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Ecological and financial aspects of gas boiler co-operation with alternative energy sources for multi-family buildings

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Abstract. Due to intensive economic and industrial development in the last decades, resulting in environmental degradation and too fast depletion of natural resources, there is an increasing interest in implementing sustainable development principles, i.e. meeting human needs with environmental considerations. The construction industry is a major consumer of energy in the world, so it is justified to aim at reducing energy consumption, increasing energy efficiency and maximizing the use of waste energy and renewable energy. In the case of residential buildings, one use the most energy for heating of water for utility purposes and for central heating purposes. Not large multi-family residential buildings are characterized by similar parameters of energy needs as single-family buildings, which results primarily from the nature of use. The main difference between single and multi-family buildings is the area per capita. Smaller area reduces energy consumption for room. On the other hand, the higher demand for hot water follow the larger number of inhabitants. As a primary source of heat in urban areas, there are currently used solid fuel boilers, gas boilers or using system heat. Owing to the smog phenomenon, old coal boilers are being modernized to reduce pollutant emissions into the atmosphere. In this publication, the example of hot water installation in a multi-family building shows what effects will be achieved if we use alternative sources such as solar collectors or heat pumps for traditional gas water heating systems. For each of the two variants, the approximate investment outlays and costs associated with the operation of the system in the variant were estimated and the estimated annual emissions from the incineration of natural gas

1. Introduction

The analysis of the effects was performed for a hot water system of a multi-family building located in the city of Rzeszów. The chosen building is a detached multi-family building with four storeys above the ground level and a basement, containing 16 flats, necessary passages and utility rooms. The floor area of the heated rooms is: 1120 m². It is assumed that there are 3 hot water users per each flat. The building is equipped with connections to the water supply system, sewage system, gas supply system and the power grid.

In the building basement there is a boiler room with the floor area of 120 m² and the capacity of 480 m³(belonging to the third group: boiler rooms with the power from 60 to 2000 kW). It is equipped with a central heating boiler (not considered in this study) and a space for a heat source for the central preparation of hot tap water. The main source of hot water is a gas condensing boiler with a closed combustion chamber. It is fuelled with methane-rich natural gas (group E)(gross calorific value $H_s = 40.14 \text{ MJ/m}^3$, net calorific value $H_i = 36.00 \text{ MJ/m}^3$). According to Regulation [1], the system ensures the hot water temperature of 55÷60°C and a periodical thermal disinfection with the water temperature



not lower than 70°C. To maintain the temperature in draw-off points, a circulating system with a flow forced by a circulating pump has been designed. The circulating pipes reach the highest points of the hot tap water system. The system has been designed to be made of copper pipes. An average demand for hot tap water between 6:00 and 00:00 and 4 hot water draw-off points per flat are assumed. The results of the general calculations concerning the hot tap water system in the building are presented in Table 1.

Table 1. List of results of the general calculations concerning the hot tap water system in the building.

Description	Symbol	Numeric value	Unit
Average daily demand	$Q_{d\ sr}$	5.760	m ³ /d
Average hourly demand	$Q_{h\ sr}$	0.320	m ³ /h
Maximum hourly demand	$Q_{h\ max}$	1.160	m ³ /h
Average demand for thermal power	Φ_{sr}	18.481	kW
Maximum demand for thermal power	Φ_{max}	66.975	kW
Average demand for thermal power for system disinfection	$\Phi_{sr\ dez}$	23.960	kW
Maximum demand for thermal power for system disinfection	$\Phi_{max\ dez}$	86.831	kW
Design capacity of hot tap water heater	V_z	724.71	dm ³
Design power of hot tap water heater	Q_z	43.830	kW

On the basis of such guidelines, three variants of the water heating system has been designed:

- variant 1 - the heat source is a gas boiler (initial variant),
- variant 2 - the heat source is a gas boiler cooperating with a solar system,
- variant 3 - the heat source is a gas boiler cooperating with an air-source heat pump.

The diagrams of the suggested systems are presented in figures 1-3.

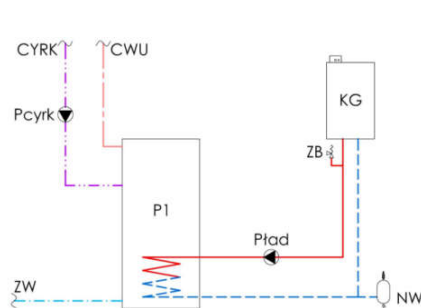


Figure 1. Diagram of Variant 1 of the system: KG – gas boiler, P1 – one-coil feedwater heater, NW – expansion vessel, ZB – safety-valve, P1ad – pump supplying the hot water tank, Pcyrk – hot water circulating pump, CWU – hot water system, CYRK – hot water circulating system, ZW – cold water supply.

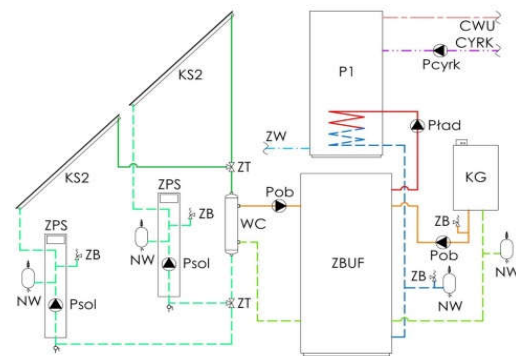


Figure 2. Diagram of Variant 2 of the system: KG – gas boiler, P1 – one-coil feedwater heater, NW – expansion vessel, ZB – safety-valve, P1ad – pump supplying the hot water tank, Pcyrk – hot water circulating pump, CWU – hot water system, CYRK – hot water circulating system, ZW – cold water supply.

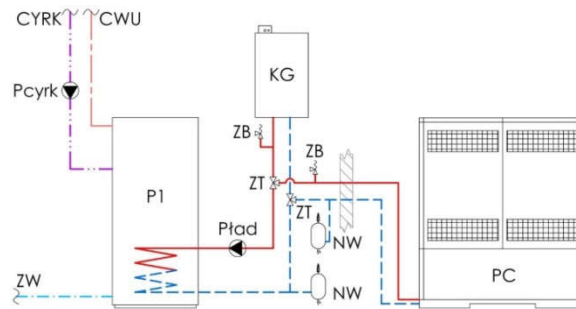


Figure 3. Diagram of Variant 1 of the system: KG – gas boiler, PC – air-water heat pump for external assembly, P1 – one-coil feedwater heater, ZT – three-way diverting valve, NW – expansion vessel, ZB – safety-valve, Plad – pump supplying the hot water tank, Pcyrk – hot water circulating pump, CWU – hot water system, CYRK – hot water circulating system, ZW – cold water supply.

2. Methodology and scope of research

The demand for hot water, fuel consumption, investment and operational costs and emission of pollutants was calculated for each variant.

The calculations and values of coefficients were determined on the basis of the Regulation of the Minister of Infrastructure and Development [1] for a building equipped with simple technical systems. The annual demand for final energy for hot water system purposes is:

$$Q_{a0} = \frac{Q_{W,nd}}{\eta_{W,tot0}} \text{ [kWh/year]}, \quad (1)$$

Q_{a0} – annual demand for final energy for hot water system purposes [kWh/year],

$Q_{W,nd}$ – annual demand for usable energy to prepare hot tap water [kWh/year],

$\eta_{W,tot0}$ – average annual total efficiency of the system [-];

$$Q_{W,nd} = V_{Wi} \cdot A_f \cdot c_W \cdot \rho_W \cdot (\theta_W - \theta_0) \cdot k_R \cdot t_R / 3600 \text{ [kWh/year]}, \quad (2)$$

V_{Wi} – individual daily demand for hot tap water [$\text{dm}^3/(\text{m}^2 \cdot \text{d})$] for a multi-family residential building: $V_{Wi} = 2.00 \text{ dm}^3/(\text{m}^2 \cdot \text{d})$,

A_f – floor area of rooms with the adjusted temperature [m^2], $A_f = 1120 \text{ m}^2$,

c_W – specific heat of water [$\text{J}/(\text{kg} \cdot ^\circ\text{C})$], $c_W = 4.19 \text{ J}/(\text{kg} \cdot ^\circ\text{C})$,

ρ_W – thickness of water [kg/dm^3], $\rho_W = 1.00 \text{ kg}/\text{dm}^3$,

θ_W – design temperature of hot tap water in the draw-off valve [$^\circ\text{C}$], $\theta_W = 55^\circ\text{C}$,

θ_0 – design temperature of water before being heated [$^\circ\text{C}$], $\theta_0 = 10^\circ\text{C}$,

k_R – correction coefficient due to breaks in using hot tap water [-]

for a multi-family residential building: $k_R = 0.90$,

t_R – number of days in the year [d], $t_R = 365 \text{ d}$;

2.1. Annual demand for auxiliary energy

Annual demand for auxiliary energy:

$$E_{el,pom} = \sum_j q_{el,j} \cdot t_{el,j} \cdot A_f \cdot 10^{-3} \text{ [kWh/year]}, \quad (3)$$

$E_{el,pom}$ – annual demand for auxiliary energy [kWh/year],

$q_{el,j}$ – demand for electric power to operate the j-th auxiliary device
 in the system of preparing hot tap water [W/m²],

$t_{el,j}$ – operation time of the j-th auxiliary device in the year [h/year];

Calculation of the annual demand for and costs of gas fuel:

$$B_{g0} = \frac{Q_{kg0}}{\eta_g \cdot H_i} \text{ [m}^3\text{/year]}, \quad (4)$$

B_{g0} – annual demand for gas fuel for Variant 1 [m³/year],

Q_{kg0} – annual gas boiler's met demand for final energy
 [MJ/year], $Q_{kg0} = Q_{a0}$,

η_g – efficiency of the boiler room [-], $\eta_g = \eta_{w,g} = 0.88$ was assumed,

H_i – net calorific value of gas [MJ/m³], $H_i = 36.0$ MJ/m³;

2.2. Fees for heat from the gas grid:

$$K_{g\text{ netto}} = O_{g1} + O_{g2} + O_{g3} + O_{g4} \text{ [PLN/year]}, \quad (5)$$

$K_{g\text{ netto}}$ – annual cost of gas heating excluding VAT [PLN/year],

O_{g1} – fee for gas fuel [PLN/year],

O_{g2} – variable fee for transmission services [PLN/year],

O_{g3} – constant fee for transmission services [PLN/year],

O_{g4} – service charge [PLN/year].

Taking into account gas consumption also for heating purposes, the examined case was categorized as the W-4 rate group. A gas fuel price and service charge were fixed on the basis of PGNiG rates [13], transmission fees - on the basis of PSG rates for the Tarnów Branch [15]. Gross Calorific Value Settlement Area for the city of Rzeszów: ORCS040077, conversion coefficient for May 2017 = 11.149 kWh/m³.

2.3. Fees for electric energy

The annual cost of electric energy is calculated as the following relationship:

$$K_{el\text{ brutto}} = E_{el} \cdot C_{el} \text{ [PLN/year]}, \quad (6)$$

where:

$K_{el\text{ brutto}}$ – annual cost of electric energy including VAT [PLN/year],

E_{el} – annual aggregated demand for electric energy [kWh/year],

C_{el} – price for electric energy for a particular rate group consumer [PLN/kWh];

Pursuant to [10] in the Rzeszów Area, for the PGE “Comfort” (G11) rates in which the electric energy rate is the same for each part of the day and night [14] after including the costs of purchase, VAT, excise, local fees and taxes, margin and the costs of the distribution and transmission companies, it was assumed that $C_{el} = 0.57$ PLN/kWh.

The capital outlay was stated separately for each variant.

2.4. Annual costs of hot water system operation

The annual cost of system operation is calculated as the following relationship:

$$K_{brutto} = K_g\text{ brutto} + K_{el\text{ brutto}} + K_{serwis} \text{ [PLN/year]}, \quad (7)$$

where:

K_{brutto} – annual cost of system operation including VAT [PLN/year],

K_{serwis} – annual cost of maintaining the system devices [PLN/year];

- Variant 1 - Gas boiler as the heat source

The heat source is a condensing boiler with the power rating of 100kW and the minimum thermal power of 12.2 kW. A free-standing one-coil hot water exchanger with the capacity of 1000dm³ was selected. Annual demand for final energy for the hot water system purposes:

The capital outlay on Variant 1 (INV_0) includes: gas condensing boiler, one-coil exchanger, auxiliary devices.

The maintenance costs of Variant 1 include: inspection, cleaning, control.

- Variant 2 - The heat source as a gas boiler cooperating with a solar system

The heat source is a gas boiler (as in Variant 1). Additionally, a simplified selection of heat exchanger was made and a buffer tank of 20 dm³ with the boiler's maximum thermal power of 1 kW was fixed [9]. The collectors were selected to totally meet the demand in June [16]. 19 flat solar collectors were chosen, with the aperture area of one collector to be: 2.36 m² and the optical efficiency of: 82.7%. They are directed northwards with the inclination of 45° [5].

The annual percentage distribution of the demand of the gas boiler and solar collectors for final energy for hot water system purposes in Variant 2 is described in figure 4.

The capital outlay on Variant 2 (INV_2) includes: gas condensing boiler, 19 collectors, one-coil exchanger, two pump control units, system of fixing collectors at the angle of 45° on a flat roof, heat exchanger, buffer tank, auxiliary devices.

The maintenance costs of Variant 2 include: inspection, cleaning, control and analysis of fumes of the gas boiler, inspection of the collectors and the glycol solar system, maintenance of the heater and the buffer tank, cleaning and maintenance of the heat exchanger, maintenance of the auxiliary devices [2,3]. The costs of gas fuel and electric energy were calculated similarly to Variant 1. The results are listed in Table 2.

- Variant 3 - The heat source as a gas boiler cooperating with an air-source heat pump.

The cooperation of the boiler with the one-coil heater as in Variant 1 and with a heat pump in the bivalent alternative system was assumed for Variant 3. According to the design materials of Viessman [8], the required temperature of hot tap water above 55°C may be achieved only when the heat pump's feeding temperature is 65°C (without the operation of any additional heaters, e.g. electrical heater in the tank). It is, however, connected with low values of COP of the pump. This study does not include the application of a smaller pump, additional heating using an electrical heater or cascade systems of several pumps; one device having the possibility to fully meet the demand for power for hot water system purposes has been chosen [4]. An air/water heat pump for external assembly has been selected. The capital outlay on Variant 3 includes: gas condensing boiler, heat pump, one-coil exchanger, auxiliary devices.

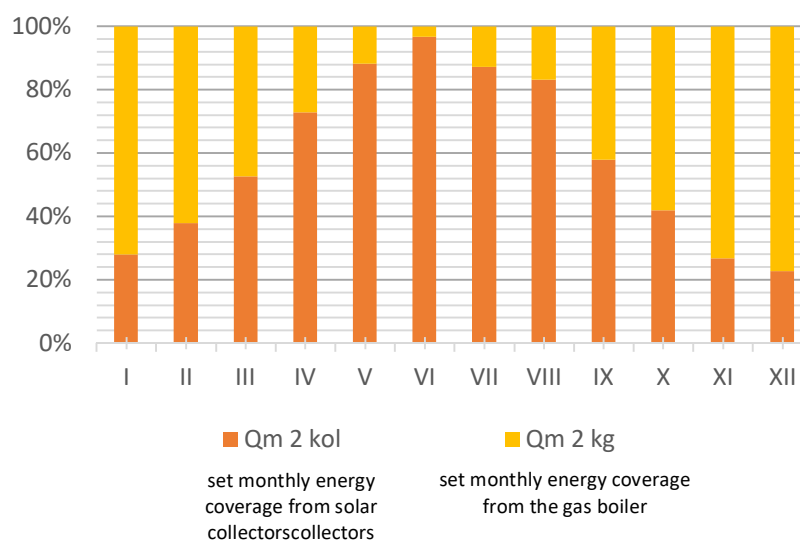


Figure 4. Annual percentage distribution of the demand of the gas boiler and solar collectors for final energy for hot water system purposes in Variant 2.

The maintenance costs of Variant 3 include: inspection, cleaning, control, maintenance of the heat pump with R417A coolant and maintenance of the heater (Table 2).

3. Analysis of assumed systems' performance effects

The list of results for all 3 variants (calculated on the basis of 1-7) is presented in Table 2.

Table 2. List of calculation results for all the variants.

Description	Symbol	Variant 1	Variant 2	Variant 3	Unit
Annual demand for final energy for hot water system purposes	Q_a	73,605.08	73,605.08	48,528.40	kWh/year
Average daily demand for final energy for hot water system purposes	Q_d	201.66	201.66	132.95	kWh/d

Average annual total efficiency of the system	$\eta_{W,tot}$	0.524	0.524	1.051	-
Annual demand for gas fuel	B_g	8,364.21	3,511.57	4,056.64	m ³ /year
Annual cost of gas heating including VAT	$K_{g\ brutto}$	17,573.46	9,177.39	10,120.48	PLN/year
Annual demand for auxiliary energy	$E_{el,pom}$	621.15	1,881.31	621.15	kWh/year
Annual demand for electric energy powering the heat source, which is not auxiliary energy	$E_{el,\acute{z}c}$	0	0	12,829.93	kWh/year
Annual aggregate demand for electric energy	E_{el}	621.15	1,881.31	13,451.08	kWh/year
Annual cost of electric energy including VAT	$K_{el\ brutto}$	354.06	1,072.35	7,667.12	PLN/year
Annual cost of maintaining the system devices	K_{serwis}	700.00	2,250.00	2,200.00	PLN/year
Annual cost of system operation including VAT	K_{brutto}	18,627.52	12,499.74	19,987.60	PLN/year
Capital outlay	INV	41,785.00	100,580.00	186,260.00	PLN

3.1. Annual demand for energy

Annual demand for final energy for hot water system purposes and the efficiency of the systems. For variants 1 and 2, the main heat source is identical so the forecast demands for energy and the efficiency of the systems are the same. i.e. 73,605.08 kWh/year. Due to the additional source which is the heat pump for Variant 3, the annual demand for final energy for the hot water system purposes is smaller, i.e. 48,528.40 kWh/year, due to high efficiency of the device cooperating with the gas boiler. Coefficient Q_a for Variant 3 was reduced by 34.07%, whereas the efficiency of the system of preparing hot water $\eta_{W,tot}$ for the same variant has increased a bit more than twice, by 100.57% to be precise, compared to the initial value.

3.2. Annual demand for electric energy

With the increase of the complexity of the system, the number of auxiliary devices is greater, which generates operational costs, including mainly fees for electric energy. For variants 1 and 2, the demands for electricity is generated only by auxiliary devices: it is 621.15 kWh/year for variant 1 and 1,881.31 kWh/year for variant 2 which is a bit more than three times higher (202.88%), compared to Variant 1. Variant 3 of the system is equipped with the same auxiliary devices as Variant 1 and an additional heat source which is a high-temperature heat pump whose demand for electric energy is significant, i.e. approx. 12,829.93 kWh/year. Aggregate coefficient E_{el} for Variant 3 is 13,451.08 kWh/year, for which the demand for auxiliary energy is only 4.62% of that value.

3.3. Annual demand for energy powering the heat source

The applied solution of the systems preparing hot tap water for Variants 2 and 3 contributes to the lower demand for gas fuel: by 51.50% for Variant 3, and the greatest reduction of the demand was achieved for Variant 2 – 58.02%. In case of Variant 3, there is an additional demand for electric energy, the aggregate demand for driving energy for that variant is 58,057.45 kWh/year.

3.4. Annual operating costs

The costs of maintenance for Variant 2 compared to Variant 1 are increasing proportionally, similarly to the demand for auxiliary energy and show an increase by 85.71% and 221.43%, respectively. The maintenance cost for Variant 3 is close to Variant 2 but a bit smaller (by 2.22%).

The aggregate operational costs of Variant 2 compared to the initial variant has been reduced by 6 127.78 PLN/year (reduction by 32.90%). The significant annual costs of electric energy for Variant 3 result in the increase of the aggregate operational costs which are more than the operational costs of Variant 1, which means a lack of economic reasons for the application of the system for the purpose of preparing hot tap water. The operational costs for Variant 2 are greater than for the initial variant by 1,360.08 PLN/year (increase by 7.30%).

The initial variant is characterized by the lowest capital outlay due to the simplest system solutions. The outlay on Variant 2 is higher by PLN 58 795 (which represents the increase of 140.71%), and on Variant 3, by 144,475.0 PLN (which represents the increase of 345.76%). Variant 3 which is the most expensive system with regard to performance requires the highest capital outlay which, compared to the examined systems, is definitely unprofitable. The capital outlay on Variant 3 of the system would allow to cover the outlay on more than 4 systems presented in the initial variant.

4. Emission of pollutants

The calculations were made on the basis of the materials of the National Base Management Team, National Emission Balancing and Management Centre [11]. The content of total sulphur in natural gas $s_{cg} = 6.0 \text{ mg/m}^3$ was taken from the data of Gaz-System Transmission Gas Pipeline Operator for May 2017 (Rzeszów – area no 432) [12].

$$E = B \cdot W \text{ [g/year]}, \quad (8)$$

where:

- E – emission of substance [g/year],
- B – fuel consumption [m^3/year],
- W – emission rate per used fuel unit [g/m^3].

The results for 3 variants were presented in Table 3.

Table 3. List of calculation results for all the variants.

No	Description	Symbol	Variant 1	Variant 2	Variant 3	Unit
1	Annual emission of sulphur monoxides	E_{SO_x}	100.37	42.14	48.68	g/year
2	Annual emission of nitric oxides	E_{NO_x}	12,713.60	5,337.58	6,166.10	g/year
3	Annual emission of carbon monoxide	E_{CO}	2,509.26	1,053.47	1,216.99	g/year
4	Annual emission of carbon dioxide	E_{CO_2}	16,728.43	7,023.13	8,113.29	g/year
5	Annual emission of total suspended particulates	E_{TSP}	4.18	1.76	2.03	g/year

The emission of pollutants depends strictly on the demand for gas fuel. For particular variants, the reductions of pollutants compared to the emission are the same as the reductions of coefficient Bg for Variant 1; and for Variants 2 and 3 they are: 25.90%, 58.02% and 51.50%, respectively. Significant emissions of greenhouse gas in a form of carbon dioxide was noted. Additionally, trace, even negligible, emissions of suspended particulates were detected.

Pursuant to Article 3(20) of the Act[7] the examined entity is not an entity which would use the environment and is not obliged to create annual reports on data concerning emissions to the air for the National Base, as referred to Article 7(1) of the Act [6]. Emission coefficients may be helpful when presenting the best technique available and to assess pollutants introduced to the air for the purpose of monitoring the environment.

5. Conclusions

The issue concerning water heating systems which have the highest efficiency of production, accumulation, transmission and using of heat, and, simultaneously, reduced operational costs and conventional fuel consumption is very complex and affected by many factors. Such factors include above all: assumed hot water system performance, way of distributing hot water, heat accumulation, heater's mode of operation, individual user's demand, water temperature, heat source and parameters of the device depending on the particular producer. Moreover, it is hard to forecast the actual performance of the systems due to varied activities of the users and, consequently, the demand for hot water, which entails a number of effects which include possible over dimensioning of the systems and devices.

In the examination case, the most profitable system with regard to performance turned out to be Variant 2 of the system, in spite of more than twice higher capital outlay compared to initial Variant 1. However, when we assume that the maximum time of its operation is 10 years, the expected profits in this particular case may not convince the designer, and much less, the investor. Systems consisting of several heat sources require a greater attention and knowledge of persons responsible for designing, operating and maintaining the system.

In case of natural gas boilers, the environmental factor is frequently passed over due to low emission levels. Therefore, the conclusion is that in the examined case, the choice of the system depends mainly on economical effects concerning the performance of the system of preparing hot tap water.

The possibility to apply Variant 3 of the system turned out to be completely unjustified with regard to economical reasons; what is more, the heat source in a form of air-source heat pump may be uncomfortable due to a significant noise level, even from the distance of 10 m from the working device.

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