litres	906.0	906.0	-	906.0	15
Collector loop heat exchanger	-		-	100.0	30
Total Investment	4981.2	6148.6	7253.9	6248.6	
Equipment	**Case V**	**Case VI**	**Case VII**	**Case VIII**	**Lifespan**
Solar collector TS 300 5x	2128.8	2128.8	2128.8	2128.8	30
Solar Preheating tank 200 litres	401.4	401.4	-	-	20
DHW standby tank 120 litres	376.0	376.0	-	-	15
Heat pump- 14 kW	14,744.0	-	14,744.0	-	15

Wood fire boiler-14 kW	-	852.0	-	852.0	15
Combination tank	-	-	-	-	25
Dual coil indirect water tank 120 litres	-	-	1944.8	1944.8	15
Space-heating buffer tank 500 litres	906.0	906.0	-	906.0	30
Collector loop heat exchanger	-	-	-	-	30
Total Investment	18,556.2	4664.2	18,817.6	5831.6	
Equipment	**Case IX**	**Case X**	**Case XI**	**Case XII**	**Lifespan**
Solar collector TS 300 5x	2128.8	2128.8	2128.8	2128.8	30
DHW standby tank 120 litres	-	-	-	-	20
Heat pump- 14 kW	14,744.0	-	14,744.0	-	15
Wood fire boiler-14 kW	-	852.0	-	852.0	15
Combination tank	3956.09	3956.09	-	-	15
Dual coil indirect water tank 120 litres	-	-	1944.8	1944.8	25
Space-heating buffer tank 500 litres	-	-	906.0	906.0	15
Collector loop heat exchanger	-	-	100.0	100.0	30
Total Investment	20,828.89	6936.89	19,823.6	5931.6	30

4. Results

4.1. The Energy Required for Every Alternative

The energy required from this source according to the simulations in every case was 8900 kWh a year (Table 3). For this house, five solar panels (TS 300, Thermosolar Žiar) were installed to provide 120 litres of DHW per day.

Table 3. The energy required (kWh/day) from auxiliary heating.

Gas Boiler		Heat Pump		Wood Pellet Boiler	
Case I	8970.7	Case V	8969.9	Case VI	8970.8
Case II	8911.9	Case VII	8970.8	Case VIII	8910.2
Case III	8934.1	Case IX	8931.5	Case X	8930.2
Case IV	8947.5	Case XI	8942.2	Case XII	8943.7

4.2. The Energy Required for Heating

Measured values from real-time were from the house in Košice with the same installation and were recalculated on the object area. Here, the highest potential value of simulation from the case was used. For instance, cases V, VII, IX, and XI included a heat pump as an auxiliary heat source. In the next case, VII had the highest value from these four cases (8970.8 kWh). The energy required for auxiliary heating-heat pump in real-time was 21.34 kWh/ (m^2 a year). We calculated this value by the object area (53 m^2), and the result was 3467.79 kWh a year. Results are depicted in Table 4, highlighting differences between software and real-time values.

Table 4. Energy demanded by heating and DHW regarding simulation software and measured actual values (kWh/year).

	Heating		Domestic Hot Water	
Cases	**Software**	**Real-Time**	**Software**	**Real-Time**
ST heat pump	8969.90	1131.02	2040.65	768.50
ST wood-fired boiler	8943.70	4547.40	2040.65	725.57
ST gas boiler	8970.70	3467.79	2040.65	792.35

4.3. Domestic Hot Water

Table 4 presents the DHW demand. The energy production from an auxiliary source in each case was due to the equal energy from the solar thermal panel and their amount in every installation. The values from the simulation software of energy for DHW were the same for each case (2040.65 kWh). The energy demand for DHW with a heat pump as another heat source was 14.5 kWh/ (m^2 a year) in real-time. We counted this value by the object area (53 m^2), and the result was 768.5 kWh a year. As it can be observed, the values from real-time were in the interval of 725–792 kWh. The lowest value for DHW energy supply was for the solar thermal installation with a gas boiler, and the best was from a wood-fired boiler installation.

4.4. Emissions and Impact on the Environment

We obtained results from simulation software for CO_2 emissions avoided and electricity savings for each of four alternatives, where a heat pump was an auxiliary heat source. In the wood-fired and the gas boiler cases, wood pellets and gas savings were calculated (Table 5).

Table 5. CO_2 emissions avoided for every alternative.

Heat Pump	CO_2 [kg]	El. (kWh)	Wood-Fired	Pellets [kg]	CO_2 [kg]	Gas Boiler	CO_2 [kg]	N.Gas [kg]
Case V	254.06	381.5	Case VI	579.7	179.7	Case I	711.29	336.4
Case VII	247.24	371.24	Case VIII	563.6	174.7	Case II	684.79	323.8
Case IX	324.78	487.7	Case X	734.3	227.6	Case III	853.08	403.4
Case XI	246.29	369.8	Case XII	560.8	173.8	Case IV	681.55	322.3

4.5. Economic Savings of the Alternatives

The economic energy savings with the data shown in Table 6 are calculated. The cost of the gas was calculated in the zero case. Every option produced an economic reduction. The costs of the pellets, gas, and more energy were considered for every choice.

Table 6. Economic monthly savings for every alternative.

Case I	**Case II**	**Case III**	**Case IV**
159.14	159.81	159.56	159.41
Case V	**Case VI**	**Case VII**	**Case VIII**
247.47	230.73	247.56	230.94
Case IX	**Case X**	**Case XI**	**Case XII**
247.53	230.87	230.87	247.51

4.6. Life Cycle Cost of the Solar Thermal Installations

With the investments and lifespan shown in Table 2 and the savings depicted in Table 6, the net present value was calculated for every case. To clarify the analysis, we showed the case I numbers.

Case I contains five Thermosolar Žiar TS 300 solar collectors (2128.8 EUR, 30 years), a 200 litre preheating tank (401.4 EUR, 20 years), one tank for DHW with 120 litres (376 EUR, 15 years), a space-heating buffer tank of 500 litres (906 EUR, 15 years), and a gas-fired boiler (1169.0 EUR, 15 years). Thus, this installation required buying some equipment (those whose lifespan is lower than 30 years) twice. The investment was calculated as follows:

$$I_0 = 4981.2 + (376.0 + 1169 + 376)e^{-15r} + (401.4)e^{-20r} \quad (2)$$

The economic savings were 159.4 EUR/month (Table 6), and the yearly savings resulted as 1909.71 EUR/year. With these numbers, we calculated the net present value:

$$NPV = -\sum I_0 e^{-rt} + \int_0^{T^*} S_i e^{-rt}\,dt = -4981.2 - (376.0 + 1169 + 376)e^{-15*0.02} - -(401.4)e^{-20*0.02} + \int_0^{30} 1909.71 e^{-0.02t}\,dt = 37{,}496.36 \text{ EUR} \quad (3)$$

The evolution in the cost of the gas boiler cases is shown in Figure 3. Table 7 shows the net present value for every solar thermal installation, and values were obtained by performing analogous calculations for every alternative. The effect of future replacement costs can be observed as decreases in the NPVs in Figure 3 (years 15 and 25).

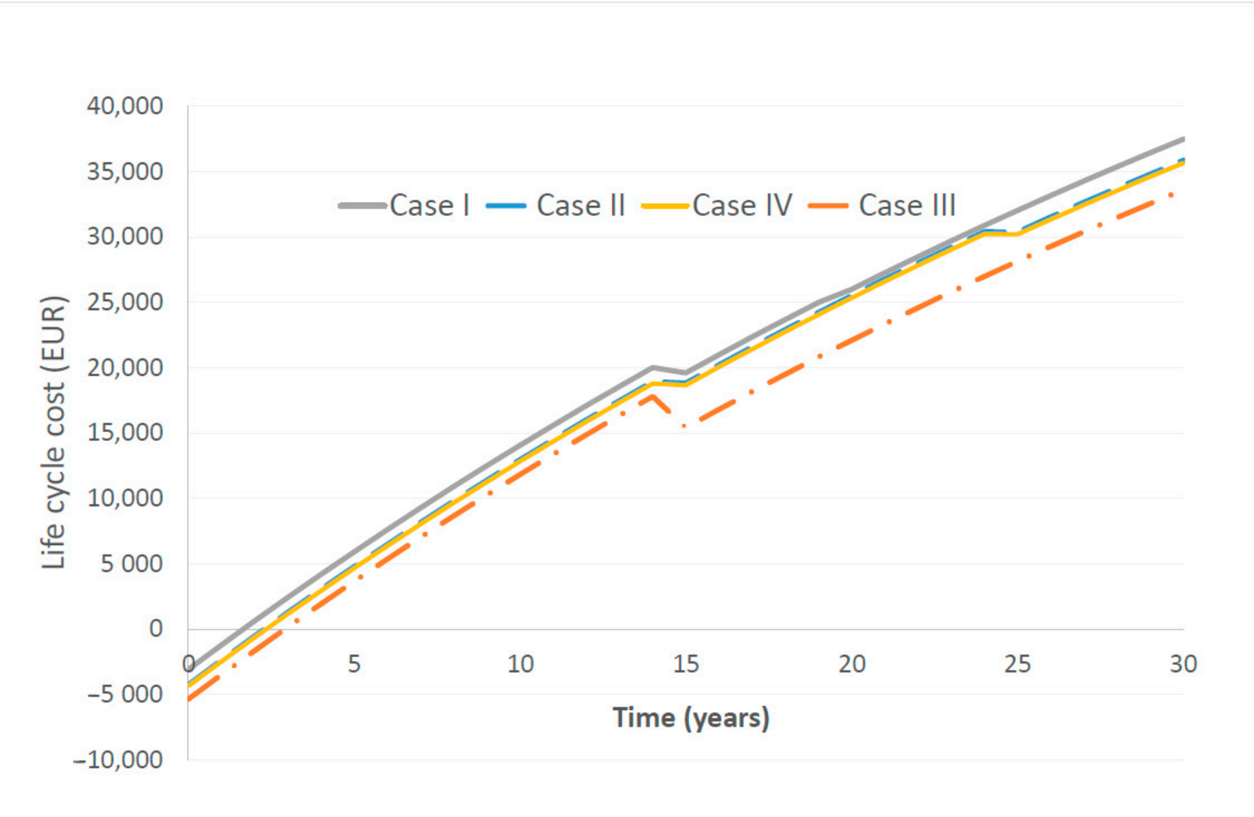

Figure 3. Net present value evolution for cases I–IV.

Table 7. The net present value for every alternative for the solar thermal (ST) lifespan (30 years).

Case I	**Case II**	**Case III**	**Case IV**
37,496.36	35,884.69	33,628.54	35,671.05
Case V	**Case VI**	**Case VII**	**Case VIII**
49,519.68	58,207.72	49,063.36	56,205.22
Case IX	**Case X**	**Case XI**	**Case XII**
45,551.76	54,261.96	47,371.21	61,262.56

4.7. Influence of the Discount Rate

We consider the discount rate as a sensitive criterion. The present value of each cash inflow/outflow considers a discount rate with this parameter. The equivalent continuous discount rate is not modifiable by users as it depends on the national country banks (−1.3% in the UK, 2.2% in the USA). This influence is illustrated in Figure 4, where high values of the equivalent discount rate reduce the economic differences for the installation scheme.

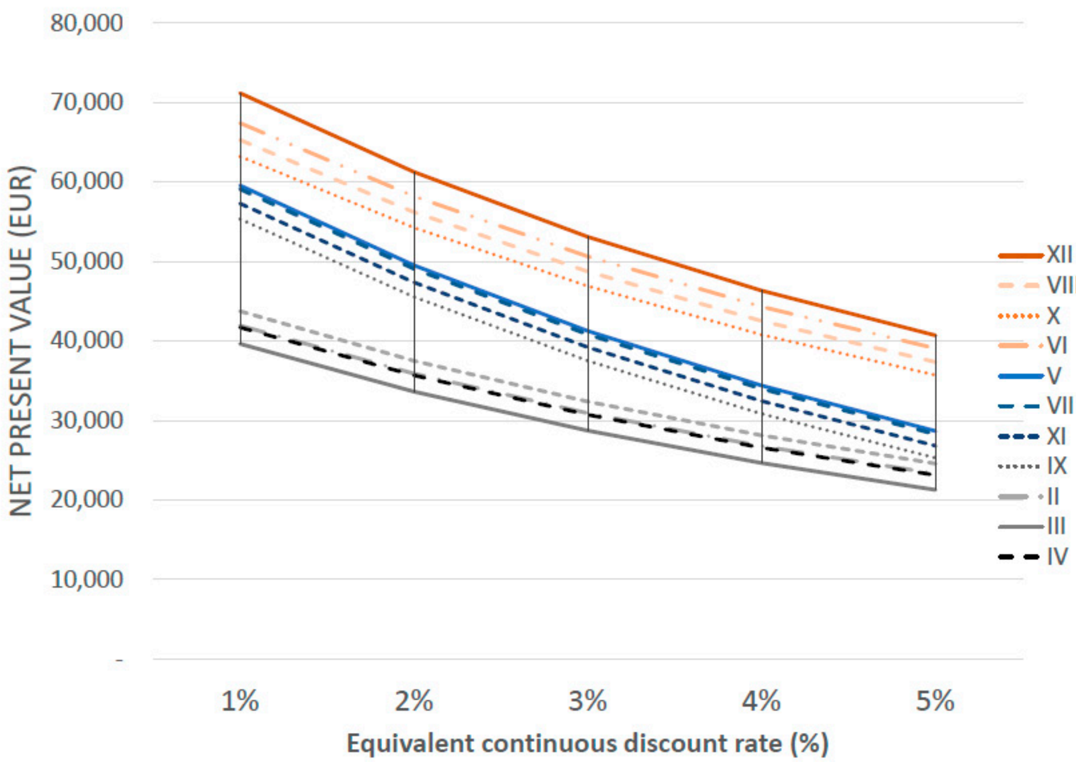

Figure 4. Net present value in year 30 for the cases studied.

4.8. Life Cycle Assessment Calculation

Table 8 presents output data from "OneClickLCA" software for all alternatives. This analysis provides quantitative amounts of the environmental impact groups such as global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), photochemical ozone creation potential (POCP), and non-hazard waste (NHW). They are expressed as kilograms of CO_{2eq}, SO_{2eq}, $(PO_4)^{3-}{}_{eq}$, CFC_{11eq}, C_2H_{4eq} and NHW.

Table 8. Output data from LCA software.

Case	GWP kg CO_{2eq}	AP kg SO_{2eq}	EP kg $(PO4)^{3-}{}_{eq}$	ODP kg CFC_{11eq}	POCP kg C_2H_{4eq}	NHW kg
I	10 549.77	48.39	17.83	0.00253	3.68	1 876.17
II	14 339.08	63.34	19.27	0.0033	3.80	1 247.27
III	24 869.33	109.32	29.09	0.0052	5.29	1 284.77
IV	21 190.66	92.92	34.97	0.0037	4.67	5 282.93
V	17 592.63	89.27	22.2	0.00398	5.33	1 833.69
VI	14 611.98	74.39	21.11	0.0029	9.11	6 178.25
VII	21 180.22	103.07	23.47	0.00468	5.39	1 197.44
VIII	18 401.30	89.34	22.55	0.0036	9.23	5 549.34
IX	34 000.20	162.11	35.26	0.00698	7.51	1 318.23
X	28 931.55	135.32	32.37	0.0056	10.72	5 586.85

XI	28 003.48	132.49	39.14	0.00508	6.26	5 232.08
XII	25 252.87	118.92	38.25	0.0041	10.10	9 585.00

According to the results, case IX had the biggest impact on GWP, AP, and ODP categories, while the highest values in EP, POCP, and NHW were found for cases XI, X, and XII. Case I had the lowest impact on GWP, AP, EP, ODP, and POCP. The lowest value in the NHW category was for case II. Percent representations of life cycle phases on environmental impact categories are depicted in Figure 5. Modules A1–A3 represent the product phase (A1—raw material, A2—transport, A3—manufacturing), and module A4 represents transport to site. Modules B4–B5 represent the use phase (B4—repair, B5—refurbishment), and B6 represents operational energy use. Modules C1–C4 represent the end-of-life phase (C1—deconstruction, C2—transport, C3—waste processing, C4—disposal). Module D is benefits and loads beyond the system boundaries.

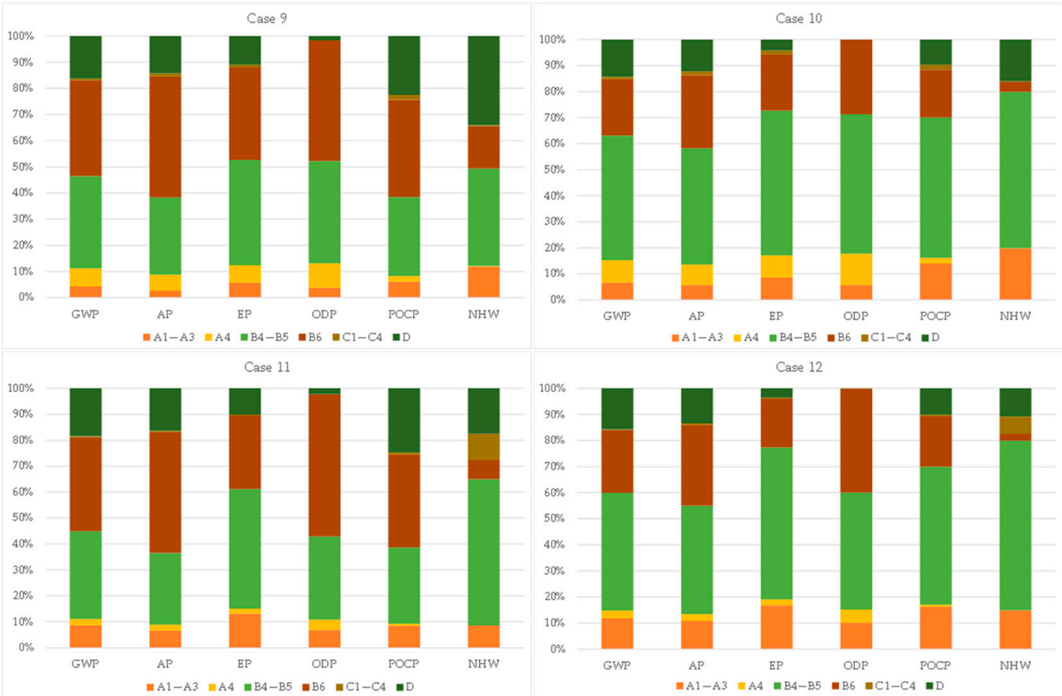

Figure 5. Percent representation of life cycle phases in environmental impact categories.

We can see that the best environmental impacts were in the use phase, modules B4—repair, B5—refurbishment, and B6—operational energy. Modules B4–B5 represent percentage of 20.8–47.9% for GWP; 13.8–44.7% for AP; 30.5–58.4 for EP; 19.2–53.6% for ODP; 25.4–54.0% for POCP; and 37.3–65.0% for NHW. Module B6 represents share of 21.8–48.1% for GWP; 28.1–60.5% for AP; 18.5–44.0% for EP; 28.6–71.1% for ODP; 18.4–39.3% for POCP; and 2.6–16.2%.for NHW. Module D, representing benefits (which have negative value), had a significant impact on the decrease in the total values of environmental impact categories, ranging 14.3–26.2% for GWP; 12.3–23.8% for AP; 3.6–15.4% for EP; 0.0–2.8% for ODP; 9.6–26.8% for POCP; and 10.8–35.1% for NHW. It also has to be mentioned that the product phase had impacts in the range of 4.3–11.9% for GWP; 2.6–10.8% for AP; 5.7–16.8% for EP; 3.7–11.3% for ODP; 6.1–17.1% for POCP; and 8.3–20.2% for NHW. Within "cradle to gate" (from resource extraction to the factory gate) effects (A1–A3), the most contributing components were solar thermal collector (30.5–74.% for alternatives 1–12); solar heat exchanger system (38.4–48.2% for cases IV, XI, and XII), heat pump (21.5–38.2 % for cases V, VII, IX, and XI), and wood fired boiler (31.1–50.4% for cases VI, VIII, X, and XII).

4.9. Multi-Criteria Decision Analysis

To choose the best alternative in calls of environmental, economic, and energy conditions, a multi-criteria analysis was performed. Based on the CDA, the summary weight of all criteria needs to have a value of 1. We assigned 0.34 for environmental (0.102 for GWP and ODP; 0.034 for AP, EP, POCP, and NHW), 0.33 for economic, and 0.33 for energy criteria. Table 9 shows the results of the multi-criteria analysis; case VI was the best and case II was the worst.

Table 9. Results of the CDA method from MCA7 software.

Ranking	Priority	Score	Ranking	Priority	Score
1	Case VI	4.4814	7	Case XI	10.3488
2	Case IX	5.3568	8	Case I	11.2578
3	Case XII	5.5442	9	Case IV	12.1477

4	Case V	7.5302	10	Case X	12.4270
5	Case VIII	7.5302	11	Case III	13.9121
6	Case VII	9.8262	12	Case II	16.9924

5. Discussion

The energy obtained by solar thermal modules was similar for every choice and, likewise, so was the supplementary energy needed by any other source (8900 kWh per year, Table 3). The results highlight that every solar thermal system is workable. In these conditions, we identified gas boiler alternatives (despite being economically viable) are far from heat pump cases. The wood-pellet boiler alternatives are the best economic options, as they do not represent a great expenditure and offer significant savings. The wood pellet boiler cases resulted in the least CO_2 emissions, as depicted in Figure 4. Among them, case XII appears to be the best economic choice (a wood fire boiler).

Case XII is the best choice from the economic standpoint, but results are affected by the equivalent continuous discount rate. Small values of the equivalent discount rate mean greater revenues. To summarise, profits must be re-established to achieve a new apparatus as the upcoming savings will be discounted, and we obtain the pay off in a smaller stage.

Practitioners consider the payback period (the time at which the full expenditure reaches the full energy cost savings on the buy) for a ST system. However, this approach may lead to avoiding economic savings for the system lifespan. The payback period analysis formulation can be calculated [55,64]:

$$T_i = \frac{-1}{r}.\ln\left(1 - \frac{r.I_o}{S_i}\right) \quad (4)$$

We can get the values displayed in Table 10.

Table 10. Payback period (years) for every alternative.

Case I	Case II	Case III	Case IV
2.68	3.31	3.94	3.38
Case V	**Case VI**	**Case VII**	**Case VIII**
6.68	1.71	6.77	2.15
Case IX	**Case X**	**Case XI**	**Case XII**
7.56	2.57	7.16	2.04

These results show that the strongest economical alternative would be case VI, not case XII. The payback period is not the proper index if only economic aspects are considered. The lowest payback period (case VI) gives lower benefits than case XII (Table 6 and Figure 4) for the life cycle cost analysis. So, we must select case XII from this economic standpoint.

Based on the results of LCA analysis considering only environmental criteria, case IX using a heat pump is the best. Most contributing components for GWP of this alternative are a solar collector (61.7%) and heat pump (38.2%). In contrast, the worst is case I, which also has a solar preheating tank, domestic hot water standby tank, space-heating buffer tank, and gas boiler. Most contributing components for GWP of this alternative are a solar collector (67.4%), gas boiler (23.5%), and hot water tank (9.1 %). The total values of the environmental impact categories are presented in Table 8. According to LCA analysis considering environmental, economic, and energy criteria, the best one is alternative 6. It also comprises a solar preheating tank, domestic hot water standby tank, space-heating buffer tank, and wood-fired boiler. Most contributing components for GWP of this alternative 6 are wood boiler (47.3%), solar collector (46.4%), and hot water tank (6.3%). Based on this study, considering all three aspects of sustainability, we can conclude the best is case VI. The study [65] dealing with the LCA of solar thermal systems also compares flat plate and vacuum tube systems. This emphasizes that both collectors can encompass more than half of the yearly hot water requirements for a family house with four inhabitants. The solar fraction values for the vacuum tube and the flat plate collector are 62.7% and 55.3%. According to this approach [37], the domestic solar water heating system market advances to expand, but the success rate depends on many circumstances that are not controlled by users (the costs of solar collectors versus ordinary heating processes, government subsidies, and the energy prices). Besides, another study [66] shows that the lowest increase in the technical building material on the overall LCA results was in a passive house because of the absence of "traditional" technical building machinery for heating.

Figure 6 shows the best-evaluated case of solar thermal installations for different evaluation methods. It can be said that the evaluation of just one aspect may not indicate the best alternative. A comprehensive assessment of several aspects, especially energy, economic, and environmental, helps us find the optimal solution.

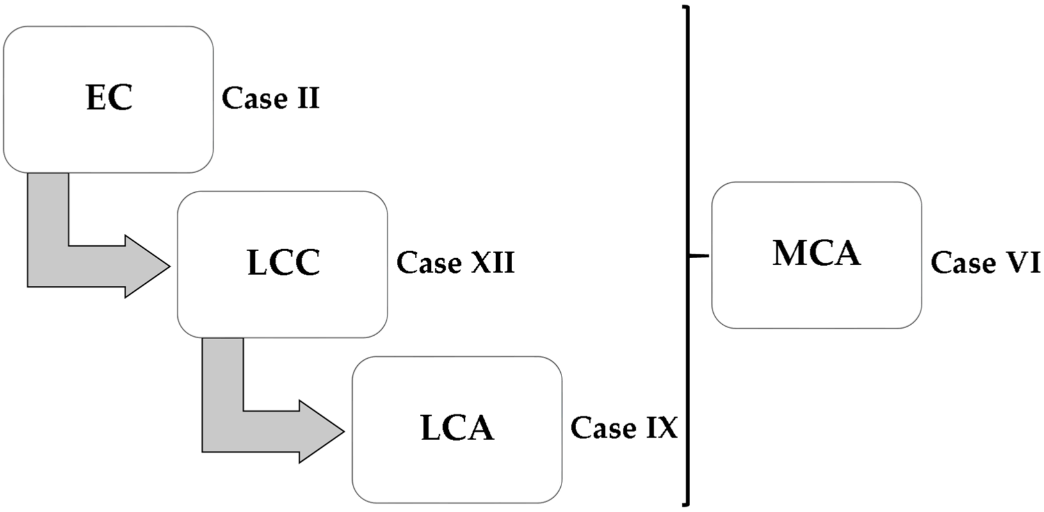

Figure 6. A diagram showing the best alternative in each evaluation method.

6. Conclusions

The energy demanded by a residential building can be calculated using software, and the result shows higher demands than raw data from real-time. This need influences the solar thermal installation proposal for every case. Converting conventional gas boiler installations into ST systems may contribute to significant savings. However, this research also emphasizes that not dealing with the opportunities (wood pellets, boilers, or heat pumps) can offer considerable savings that are not handled. Wood-fired cases (XII, VIII, VI, X) resulted as the most interesting options only considering the economic aspects with a positive NPV oscillating among 54,261.96 and 61,262.56 EUR. All cases proved to be a good opportunity from an economic standpoint. This means it is feasible to convert gas boilers into ST systems. The cost analysis is proposed for assessing various options dealing with all the present expenditures and future earnings expressed in financial units at present (adopting the discount rate, r). This cost analysis reports the strongest opportunity, as with the highest savings for the installation lifespan.

We propose a method to determine which alternative is more workable, bearing in mind auxiliary heating sources. The different energy contribution is considered in specific software. By dealing with future expenses and savings for the lifespan of the machinery, the best alternative among the options in a real family house is calculated

We associate the greatest annual operating costs by preparing heat for heating and DHW. This study [46] points out interesting information resulting from a comparison of heating systems and heat sources over 15 years, which correlates with the results of our study. It states that, regarding the total cost of the heating system during the 15-year evaluation period, wood heating is the most helpful, followed by natural gas, pellets, and a heat pump. If user comfort is included in the evaluation, then heating by natural gas is the most suitable choice in terms of price [46]. The disadvantage is that solar energy was not applied to the heat source, which would bring the results of the analysis closer to our results. Regarding the energy requirements of every case, we can assure that every scheme compared achieves the demands, and raw data from real-time present lower values than those simulated (Table 4). Finally, the life cycle analysis highlights the environmental concerns for the entire cradle-to-grave process.

In Slovakia, practitioners consider investment costs in the planning step of a building and technical systems. However, the costs of maintenance, system installation, and operation also describe a certain item in costs. Assessment of the life cycle costs can offer an optimal design and cost-effective heating and DHW system. Current global requirements to carry out a low-carbon environment force us to deal with environmental needs to a greater extent.

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Nomenclature

AP	acidification potential
CDA	Concordance Discordance Analysis
DHW	Domestic hot water
EC	Energy Criteria Analysis
EP	eutrophication potential
EU	European Union
GWP	global warming potential
LCA	Life cycle assessment
LCC	Life Cycle Cost
MCA	Multi-criteria analysis
MCA7	Software for performing MCA
NHW	non-hazard waste
NPV	Net present value
PBP	Pay Back Period
POCP	photochemical ozone creation potential
OneClickLCA	Software for performing LCA
ODP	ozone depletion potential
ST	Solar thermal
T*SOL	Software for ST calculations

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