Research Article

Wojciech Drozd* and Marcin Kowalik

Analysis of renewable energy use in single-family housing

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Abstract: The article presents the most frequently chosen heating systems for single-family houses and utility water heating by investors. The most popular installations based on conventional fuels using renewable energy sources were compared. A technical and cost analysis of the adopted cases was carried out. Finally, the most important conclusions resulting from the analysis were given. The article is mainly intended to encourage the reader - the investor to be to choose pro-ecological solutions based on modern technology that guarantees comfortable use and limited environmental pollution. The authors wanted to achieve the intended goal by presenting available heating systems and performing an in-depth analysis, after which the obtained results would be similar to the real situation.

Keywords: single-family housing, renewable energy

1 Introduction

Economic, economical, ecological systems of obtaining energy used in housing construction should be a duty and a requirement of modern times [1–3]. The current technique gives us the opportunity to combine comfort, safety and economical use with an environmentally friendly approach [4, 5]. The continuous increase in energy demand and shrinking deposits of conventional fuels lead to the discovery of more and more new renewable energy sources.

An important factor influencing the analysis of the use of energy from renewable sources in the construction industry is to investigate for what purpose most of the energy is consumed in the building. Thanks to such a study, you can choose the direction of saving that guarantees the greatest benefits of cheap operation. Nowadays, energy is mainly used up to [6]:

- space heating
- DHW heating
- lighting
- electrical devices
- cooking

It is obvious that different types of buildings and facilities have different needs, resulting primarily from differences related to the nature of use. Other energy needs have residential buildings, and other public buildings, such as schools, hospitals, offices or sports facilities. The conclusion is that a multi-criteria study should be carried out, which will clearly determine the correlation of energy use in a given type of facility, and thus indicate the most favourable development path.

The subject of the analysis in the article is exclusively single-family housing, because one investment entity decides about the investment choices. The study is to help the investor to make decisions most often based on financial options.

The presented energy balance (Figure 1) shows that heat required for space heating and domestic water heating has the largest share in the energy demand. It accounts for about 80 - 90% of total consumption, and thus it is a source of potential energy savings in the building operation process and thus is the main direction of technical and cost analysis in the article.

The method of space heating used, as well as insulation of walls, ceilings or roofs is very important, however,
the article sets the best solution for heat distribution and thermal insulation that guarantees the lowest heat transfer coefficient. Thus, the heat source, the energy carrier used in it and the price of assembly and operation were analyzed.

Nowadays, the biggest dilemma for the investor, in this case for the building owner, is the use of systems using a renewable energy source (RES). Among people there is a lot of interest in such a solution, but still the question of the profitability of purchase and operation raises doubts. Every buyer would like to know what to choose, what to pay attention to, whether the costs of purchase and subsequent use are the cheapest of all solutions. Important issues for buyers are also: the selection of equipment and what to follow during the purchase and assembly, so that the entire heating system meets the required demand at a minimum cost.

2 Description of the most commonly used heating systems

Nowadays, many different heating systems for buildings i.e. central heating (CH) and domestic water heating (DHW) are installed. Generally, the conventional energy sources are used, however, they are partially or even completely becoming substituted via alternative sources. With such a large variety of systems, the analysis would be very difficult and the achieved goal would be less clear. Therefore, the article compared the most popular systems, i.e. the use of hard coal and natural gas from traditional sources, and solar installations and the use of renewable biomass from Oji. Popularity in the use of selected systems has been confirmed in a survey conducted among 60 respondents using various energy carriers. Its results were used in the article. The preliminary objective of the survey was to obtain a percentage share of energy carriers in the central heating and domestic water heating. Each respondent could indicate only one main carrier with one use. In the case of heating water, he was to indicate the medium that is used in the summer months [7].

The diagram shown in Figure 2 presents that conventional sources dominate over renewable ones. As much as 51% of respondents indicated hard coal as the basic fuel. Only every fifth respondent in his building uses RES.

Figure 3 shows that gas-fired heaters indicated 40% and RES by 43% of respondents. In the case of hot water, the share of biomass accounts for 2/3 of the RES result, because many people use coal-fired boilers to burn a specific type of biomass. For heating water in the summer months, biofuels are used in the form of firewood or wood waste instead of coal, because they have lower heat (warm water requires less heat than heating) and does not require much effort in ignition (it is easy to light up wood) adequate humidity, which quickly gives away the heat heated by water).

Figures 2 and 3 show that users more often reach for conventional energy sources such as coal or natural gas. At present, RES is rarely chosen in Poland, and if so - it is based mainly on solar energy and biomass.

3 Energy demand in a single-family house

For the purpose of the analysis, the energy required for space heating and water heating in a building inhabited by a family of 5, located in the third climate zone, for which the design outdoor temperature is \(-20^\circ\text{C}\), was calculated, where:

\[
\text{system C.H.: } Q = \frac{10962.21}{\eta_w} [\text{kWh/year}] \times \frac{39.46}{\eta_{DHW}} [\text{GJ/year}] \quad (1)
\]

\[
\text{system DHW: } Q = \frac{3346}{\eta_w} [\text{kWh/year}] \times \frac{12.05}{\eta_{DHW}} [\text{GJ/year}] \quad (2)
\]
where:
\( \eta_w \) - efficiency of heat generation - the value depends on the adopted source of heat,
\( \eta_{DHW} \) - overall efficiency of the hot water preparation system - the value depends on the adopted system.

4 Technical and cost analysis of selected solutions

Two solutions from four energy sources (coal boilers, gas furnaces, biomass boilers, and solar collectors) used in central heating systems were selected for the analysis, as well as the heat supply unit. Then the total cost was determined for them and the payback period was indicated.

As the total cost (Kc) it is understood:

- the initial cost (Kp):
  - the purchase cost of equipment (Kz),
  - the assembly costs (Km),
  - the start-up cost (Kr).

- the annual costs of use (Ku):
  - the cost of the energy carrier (Kn) used,
  - the cost of electricity consumed by devices (Ke),
  - any additional costs related to operation (Kd).

4.1 Coal boilers

Variant I concerns the purchase of a cheap popular boiler with lower combustion, in which the basic fuel is hard coal, sorted, nut type. Boilers of this type are equipped with a controller and a blower fan, therefore they have greater stability of work, saving and efficiency in use.

Characteristic
- Nominal power: 12 [kW]
- Fuel: hard coal
- Efficiency: 80%
- Power consumption: 40 [W]
- Average fuel consumption: 1.1 [kg/h]
- Warranty: 4 years
- Boiler price: 879 [EUR]

The price of fuel depends largely on the location. The coal recommended in this boiler (Walnut II) is sold by the mine at a price of about 160.5 [EURO], while with handling costs and transport to the customer at a price of 176.5 [EUR/t] for coal with a calorific value of 28 [MJ/kg] [8].

Variant II was based on the purchase of a more modern boiler equipped with a retort burner enabling more efficient combustion of coal fuel. The furnace is equipped with a control, a blower fan, and a fuel feeder enabling a longer, maintenance-free work. The recommended type of fuel is hard coal (pea type).

Characteristic
- Nominal power: 14 [kW]
- Fuel: hard coal
- Efficiency: 85%
- Power consumption: 180 [W]
- Average fuel consumption: 1.0 [kg/h]
- Warranty: 5 years
- Boiler price: 1965 [EUR]

In the selected combustion boiler, low granulation coal is recommended, which results from the used burner and fuel feeder. The price of coal burned in such a boiler with its calorific value 27 [MJ/kg] [8] is about 167.5 [EUR/t].

In the given solutions, it will be necessary to purchase a heat exchanger that will accumulate hot usable water heated by a coal-fired boiler. The exchanger should have a capacity of 150% of the daily requirement, i.e. in this case 250 - 300 [dm³].

Calculations [9]:

| Initial cost:         | Variant I | Variant II |
|-----------------------|-----------|------------|
| Boiler purchase [EUR] | 879       | 1965       |
| Purchase of heat exchangers heat [EUR] (2x140l-695 EUR/unit) | 323 | 323 |
| Boiler installation [EUR] | 116 | 174 |
| Installation of the exchanger [EUR] | 46.5 | 46.5 |
| Initial start [EUR] | 11.5      | 23         |
| **Total Kp [EUR]**   | **1376.5**| **2531.5** |

The demand for thermal energy [GJ/year] is the sum of individual energies in central heating and domestic water heating divided by appropriate heat sources efficiency:

For variant I:

\[
\frac{39.46}{\eta_w} [\text{GJ/year}] + \frac{12.05}{\eta_{DHW}} [\text{GJ/year}] = \frac{39.46 + 12.05}{80\%} [\text{GJ/year}] = 64.39 [\text{GJ/year}]
\]

For variant II:

\[
\frac{39.46}{\eta_w} [\text{GJ/year}] + \frac{12.05}{\eta_{DHW}} [\text{GJ/year}] = \frac{39.46 + 12.05}{85\%} [\text{GJ/year}] = 60.60 [\text{GJ/year}]
\]
where:
\( \eta_w \) - efficiency of heat generation - the value depends on the adopted source of heat,
\( \eta_{DHW} \) - overall efficiency of the hot water preparation system - the value depends on the adopted system.

With the demand for electric energy used for the operation of fans, feeders and controllers, it was assumed that they work \( \frac{2}{3} \) of the total boiler operation time, i.e. \( \frac{2}{3} \) of 5100 h (of which 5100 h is the average number of hours in the heating period).

For variant I:
\[
40W \times \frac{2}{3} \times 5100h = 136000Wh = 136[kWh]
\] (5)

For variant II:
\[
180W \times \frac{2}{3} \times 5100h = 612000Wh = 612[kWh]
\] (6)

### Usage costs:

|                          | Variant I | Variant II |
|--------------------------|-----------|------------|
| Required fuel quantity   | \( \frac{64.39}{28L} \) | \( \frac{60.60}{27L} \) |
| [t/year]                 | 2.30      | 2.24       |
| The unit price of coal   | 176.5     | 167.5      |
| [EUR/t]                  |           |            |

Total \( Kn \): 406 EUR 375 EUR

### Demand for electricity

|                          | Variant I | Variant II |
|--------------------------|-----------|------------|
| Electric power consumption| \( \frac{64.39}{28L} \) | \( \frac{60.60}{27L} \) |
| [kWh/year]               | 2.30      | 2.24       |
| Unit price [EUR/kWh]     | 0.13      | 0.13       |

Total \( Ke \): 17.5 EUR 80 EUR

### Additional costs related to operation

Cleaning agent for soot boiler (3kg of measure for 1t of coal, 1kg)

\[ 19 EUR \quad 18.5 EUR \]

The sum of annual costs of use: \( Ku = Kn + Ke + Kd \)

For variant I:
\[
Ku = 406EUR + 7.5EUR + 19EUR = 442.5EUR
\] (7)

For variant II:
\[
Ku = 375EUR + 80EUR + 18.5EUR = 473.5EUR
\] (8)

Total cost: \( Kc = Kp + Ku \times t \), (9)

Where:
\( Kc \) – the total cost,
\( Kp \) – the initial cost,
\( Ku \) – the costs of use,
\( Kn \) – the cost of the energy carrier used,
\( Ke \) – the cost of electricity consumed by devices,
\( Kd \) – any additional costs related to operation.

\( t \) – time of use given in years, assuming a service life of 20 years:

For variant I:
\[
Kc = 1376.5[EUR] + 442.5[EUR/year] \times 20[years]
\] = 10226.5[EUR]

For variant II:
\[
Kc = 2532.5[EUR] + 473.5[EUR/year] \times 20[years]
\] = 12002.5[EUR]

The obtained results indicate that it is more advantageous to install a cheaper coal boiler, which does not require a large amount of electricity for its work. A modern burner, thanks to which the boiler achieves higher efficiency, requires a fuel feeder with additional equipment, which consumes several times more electricity than a traditional solution, based on manual refuelling. Please note that the analysis did not take into account the work and comfort of the owner and all other factors other than economic.

### 4.2 Gas boilers

Variant I concerns the purchase of a conventional dual-function gas boiler, with a closed combustion chamber, with the following parameters [10]:

- Power for central heating: 8.9-24 [kW]
- Power for heat (DHW): 24 [kW]
- Maximum efficiency: 91%
- Electric power consumption: 130 [W]
- Fuel type: natural gas type E / Lw / Ls / propane
- Average fuel consumption: E2.77 / Lw3.38 / Ls3.85 [m³/h]
- Warranty: 5 year
- Price of the boiler: 1003.5 [EUR]

Variant II concerns the purchase of a condensing gas boiler with an integrated storage heater. Parameters of the boiler:

- Power for central heating: 6.6-24 [kW]
- Power for heat (DHW): 29.7 [kW]
- Maximum efficiency: 109%
- Electric power consumption: 110 [W]
- Fuel type: natural gas type E / Lw / Ls / LPG
- Warranty: 5 years
- Price of the boiler: 2734 [EUR]
In both cases, the recommended type of fuel is high-methane natural gas (type E) with heat combustion 39.5 [MJ/m$^3$] and a calorific value 34.5 [MJ/m$^3$].

Otherwise, the investor should purchase a conversion kit (about 70 EUR), and the boiler itself should be adjusted by the service.

Calculations \[10\]:

| Initial cost: | Variant I | Variant II |
|---------------|-----------|------------|
| Boiler purchase [EUR] | 1003.5 | 2734 |
| Installation [EUR] | 139.5 | 139.5 |
| Initial start [EUR] | - | - |
| **Total Kp [EUR]** | 1143 | 2873.5 |

The demand for thermal energy [GJ/year] is the sum of individual energies in central heating and domestic water heating divided by appropriate heat sources efficiency:

For variant I:
\[
\frac{39.46}{\eta_w} [\text{GJ/year}] + \frac{12.05}{\eta_{DHW}} [\text{GJ/year}] = 39.46 + \frac{12.05}{\eta_{DHW}} [\text{GJ/year}] = 56.60 [\text{GJ/year}]
\]

For variant II:
\[
\frac{39.46}{\eta_w} [\text{GJ/year}] + \frac{12.05}{\eta_{DHW}} [\text{GJ/year}] = 39.46 + \frac{12.05}{\eta_{DHW}} [\text{GJ/year}] = 47.26 [\text{GJ/year}]
\]

where:
\(\eta_w\) - efficiency of heat generation - the value depends on the adopted source of heat,
\(\eta_{DHW}\) - overall efficiency of the hot water preparation system - the value depends on the adopted system.

The demand for electricity used for the correct operation of boilers was assumed in the same way as in the case of coal boilers. The exact momentary power consumption values are not taken into account, as this is not the subject of analysis.

For variant I:
\[
130W \times \frac{2}{3} \times 5100h = 442000Wh = 442[kWh]
\]

For variant II:
\[
110W \times \frac{2}{3} \times 5100h = 374000Wh = 374[kWh]
\]

Usage costs:

| Usage costs: | Variant I | Variant II |
|--------------|-----------|------------|
| Required fuel quantity [m$^3$/year] | 56.60 | 47.26 |
| Unit price of gas [EUR/m$^3$] | 0.57 | 0.57 |

The obtained results indicate that a more favourable solution is to install a modern condensing boiler with very high efficiency of work, and thus lower consumption of natural gas, that is - lower costs. In this case, the investment in a new technology turns out to be profitable despite more than twice higher initial costs.
5 Calculation of the simple payback period (SPBP)

\[ SPBP = \frac{\Delta K_p}{\Delta K_u} - \text{the ratio of the difference between the initial costs and the difference in the cost of use} \]

\[ \Delta K_p = \Delta Kp(B) - \Delta Kp(A) = 2873.5 \text{[EUR]} \quad (21) \]

\[ \Delta K_p = \Delta Kp(B) - \Delta Kp(A) = 1730.5 \text{EUR} \]

\[ \Delta K_u = \Delta Ku(A) - \Delta Ku(B) = 152 \text{EUR/year} \quad (22) \]

\[ SPBP = \frac{1730.5 \text{ EUR}}{152 \text{ EUR/year}} = 11.38 \text{ years} \quad (23) \]

A simple payback period shows that it takes a little over 11 years of trouble-free operation to make an investment in a dual-purpose condensing gas boiler to pay back. Comparing gas and coal boilers you can see that the costs of use are much higher for gas combustion, and the analysis of the 20-year period shows that this system is 80% more expensive. Despite of this, heating installations based on this type of fuel are very popular.

5.1 Biomass boilers

Variant I enables to calculate the purchase of a gasifying boiler with a structure allowing for burning briquette, firewood and waste from it. It is now a very popular solution, because most of boilers offered have the option of burning also coal. The calorific value of the fuel that has been accepted for the calculation is 15 [MJ/kg]. This is the value corresponding to beech wood with a humidity of 15%. The price of beech wood is about 46.5 [EUR/m³], which with its density of 600 [kg/m³] gives about 76.5 [EUR/t] [11].

Parameters of the boiler:

- Nominal power 14 [kW]
- Maximum efficiency: 80%
- Electric power consumption: 40 [W]
- Fuel type: wood/briquettes/wood chips/wood
- Warranty: 7 years
- Price of the boiler: 1000 [EUR]

Variant II applies to the installation of a boiler equipped with a modern burner, controller and feeder. The unit is fully automated, ensuring minimal losses with maximum safety and comfort of use. It is a solution for burning pellets and oats, which are automatically fed to the boiler from the tank. The tank itself, depending on the boiler load, is topped up with fuel every 3 to 14 days, which ensures larger comfort of use. The calorific value of the pellet is approximately 19 [MJ/kg]. It is delivered throughout Poland at a price of around 186 [EUR/t]. The oat calorific value is 17 [MJ/kg], and its price with the supply is 158 [EUR/t]. Equal amounts of both fuels are fed, 50/50, therefore the average calorific value is 18 [MJ/kg] and the average price of 172 [EUR/t] was adopted [11].

Parameters of the boiler:

- Nominal power 14 [kW]
- Fuel: pellets / pellets-oats in a 50/50 ratio
- Efficiency: 92.8%
- Momentary power consumption during firing up: 400 [W]
- Warranty: 7 years
- Price of the boiler: 1965 [EUR]

In the given solutions, similarly to coal-fired boilers, it will be necessary to purchase a heat exchanger that will accumulate hot utility water heated by a coal-fired boiler. The capacity of the tanks is selected similarly, i.e. 2x140l.

| Initial cost:     | Variant I | Variant II |
|-------------------|-----------|------------|
| Boiler purchase [EUR] | 1000      | 1965       |
| Purchase of heat exchangers heat [EUR] | 323       | 323        |
| Boiler installation [EUR] | 116       | 174        |
| Installation of the exchanger [EUR] | 46.5       | 46.5       |
| Initial start [EUR] | 11.5       | 23         |
| **Total Kp [EUR]** | **1497**  | **2531.5** |

Demand for heat energy [GJ/year], calculated in the same way as for coal and gas boilers:

For variant I:

\[ \frac{39.46}{\eta_w} [\text{GJ/year}] + \frac{12.05}{\eta_{DHW}} [\text{GJ/year}] \]

\[ = \frac{39.46 + 12.05}{80\%} [\text{GJ/year}] = 64.39 [\text{GJ/year}] \quad (24) \]

For variant II:

\[ \frac{39.46}{\eta_w} [\text{GJ/year}] + \frac{12.05}{\eta_{DHW}^{[c]}} [\text{GJ/year}] \]

\[ = \frac{39.46 + 12.05}{92.8\%} [\text{GJ/year}] = 55.51 [\text{GJ/year}] \quad (25) \]

where:

\( \eta_w \) - efficiency of heat generation - the value depends on the adopted source of heat,

\( \eta_{DHW} \) - overall efficiency of the hot water preparation system - the value depends on the adopted system.

The demand for electricity consumed for boiler operation in option I was calculated in accordance with previous
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For variant I:
\[ 40W \times \frac{2}{3} \times 5100h = 136000Wh = 136[kWh] \]  \hspace{1cm} (26)

For variant II:
\[ 3.6[GJ] - 1000[kWh] \rightarrow 55.51[GJ] \]  \hspace{1cm} (27)
\[ = 15419.44[kWh] \]

\[ 1[kWh] - 0.005[kWh_e] \]  \hspace{1cm} (28)
\[ \rightarrow 15419.44[kWh]77.10[kWh] \]

### Usage costs:

|                     | Variant I | Variant II |
|---------------------|-----------|------------|
| Required fuel quantity [t/year] | $\frac{64.39}{15}[\frac{t}{h}]$ | $\frac{55.51}{18}[\frac{t}{h}]$ |
| The unit price of gas [EUR/t] | 77 | 172 |

**Total Kn:**

- **Variant I:** 330 EUR
- **Variant II:** 530 EUR

**Demand for electricity [kWh/year]:**

- **Variant I:** 136 kWh/year
- **Variant II:** 77.10 kWh/year

**Unit price [EUR/kWh]:**

- **Variant I:** 0.13 EUR/kWh
- **Variant II:** 0.13 EUR/kWh

**Total Ke:**

- **Variant I:** 17.5 EUR
- **Variant II:** 10 EUR

**Additional costs related to operation**

| Boiler cleaning agent (3 kg of agent for 1 t of fuel, 1 kg = 2.8 EUR) | 36 EUR | 26 EUR |

The sum of annual costs of use: \( Ku = Kn + Ke + Kd \)

**For variant I:**
\[ Ku = 330EUR + 17.5EUR + 36EUR = 383.5EUR \] \hspace{1cm} (29)

**For variant II:**
\[ Ku = 530EUR + 10EUR + 26EUR = 566EUR \] \hspace{1cm} (30)

**Total cost:**
\[ Kc = Kp + Ku * t, \] \hspace{1cm} (31)

Where:
- **Kc** – the total cost,
- **Kp** – the initial cost,
- **Ku** – the costs of use,
- **Kn** – the cost of the energy carrier used,
- **Ke** – the cost of electricity consumed by devices,
- **Kd** – any additional costs related to operation.

\( t \) – time of use given in years, assuming a service life of 20 years:

**For variant I:**
\[ Kc = 1497[EUR] + 383.5[EUR/year] * 20[years] \]
\[ = 9167[EUR] \]

**For variant II:**
\[ Kc = 2531.5[EUR] + 566[EUR/year] * 20[years] \]
\[ = 13851.5[EUR] \]

The results obtained show the unprofitability of investments in the new technology. Variant II with a pellet boiler proves to be too expensive at the moment, and later operating costs lead to higher expenses than with a wood-fired boiler. This is due to the low availability on the fuel market. You can easily buy firewood, and it is much harder to refine your fuel. The only savings result from the consumption of electricity, which in option II is two times smaller. In this case, there is no question of counting a simple payback period, because \( Kp \) and \( Ku \) pellet boilers cost much higher, so the initial investment will not be refunded. Comparing with coal boilers, which are very similar to biomass boilers, the obtained results are similar, but it is not difficult to notice that in both cases modern means are more expensive. The cheapest solution turns out to be a gasification boiler for fuel, in which you can burn many types of fuel as well. Apart from its price, this is the main argument supporting its purchase.

### 5.2 Solar collectors

Variant I shows the purchase of flat, liquid solar collectors for the preparation of hot utility water, mainly in the summer months. It meets 99% of the demand for hot water. The profitability of this solution will apply to the period of time after which the investment costs will be reimbursed.

The summary will include the costs of a bivalent solar tank with two 300-liter coils. The main advantage of such a tank is the ability to heat water from two heat sources - solar collectors and an alternative source [12]. In addition to the collectors and the solar tank, it is necessary to purchase a pumping unit and a solar regulator. These are devices that ensure safe and economical use. Currently, many types of solar regulators are produced, differing primarily with functions that help protect the solar installation from damage, while ensuring maximum thermal efficiency. Manufacturers have prepared solar sets for customers, depending on the number of household members and destination. These are more advantageous offers, because buy-
ing in one place saves time and money, and above all guarantees full cooperation of devices with each other. In this case, the customer is sure that the purchased installation will work in the right way.

The article includes a ready set containing [13]:

- 2 flat-plate solar collectors with a total aperture area of 3.74 m²,
- bivalent tank with a capacity of 300 l,
- solar controller,
- solar pump group with solar fluid,
- an expansion tank with a capacity of 18 l,
- additional mounting elements - nipples, couplings, handles and end caps.

Parameters of collectors:

- Gross area of one collector: 2.04 m²
- Absorber area: 1.88 m²
- Collector absorption: 95%
- Collector efficiency: 75.6%
- Coefficient of heat loss a₁: 3.545 W / (m²/K)
- Maximum power: 1414 W
- Lifetime: 25 years
- Warranty: 10 years
- The purchase price of one collector: 310 EUR
- Price of the solar set adopted: EUR 1759.5

Variant II includes the purchase of a solar set intended for the preparation of utility water for 3 - 5 people and support for the installation of central heating in a single-family house, with an area up to about 100 m². The set is based on the use of vacuum collectors with a total aperture area of 5.43 m² and a heater with a "tank in a tank" design, equipped with a double coil.

The adopted set includes:

- 3 liquid vacuum collectors,
- dual purpose tank with a capacity of 120/380 l,
- a set for connecting collectors,
- solar controller,
- solar pump group with solar fluid,
- an expansion tank with a capacity of 50 l,
- additional mounting elements - nipples, connectors
- and handles and end caps.

Parameters of collectors:

- Gross area of one collector: 2.04 m²
- Working area: 1.805 m²
- Collector absorption: 95%
- Collector efficiency: 61.1%
- Heat loss coefficient a₁: 0.84 W / (m²/K)
- Heat loss coefficient a₂: 0.0053 W / (m²/K)
- Maximum power: 1106 W
- Lifetime: 25 years
- Warranty: 10 years
- The purchase price of one collector: 534 EUR
- Price of the adopted solar set: 3125 EUR

In both cases, it is additionally necessary to purchase a collector mounting frame for the roof slope. The price for flat and vacuum collectors varies and amounts to EUR 46 to 50 per holder for one collector.

| Initial cost:                  | Variant I | Variant II |
|-------------------------------|-----------|------------|
| Price of the set [EUR]        | 1759.5    | 3125       |
| Purchase of mounting brackets [EUR] | 92       | 150.5      |
| Collector installation [EUR]   | 349       | 372        |
| Initial start [EUR]           | 23        | 23         |
| Total Kp [EUR]                | 2223.5    | 3670.5     |

In the case of solar collectors, the savings from installed collectors and the payback period were calculated. As the costs of using solar collectors, the cost of electricity required for the operation of the solar pump and controller as well as service costs to be incurred in order to maintain the efficiency of the installation were assumed. In both variants an identical power consumption of 50W was introduced. It was assumed that the pump with a regulator works 8 hours a day, which gives: 50W * 365 days * 8h = 146 kWh

Accepted price for 1 kWh is EUR 0.13, so the cost of use for both variants is: EUR 19.

The price for cleaning, maintenance and other service work is EUR 69.5 per solar kit. These activities are carried out once every 3 years.

An important issue is the efficiency of collectors. The efficiency reported by manufacturers is the maximum value that needs to be adjusted depending on the temperature difference between the environment and the absorber.

![Figure 4: Efficiency of solar collectors [14].](image-url)
Table 1: Final results of collector efficiency.

| Month     | Ambient temperature [∘C] | Temperature difference [K] | Flat collector efficiency [%] | Efficiency of the vacuum collector [%] |
|-----------|---------------------------|----------------------------|-------------------------------|---------------------------------------|
| January   | −5                        | 55                         | 61.2                          | 54.9                                  |
| February  | −2                        | 52                         | 61.8                          | 55.3                                  |
| March     | 0                         | 50                         | 62.1                          | 55.6                                  |
| April     | 10                        | 40                         | 64.1                          | 56.9                                  |
| May       | 23                        | 27                         | 67.3                          | 58.4                                  |
| June      | 28                        | 22                         | 68.6                          | 59.0                                  |
| July      | 30                        | 20                         | 69.2                          | 59.2                                  |
| August    | 30                        | 20                         | 69.2                          | 59.2                                  |
| September | 22                        | 28                         | 67.0                          | 58.3                                  |
| October   | 10                        | 40                         | 64.1                          | 56.9                                  |
| November  | 3                         | 47                         | 62.7                          | 56.0                                  |
| December  | −2                        | 52                         | 61.8                          | 55.3                                  |

Source: Own study.

According to the given formula, the efficiency of collectors in the adopted variants was calculated (Table 1). The average absorber temperature is 50 °C, while the ambient temperature depends on the month as the average temperature at which water is heated. In the example shown $E_g$ is the value of insolation. In the calculations, the $E_g$ value was assumed at 1000 W/m$^2$, as this is the value determined in the standard studies. Coefficients of losses $a_1$, $a_2$ and optical efficiency in accordance with assumed solar collectors.

| Variant I | Variant II |
|-----------|------------|
| $a_1 = 3.545$ W/(m$^2$K) | $a_1 = 0.84$ W/(m$^2$K) |
| $a_2 = 0.017$ W/(m$^2$K) | $a_2 = 0.0053$ W/(m$^2$K) |
| $\eta_0 = 75.6\%$ | $\eta_0 = 61.1\%$ |

where:
- $a_1, a_2$ – heat loss coefficients,
- $\eta_0$ – efficiency of collectors,
- $E_g$ – the value of insolation.

Table 1 indicates the actual efficiency of the collectors in terms of their operation. It may be seen from the results that vacuum collectors do not lose their efficiency level in such a violent way as liquid collectors. Nevertheless, they have lower work efficiency throughout the year. This is caused by too small temperature differences, to which the flat collectors are extremely sensitive.

Heat demand in the heat pump system is:

$$Q_{DHW} = \frac{3346}{\eta_{DHW}} \text{ [kWh/year], (279kWh/month).} \quad (34)$$

Taking into account the efficiencies presented in Table 1, the total thermal energy demand was obtained (Table 2).

The average daily irradiation for Poland is shown in Table 3, respectively.

The next step is to consider meeting the demand for thermal energy by the collectors.

For better readability calculations were carried out separately for each variant.

For variant I:

Multiplying the values of average irradiation by the active surface area of the collectors received the daily energy consumed by the collectors (Table 4).

Assuming that during the day the demand is $\frac{5167 \text{ kWh/year}}{365 \text{ days}} = 14.16 \text{ kWh/day}$ for 5 people using 35 litres of hot water, it can be assumed that from the beginning of May to the end of August that is for 4 months the collectors cover the needed amount. (Table 5) meet set needs in 100%. In the remaining months, the water will not be heated to the required temperature (with the assumed amount), therefore it will be necessary to heat the water by another heat source.

By multiplying the fulfilment values (Table 5) by the monthly demand presented in Table 2, the annual value of thermal energy produced by the collectors used in option I was obtained.

For variant II:

The calculations were carried out in the same way as for variant I. Table 7 presents the values of daily energy consumed by the collectors in the following months.

The daily requirement is: $\frac{5870 \text{ kWh/year}}{105 \text{ days}} = 16.08 \text{ kWh/day}$, which was accepted for further calculations. The degree of meeting the demand in the following months is presented in Table 8.
Table 2: Total heat demand.

| Month   | Flat collector efficiency [%] | Efficiency of the vacuum collector [%] | Heat demand for variant I [kWh/month] | Heat demand for variant II [kWh/month] |
|---------|-------------------------------|----------------------------------------|--------------------------------------|---------------------------------------|
| January | 61.2                          | 54.9                                   | 465                                  | 508                                   |
| February| 61.8                          | 55.3                                   | 452                                  | 505                                   |
| March   | 62.1                          | 55.6                                   | 449                                  | 502                                   |
| April   | 64.1                          | 56.9                                   | 435                                  | 490                                   |
| May     | 67.3                          | 58.4                                   | 415                                  | 477                                   |
| June    | 68.6                          | 59.0                                   | 407                                  | 473                                   |
| July    | 69.2                          | 59.2                                   | 403                                  | 471                                   |
| August  | 69.2                          | 59.2                                   | 403                                  | 471                                   |
| September| 67.0                          | 58.3                                   | 416                                  | 478                                   |
| October | 64.1                          | 56.9                                   | 435                                  | 490                                   |
| November| 62.7                          | 56.0                                   | 445                                  | 498                                   |
| December| 61.8                          | 55.3                                   | 452                                  | 505                                   |

Sum: 5167 5870

Source: Own study.

Table 3: Average daily irradiation [9].

| Month  | Average irradiation [kWh/m²/day] |
|--------|----------------------------------|
| January| 0.71                             |
| February| 1.36                           |
| March  | 2.50                             |
| April  | 3.69                             |
| May    | 4.84                             |
| June   | 5.17                             |
| July   | 4.97                             |
| August | 4.21                             |
| September| 2.87                         |
| October| 1.73                             |
| November| 0.79                          |
| December| 0.52                          |

Source: Own study.

Table 4: Daily energy consumed by collectors in given months (Variant I).

| Month  | Thermal energy [kWh/day] |
|--------|--------------------------|
| January| 2.66                     |
| February| 5.09                    |
| March  | 9.35                     |
| April  | 13.80                    |
| May    | 18.10                    |
| June   | 19.34                    |
| July   | 18.59                    |
| August | 15.75                    |
| September| 10.73                  |
| October| 6.47                     |
| November| 2.95                    |
| December| 1.94                    |

Source: Own study.

Variant II also includes supporting applications for vacuum collectors in the central heating system, therefore, when analysing the results from Table 8, the months in which the rooms are heated should be taken into account.

With the solution applied, only April is the month in which the degree of meeting the demand in the heat pump system exceeds 100% and it is a heating month. In order to include central heating in further calculations for April, the value of 125% was assumed instead of 100%.

By multiplying the fulfilment values (Table 8) by the monthly demand presented in Table 2, the annual value of thermal energy produced by the collectors used in option II was obtained.

Flat collectors obtain 3265 kWh / a thermal energy to heat the water. Vacuum collectors, on the other hand, obtain 4255 kWh / year, of which 123 kWh / a thermal energy is used to heat the rooms. The conclusion from the calculations is that option II delivers very little heating to the rooms, and the high costs are caused by the purchase of a modern tank, which is required for the proper functioning of solar collectors in a dual-task installation (hot and cold). Analysing the offers of producers, the use of the variant based solely on the sole task and the use of the same number and type of collectors reduces the initial costs by EUR 465. This does not mean, however, that it is unprofitable.
Table 5: The degree of fulfillment of the demand (Variant I).

| Month       | Value of fulfillment [%] |
|-------------|--------------------------|
| January     | 19                       |
| February    | 36                       |
| March       | 66                       |
| April       | 97                       |
| May         | 128                      |
| June        | 137                      |
| July        | 131                      |
| August      | 111                      |
| September   | 76                       |
| October     | 46                       |
| November    | 21                       |
| December    | 14                       |

Source: Own study.

To demonstrate the profitability of investments in solar collectors, comparisons with other energy sources should be made. Therefore, the cost of generating 1 kWh of energy by the solutions analysed in the article was calculated. This will allow you to calculate the annual savings from the use of solar collectors:

- **Annual costs of use:**
  - Coal boiler I ("W-I") - 442.5 EUR
  - Coal II boiler ("W-II") - 473.5 EUR
  - Gas boiler I ("G-I") - EUR 1062.5
  - Gas boiler II ("G-II") - 910.5 EUR
  - Biomass I boiler ("B-I") - 383.5 EUR
  - Biomass boiler II ("B-II") - 566 EUR
  - Solar collectors I ("K-I") - 19 EUR
  - Solar collectors II ("K-II") - EUR 19

- The amount of energy produced during the year
  - Coal boiler I ("W-I") - 17866,11 kWh
  - Coal II boiler ("W-II") - 16833,33 kWh
  - Gas boiler I ("G-I") - 15722,22 kWh
  - Gas boiler II ("G-II") - 13127,78 kWh
  - Biomass I boiler ("B-I") - 17866,11 kWh
  - Boiler for biomass II ("B-II") - 15419,44 kWh
  - Solar collectors I ("K-I") - 3265 kWh
  - Solar collectors II ("K-II") - 4255 kWh

- By dividing the annual costs of use by the amount of energy generated during the year, we receive the cost of producing 1 kWh of thermal energy (Figure 5).

- The price of generating 1 kWh of heat energy by the collectors is the lowest and, for example, by EUR 0.063 cheaper than the condensing gas furnace. By multiplying the corresponding cost differences by the amount of energy produced by the solar installation, the annual savings value was obtained (Figure 6).

  **Figure 5:** Production costs of 1 kWh of thermal energy
  Source: Own study.

  **Figure 6:** Annual savings from the use of solar collectors. Source: Own study.

  The simplest way to determine the profitability of collectors leads by indicating the simple payback period of the SPBP, which in this case was calculated by dividing the initial costs of solar collectors by the calculated savings (Figure 6).

  Figure 7 shows the simple period of return on investment in solar collectors. In most cases, this period is longer than the lifetime of collectors, so the investment will never return. The shortest period is given by gas boilers, but it is not a satisfactory result because it is longer than the guarantee time for solar collectors. There is one more issue in all cases, option II, i.e. liquid and vacuum collectors, are a worse cost option. This is due to the too high initial ex-
Table 6: Value of thermal energy obtained by the solar installation (Variant I).

| Month     | Value of fulfillment | Heat demand for variant I [kWh/month] | Heat energy obtained in variant I [kWh/month] |
|-----------|----------------------|----------------------------------------|-----------------------------------------------|
| January   | 19                   | 465                                    | 85                                            |
| February  | 36                   | 452                                    | 162                                           |
| March     | 66                   | 449                                    | 297                                           |
| April     | 97                   | 435                                    | 424                                           |
| May       | 128                  | 415                                    | 415                                           |
| June      | 137                  | 407                                    | 407                                           |
| July      | 131                  | 403                                    | 403                                           |
| August    | 111                  | 403                                    | 403                                           |
| September | 76                   | 416                                    | 316                                           |
| October   | 46                   | 435                                    | 199                                           |
| November  | 21                   | 445                                    | 93                                            |
| December  | 14                   | 452                                    | 62                                            |

Source: Own study.

Table 7: Daily energy consumed by collectors in given months (Variant II).

| Month     | Thermal energy [kWh/day] |
|-----------|--------------------------|
| January   | 3.86                     |
| February  | 7.38                     |
| March     | 13.58                    |
| April     | 20.04                    |
| May       | 26.28                    |
| June      | 28.07                    |
| July      | 26.99                    |
| August    | 22.86                    |
| September | 15.58                    |
| October   | 9.39                     |
| November  | 4.29                     |
| December  | 2.82                     |

Source: Own study.

Table 8: Degree of meeting the demand.

| Month     | Value of fulfillment [%] |
|-----------|--------------------------|
| January   | 24                       |
| February  | 46                       |
| March     | 84                       |
| April     | 125                      |
| May       | 163                      |
| June      | 175                      |
| July      | 168                      |
| August    | 142                      |
| September | 97                       |
| October   | 58                       |
| November  | 27                       |
| December  | 18                       |

Source: Own study.

The survey shows that 51% of respondents would like to have solar panels installed in their own home as the basic source of heat in the heat pump system. However, the factor that affects the low level of renewable energy use is the too expensive purchase of components and their assembly (40% of respondents) and the lack of specific information on solutions, their advantages and disadvantages (30%).

6 Summary

The survey shows that 51% of respondents would like to have solar panels installed in their own home as the basic source of heat in the heat pump system. - a modern and future-proof solution. However, the factor that affects the low level of renewable energy use is the too expensive purchase of components and their assembly (40% of respondents) and the lack of specific information on solutions, their advantages and disadvantages (30%).
Table 9: Value of thermal energy obtained by the solar installation (Variant II)

| Month       | Value of fulfillment [%] | Heat demand for variant II [kWh/month] | Heat energy obtained in variant II [kWh/month] |
|-------------|--------------------------|----------------------------------------|-----------------------------------------------|
| January     | 24                       | 508                                    | 122                                           |
| February    | 46                       | 505                                    | 232                                           |
| March       | 84                       | 502                                    | 424                                           |
| April       | 125                      | 490                                    | 613                                           |
| May         | 163                      | 477                                    | 477                                           |
| June        | 175                      | 473                                    | 473                                           |
| July        | 168                      | 471                                    | 471                                           |
| August      | 142                      | 471                                    | 471                                           |
| September   | 97                       | 478                                    | 464                                           |
| October     | 58                       | 490                                    | 286                                           |
| November    | 27                       | 498                                    | 133                                           |
| December    | 18                       | 505                                    | 89                                            |

**Sum:** 4255

Source: Own study.

The question arises as to which collectors to choose - flat or vacuum. The price of vacuum collectors is currently too high in relation to the benefits that can be achieved. During the analysis it was obtained that only 109 kWh of thermal energy will provide the collectors from variant II as an auxiliary value central heating. It is only 1% of the annual energy demand in the space heating system. Such a low value results from the specifics of the work of solar collectors. Collectors in heating months (October to April) have lower efficiency and the average irradiation value is much lower.

Another aspect of this article is to indicate the cheapest solution that fully meets the heat demand in the central heating system and domestic water heating. It turns out that the biomass boiler (variant I), in which wood fuel is burned, is the most advantageous solution. The total cost for 20 years of use is around EUR 9167, which is more than twice less than gas boiler systems, which is the most expensive solution (around EUR 21083.5). An important issue is also the fact that the purchase of an advanced boiler, which is better equipped (variant number II), leads to higher parameters and greater comfort of use. However, only in the case of gas boilers incurred twice the higher initial costs will be refunded.

The analysis shows that an investment in renewable energy can be profitable. The article presents a simple way of calculation of costs related to the heat source, so that every interested person could perform such a calculation for his own individual case and obtain a reliable result. However, the decision to choose a system is an individual matter and not always related to the cost criterion.

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