TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 141, 2018, 3–30

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Modelling of hybrid renewable energy system consisting of microcogeneration unit and photovoltaic installation

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Abstract

In the wake of much needed energy transformation, European Union urges member states to take action for supporting microgeneration. As Poland introduced novel to Renewable Energy Act in mid-2018, microgeneration systems of up to 50 kWe installed can benefit from a prosumer scheme. This paper investigates scenarios for installation of a hybrid system composed of a microcogeneration unit and a photovoltaic installation, applied to an existing public building located in northern Poland. The building is heated by a 32 kW oil-fired boiler and gets all it's 60.9 MWh of the annual electricity needs from the distribution system operator grid. The actual state was assumed as a reference scenario. The microgeneration unit is composed of a wood pellet-fired boiler of 25 kW nameplate capacity and the linear free piston Stirling engine of 1 kW electric nameplate power. The microcogeneration unit works together with 24 kWp rooftop photovoltaic system, configured in East-West setup. Modelling heat and power demand and production via the energy conversion units was conducted in the commercial modelling software package. The models were built based on the actual data and time series for external weather conditions. Two scenarios were analysed – one where the basic setup of microcogeneration unit and photovoltaic system is topped up with 3 m^3 buffer tank and another, where instead of buffer, 10 kW electrical boiler is used for peak loads. Relevant simplified investment and operation expenditures were calculated over a period of 10 years. Calculations proved that despite very little electricity surpluses available for the prosumer support scheme, both scenarios bring positive cash flows within 5.5 and 7.1 years, respectively.

Keywords: Linear Free Piston Stirling Engine; Biomass; Photovoltaic; Renewable energy; Energy production and consumption profiles; Microgeneration

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Abbreviations

BIOmCHP	–	biomass-based micro cogeneration of heat and power
BoS	–	balance of system
DHW	–	domestic hot water
DSO	–	distribution system operator
LFPSE	–	linear free-piston Stirling engine
PV	–	photovoltaics
RES	–	renewable energy sources
SPBT PV	–	simple payback time photovoltaic

1 Introduction

At present, significant changes in the energy sector have been observed. The solutions used have moved towards combined heat, cooling and power generation, decentralised power generation (i.e., in a vicinity of consumers), the use of renewable energy sources, the miniaturization of technology and the reduction of environmental impact at the same time. Many countries declare specific and ambitious targets for carbon neutrality or the composition of their energy mix.

A large share of distributed renewable energy sources (RES) with unstable characteristics in the energy mix requires a change in the structure of traditional energy systems to increase their dynamics while improving the efficiency. The RES are intended to be the basis of the system rather than complement it [1]. This trend is observed both at the level of large-scale sources and at the level of households, local authorities or the micro, small and medium-sized enterprises segment.

The implementation the microgeneration can be enhanced via the legislation pathway. For example, European Parliament, in its resolution of 22 April 2013 "European Parliament resolution on microgeneration – electricity generation and small-scale heat generation" advocates that [2]:

> "(...) small-scale and decentralised energy generation represents an opportunity for households and small and medium-sized enterprises, as well as for communities in both urban and rural areas, to work together to combat climate change by becoming energy producers (...)"
>
> "(...) consumers should acquire awareness of efficient ways to produce and consume energy (...)"
>
> '(...) the Commission communication on the internal energy market addresses the issue of empowering such 'prosumers' (...)"

> "(. . .) while the Communication on the Internal Energy Market addressed the issue of strengthening prosumers, the creation of a society of prosumers still requires many challenges in the market (. . .)"
>
> "'(. . .) the introduction of large-scale microgeneration will have a significant impact on the network, resulting in huge challenges for regulators and network operators at different levels of (. . .)"
>
> "(. . .) small-scale energy generators interact with the distribution network in a different way than large-scale generators and should therefore be treated differently in future legislation (. . .)"
>
> "(. . .) calls on the Commission to carry out a comprehensive assessment of potential microgeneration opportunities within the European Union and the possible impact of large-scale microgeneration on European internal energy markets (. . .)"

These trends are a part of the concept of prosumers, including the one defined in the Renewable Energy Act [3]. A prosumer is a micro-installation user of exclusively-1579842986-1579842986 a renewable energy source with an electrical power not exceeding 50 kW. The prosumer can use the so-called net metering, that is, supply-1579842985-1579842985 unused surplus of electricity produced to the distribution system operator (DSO) network and pick up part of it free of charge within 12 months.

This mechanism has enabled a very dynamic increase in the number of micro-installations, particularly in the field of photovoltaic systems (PV). According to the data presented in the report 'Photovoltaic market in Poland', at the end of 2017, 29000 prosumers joined the DSO networks, with increasing growth dynamics [4]. This report indicates that investment costs are decisive, and a simple payback time (SPBT) of approximately 7-9 years is acceptable for many users. The basic motive for investing in micro-installations is the expected return of investment.

The PVs is the most frequently chosen technology by prosumers. Apart from many advantages, the technology has the following limitations [5]:

- Daily production irregularity due to changes in the sunlight.
- No production at night.
- A significant part of the annual production from March through September at-1579842982-1579842982 latitudes of Poland.
- The ability to install adequate power due to the architecture of the object and the shape of the environment.

Combining different technologies can allow for:

- increasing the share of own production in covering the overall electricity consumption,
- increasing the share of RES in primary energy consumption resulting in a significant improvement in the energy performance of buildings.

The amendment of the RES Act from June 2018 defines the prosumer as the recipient of the final electricity that generates electricity for its own consumption, not related to the business carried out. This means that this definition covers, among others: households, public finance entities, cooperatives and housing communities, churches and religious associations, forestry, etc. [3].

The requirement to use only a renewable energy source as a source of primary energy for the microcogeneration system is a technical challenge. One way to satisfy the requirement may be a cogeneration micro-assembly that uses the Stirling engine-powered generator. The possibilities for using this technology in a biofuel-powered cogeneration system are extensively commented by a monographic edition by Piętak *et al.* [6].

The choice of such a configuration of the cogeneration micro-assembly is supported by:

- an engine with the so-called external combustion, this is a dust-resistant solution that is faced with solid fuel exhaust gas [7],
- Stirling engine design, with limited number of bearings, shafts, crank, resulting in trouble-free operation and low energy losses,
- low noise levels compared to e.g. piston motors, which is important in home solutions,
- Stirling low-power engines are available in mass series.

The source of heat for the engine may be exhaust gases from an automatic biomass-fired boiler [7,8].

The number of individual heating systems with solid fuel boilers and fuel oil is not properly documented, but rough estimations indicate millions of such installations on a scale of Poland. Annual market can be counted in tens of thousands per year. The biomass-fired boiler market alone in 2015 was estimated at 26000 units, and the most popular segment is a power range of 20-30 kW [9].

The aim of the study is a model-based analysis of different configurations for small-scale combined heat and power production in a public building located in northern Poland. To apply the prosumer scheme solution, a hybrid installation consisting of the microcogeneration system equipped with the wood pellets-fired boiler and the linear free-piston Stirling engine (LFSPE) (biomass-based microcogeneration of heat and power – BIOmCHP), and the PV system was proposed. In the alternative scenarios, a buffer tank and an electric boiler, respectively, were investigated as the complementary equipment. Both, the investment costs and the operational expenditures as well as the economic efficiency were estimated and compared with the reference scenario representing the actual state.

2 Methodology

The modelling study was carried out in the commercial energyPRO software package [15] offered by EMD A/S. EnergyPRO calculations are based on time series with respect to the energy demand or production profiles. Any given total energy demand or production, i.e., electricity or heat, can be distributed along the weather data implemented in modelling software package.

A small public building (forester's house) located in Gniewino (northern Poland) was adopted for the analysis. The characteristics of the study site is given in Tab. 1.

Table 1: Characteristics of the study site.

Parameter	Value
Heated surface	525,6 m^2
Maximum heat demand	32 kW
Annual heat consumption for space heating	61,1 MWh
Annual heat consumption for domestic hot water	14,4 MWh
Annual electricity consumption	60,9 MWh
Central heating system type	Radiators at 70/55 °C
Staffing	20 persons, incl. Office and physical workers
Working hours	7:30 am till 3:30 pm

In the studied case, the data from the climate forecast system reanalysis (CSFR2) system for the location nearest to Gniewino was selected. The available data include temperature, wind speed, humidity, solar radiation and precipitation. Data sets are based on records collected throughout several years.

The distribution of ambient temperature (Fig. 1) and solar radiation (Fig. 2) for the given location over the year are presented on the graphs.

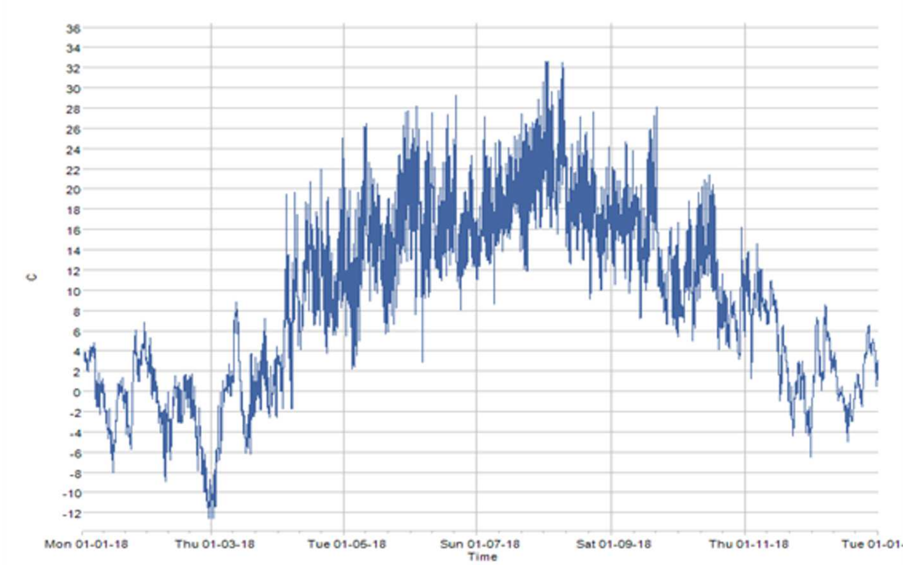

Figure 1: Outside temperature for given location based on CSFR2 time series.

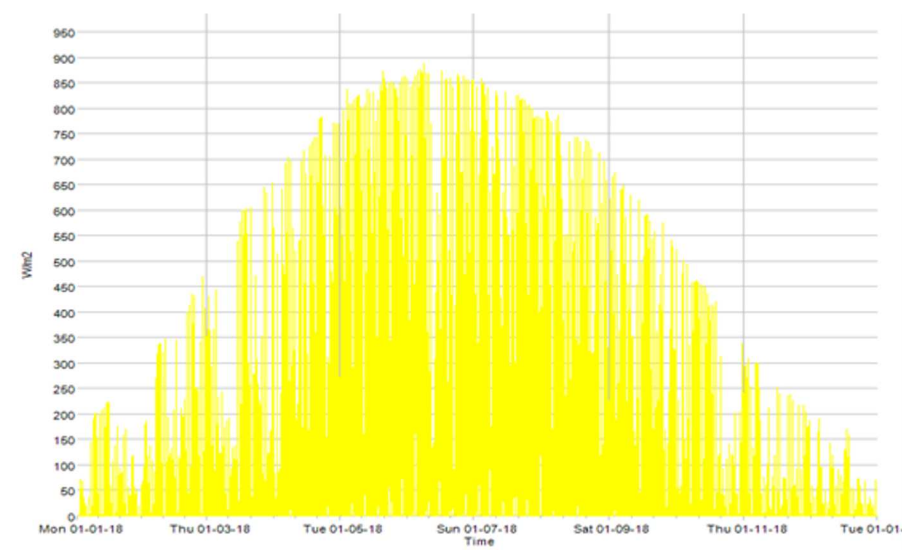

Figure 2: Solar radiation for given location based on CSFR2 time series.

To verify the cost-effectiveness of the investment, the simulations were carried out over a period of 10 years, which corresponds to the guaranteed service

life of the main components of the system (including the boiler, Stirling engine, photovoltaic modules, inverter).
Three scenarios were analysed for the comparison purposes:

- Scenario 1 – reference: represents the actual state, i.e. heating oil purchased from the local supplier and electricity purchased from the DSO grid
- Scenario 2 – BIOmCHP unit, PV system and the buffer tank (3 m^3)
- Scenario 3 – BIOmCHP unit, PV system and the electric boiler

All of the scenarios base on the same distribution of the electricity and heat demand for the building, modelled as described above.

2.1 Electricity consumption

Full annual data representing the profile of the actual electricity demand were available for the studied case, with 5-minute intervals. These records were aggregated to 1-hour intervals to match the intervals of the heat demand profile. Total annual electricity consumption was 60.9 MWh. The electric energy consumption is quite high during summer, as the building is equipped with compressor-based air conditioning system. The electricity consumption profile is shown in Fig. 3 and duration curve for electricity consumption is presented in Fig. 4.

2.2 Heat consumption

The total annual heat consumption was 75.4 MWh according to the data from the technical documentation of the building. This amount includes 60.9 MWh for space heating and 14.4 MWh for preparing domestic hor water (DHW).

The heat demand for space heating is seasonal and limited within the period between 15th of September and 15th of May. The annual heat demand is profiled against outside temperature time series, collected from CFSR2 data base, offered by energyPRO.

Figure 5 shows the results of profiling the space heating demand. The heat demand for DHW is modelled on the weekly basis throughout the year. On a working day, between 6 am and 4 pm, 4 kW of heating power for DHW is needed on average. Beyond this time and throughout weekends just 1 kW of heating power is applied. Sample week profile of the heat demand for DHW is presented in Fig. 6. Duration curve for the total heat demand can be plotted as presented in Fig. 7.

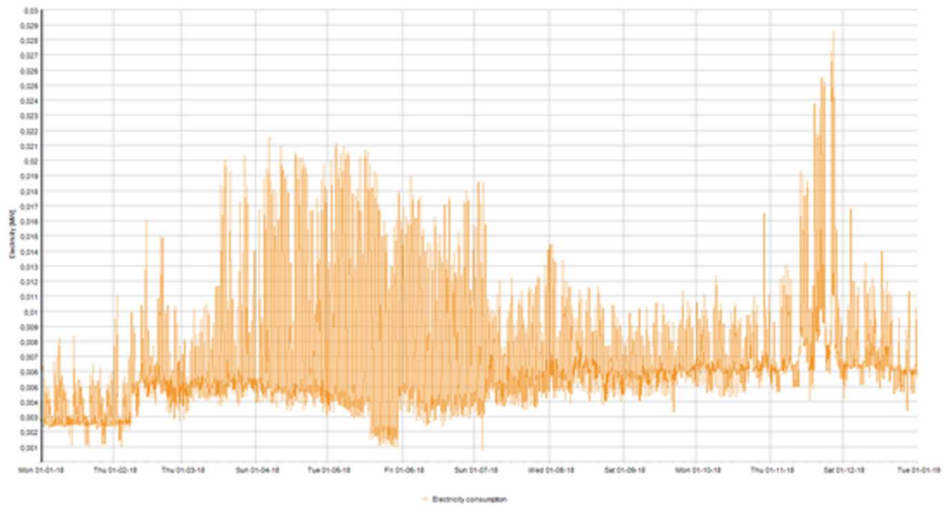

Figure 3: Electricity consumption profile.

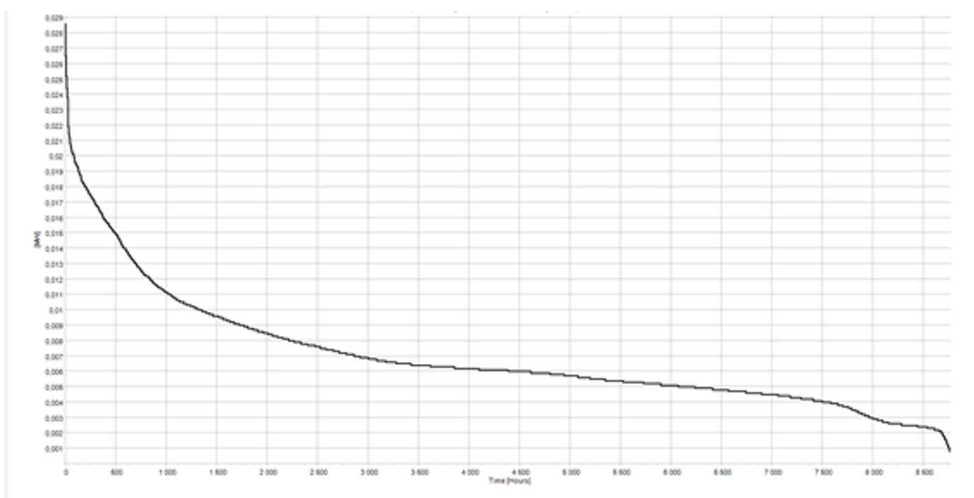

Figure 4: Duration curve for electricity consumption.

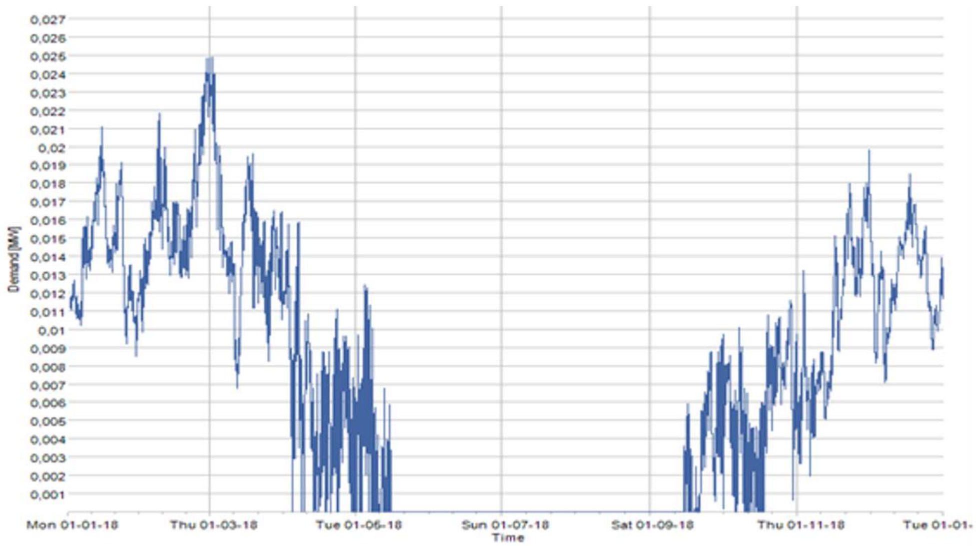

Figure 5: Space heating demand profile.

2.3 Energy conversion units

2.3.1 Biomass-based micro cogeneration of heat and power system

2.3.1.1 Biomass boiler

Following the definition of the prosumer given in RES Act [3], any micro installation must consist of the RESs only. For this reason, replacement of the heating source from oil to wood pellets is considered in the present study. A boiler with a pellets-fired furnace was reported as a good potential source of primary energy for the Stirling engine [8,10].

As technical and economical parameters have to be taken into account, a sample boiler that meets market conditions as well as efficiency and emission standards was assumed. The kind of boiler selected for simulations has the sales potential in Polish market counted in tens of thousands [4]. It was also important, that the new technology does not worsen safety and comfort of the end users. Technical parameters of the assumed boiler are presented in Tab. 2.

Due to the operating conditions deviating from the nominal ones (fouling of the heat exchange surfaces, start-up from the cold state, changes in the characteristics of the fuel, etc.), the annual average efficiency of the boiler system was appropriately adopted for modelling purpose: for nameplate capacity – 77%, for

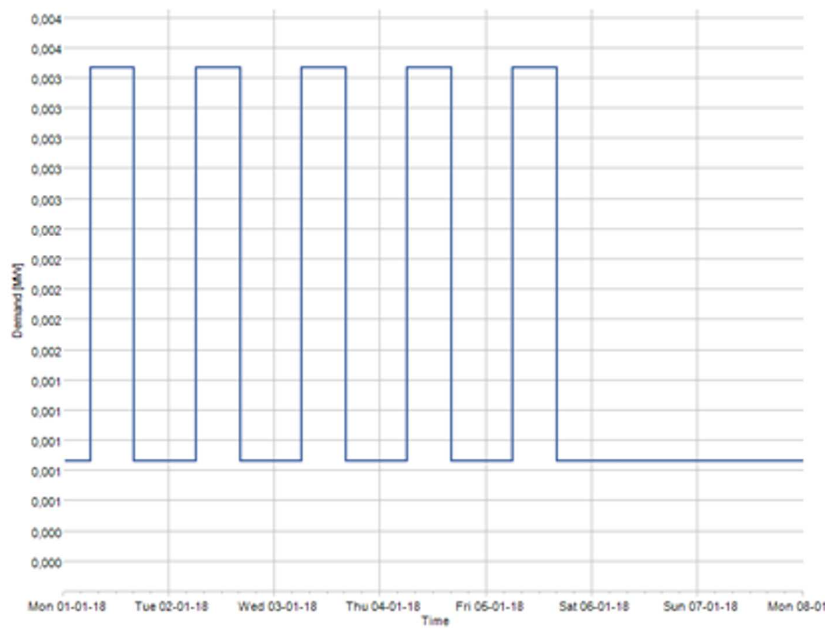

Figure 6: Weekly profile for domestic hor water (DHW).

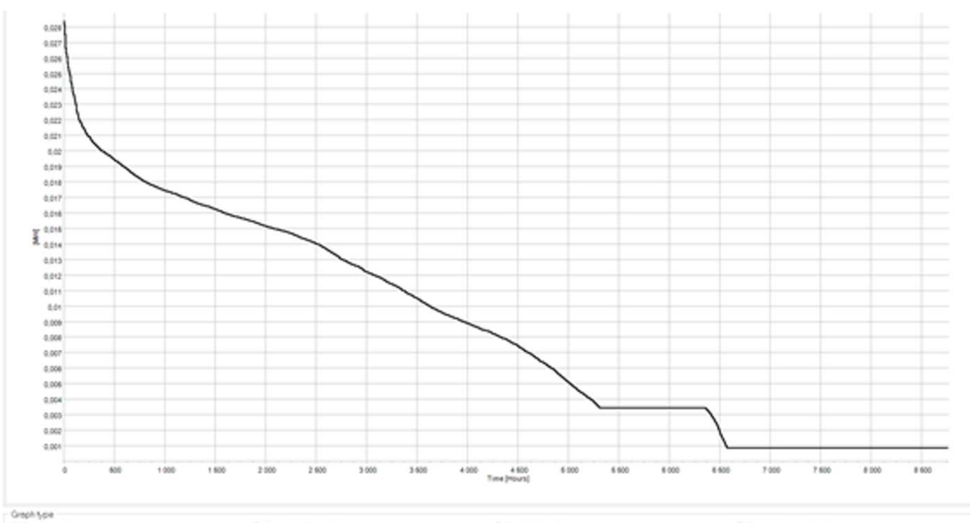

Figure 7: Duration curve for total heat demand.

Table 2: Parameters of pellet boiler.

Parameter	Value
Nameplate capacity	25 kW
Minimum capacity	8 kW
Efficiency for nameplate capacity	94%
Efficiency for minimum capacity	93%
Flue gas mass stream for nameplate capacity	51.1 kg/h
Flue gas mass stream for minimum capacity	18.3 kg/h
Energy efficiency class	A+
Nominal operating pressure	3 bar
Flue gas temperature in the combustion chamber	900–1100 °C
Max water flow temperature	95 °C
Exhaust emissions at 13% excess air when operating with nameplate capacity (according to EN 303-5:2012).	CO: < 30 mg/m^3 Dust: < 15 mg/m^3
Retort grate	Y
Fuel feeder with ventricular valve	Y
Under pressure based control of the combustion process	Y
Automatic ignition with hot air blower	Y
Automatic cleaning system of heat exchange surfaces	Y
Standard-compliant design PN-EN 303-5:2012, class 5	Y

minimum capacity – 73%.

Based on the data reported in [9], a price index of PLN 600/kW was adopted, resulting in the boiler price accepted for further simulations 15 000 PLN excl. VAT.

2.3.1.2 Stirling engine based electricity generator

For electricity production, the external combustion Stirling engine module was assumed in the present study, as suitable for combination with the biomass furnace of the boiler (see Tab. 3). The LFPSE module is manufactured by Microgen Engine Corporation and is available ready for different applications, e.g., a gas-fired burner, a biomass furnace or a solar concentrator [11].

This construction has only 3 moving parts: displacer piston, power piston and planar spring, which allows for smooth, long and maintenance free operation (Fig. 8). The hermetically closed system is filled with helium, which is a working medium. Helium is heated by the external burner from the lower side and is

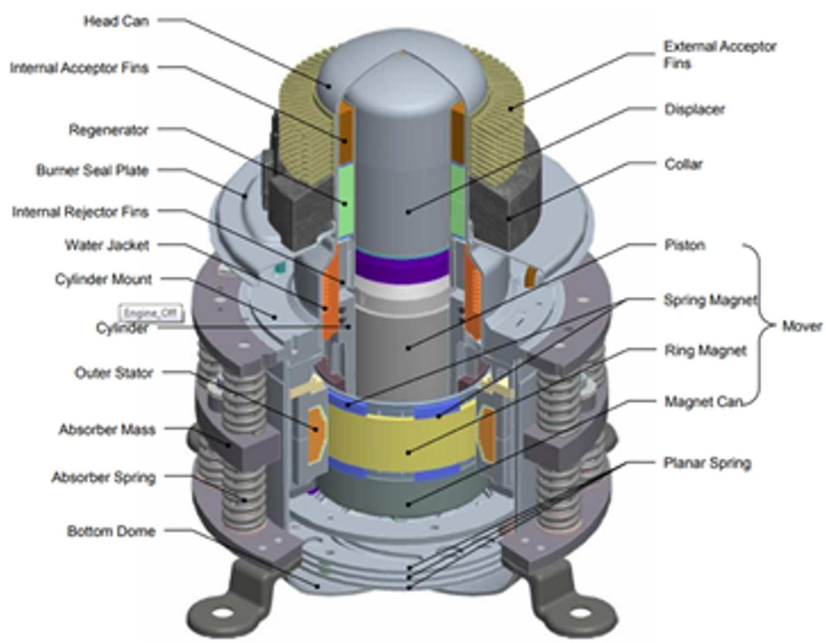

Figure 8: Basic elements of LFPSE.

cooled by circulating water at the upper side. The heat produced by the burner is transmitted by heat carriers to the engine's head. When operating with full load, the head temperature reaches 500 °C. The regenerator is located between the hot and cold ends of the LFPSE. The upper piston, the so-called the displacer piston, moves helium cyclically between the hot and the cold end. As a result of pressure difference during expansion of helium, the power piston is put into motion. The motor energy is converted into electricity by a linear generator. LFPSE works quietly and does not require maintenance. The running conditions of a free piston engine are determined by the grid it is connected to.

The grid voltage sets the piston amplitude and the engine frequency synchronises with the grid frequency. Four general factors affect the engine power: grid voltage and grid frequency which are set by the grid operator, head temperature determined by the appliance controls as well as coolant temperature determined by the system design/operation [12].

To reflect more realistic working conditions, the LFPSE availability should be taken into consideration. Heat transfer to the engine head depends on the thickness of a fouling layer composed of the products of combustion. This fouling needs to be removed periodically [7]. Any manual operations at the engine head

Table 3: Nominal parameters of MEC LFPSE generator.

Parameter	Value
Nameplate capacity	1000 W; 230 V; 50 Hz
Water flow	min. 4 dm^3/min, nominal 15 dm^3/min
Water temperatures	30 °C nominal, max continuous 70 °C
Efficiency at nominal conditions engine only	22%
Rest helium pressure	23 bar at 25 °C
Max working helium pressure	367 bar
Heat output to coolant	3+/-0.5 kW nominal
Grid synchronization head temperature	200 °C

should not be conducted when the head temperature is above 120 °C [12]. Cooling the head from the working temperature of approximately 300 °C down to 120 °C takes about 1.5 hours.

The model of BIOmCHP calculates 2 hours per month of non-availability. This corresponds with maintenance time needed for the pellet boiler.

The generator power is a function of the piston amplitude. The latter depends on the coolant flow temperature (i.e. return temperature from building's heating system). For example, at the nominal head temperature of 500 °C, at 30 °C coolant temperature the engine electrical output is 1100 W and at 70 °C the output is 980 W [13].

To reflect the influence of fouling and the coolant temperature variations in the present model, it was assumed, that for the nameplate boiler capacity, the power output of the LFPSE is 900 W and for the minimum boiler capacity, the power output of the LFPSE is 500 W. According to the manufacturer, a lifetime of the LFPSE is approximately 50 000 h. For the modelling purpose, the price of the complete engine compound was set at 17 000 PLN excl. VAT.

2.3.1.3 Total investment costs of BIOmCHP

The total investment costs of the BIOmCHP consist of the abovementioned costs of the devices as well as the costs of balance of system (BoS). The latter includes workload, transport, auxiliary parts and equipment, commissioning and testing at the installation site.

In the present study, the following investment costs for BIOmCHP were considered (see Tab. 4):

Table 4: BIOmCHP investment costs.

Parameter	Value
Biomass boiler	15 000 PLN
LFPSE	17 000 PLN
BoS	15 000 PLN
Total BIOmCHP	47 000 PLN

2.3.2 Photovoltaic system

2.3.2.1 PV modules array arrangement

It was assumed, that the building was equipped with a rooftop PV system with total installed capacity of 24 kWp. The system is configured symmetrically as East-West setup, i.e. 12 kWp per each side. The slope of the roof is 10° in relation to the terrain level. The system is based on 270 Wp PV modules. For the modelling purposes, two PV modules arrays were calculated – one facing the East and one facing the West.

Total annual electricity production from the PV system was estimated to 21.9 MWh. This amount was distributed according to time series for solar radiation and outside temperatures from the CFSR2 data sets. The resulting profile of the PV system electricity production is shown in Fig. 9.

2.3.2.2 Investment costs of the PV system

According to the information compiled in the Institute for Renewable Energy (IEO) report, the average price index for a complete PV micro-installation was ca 4 800 PLN excl. VAT in mid-2018 [4]. This number gives the total capital expenditures for the investigated PV system of 115 200 PLN excl. VAT.

2.4 Description of scenarios

2.4.1 Scenario 1

Scenario 1 represents the actual state if the study site. The heating comfort state in the building is maintained by the heating oil boiler of 32 kW nameplate capacity. The average annual efficiency of the boiler is 82%. The boiler covers the

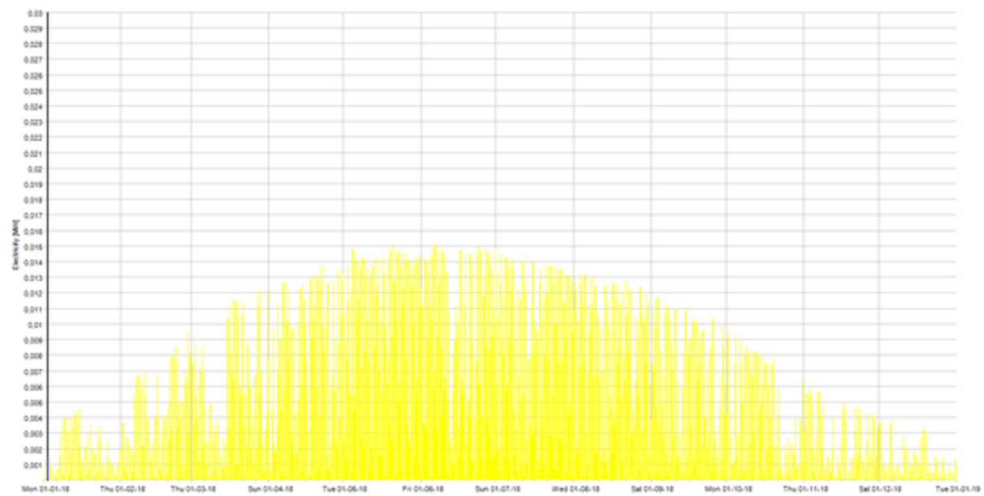

Figure 9: System electricity production profile.

total annual heat demand of the building. Heating oil used is EkoTerm produced by PKN Orlen S.A., with lower heating value of 36.6 MJ/dm^3. The price of the fuel in November 2018 was ca 2 800 PLN/m^3 excl. VAT [13]. The electricity demand is covered in 100% by purchasing energy from Energa Operator S.A. – the regional DSO. Electricity is delivered with fixed flat tariff G11, at the average price of 450 PLN/MWh excl. VAT [14]. Graphical representation of the model for this scenario in energyPRO is shown in Fig. 10. No capital expenditures were applied.

2.4.2 Scenario 2

Scenario 2 assumes installation of the BIOmCHP unit and the PV system described above. Nameplate heating capacity of the boiler – 25 kW – is lower than the maximum heat demand 32 kW. To offset this gap, the buffer tank of 3 m^3 was implemented in the model. This solution allows the boiler to work longer with higher efficiency, as well as can delivered stored heat during the BIOmCHP non-availability periods. Heat losses in the buffer tank are calculated by the software. Pellets of lower heating value of 18 GJ/Mg is purchased at 750 PLN per Mg. Surplus electricity production is fed into the grid. According to the prosumer scheme, 70% of this surplus can be pulled back from the grid within 12 months. This amount of energy is relevant to income in the model, and thus decreasing the

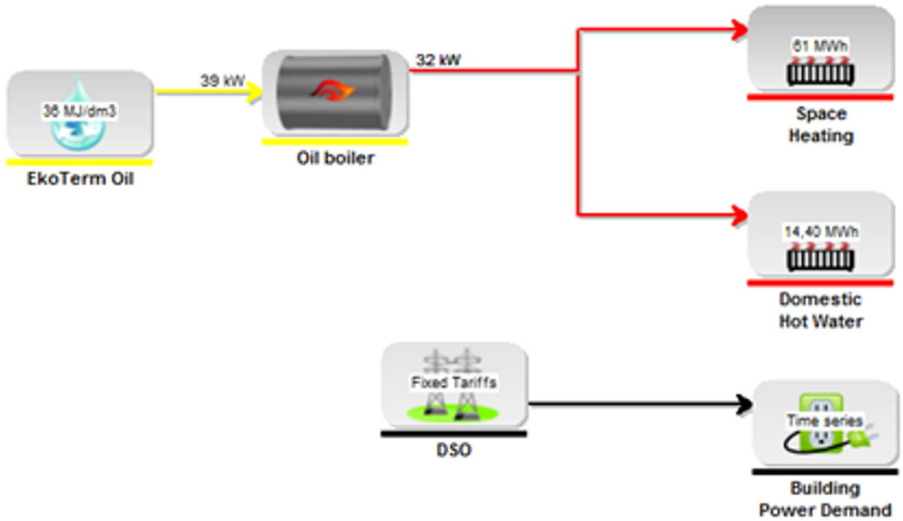

Figure 10: Graphical representation of Scenario 1.

operation costs. Additional capital expenditures for the buffer tank installation as high as 12 000 PLN excl. VAT are included. The model layout for Scenario 2 is shown in Fig. 11.

2.4.3 Scenario 3

Scenario 3 is basically similar to Scenario 2, instead of the buffer tank, which was replaced with the electric boiler of 10 kW to cover the heat demand peak loads. As the PV system generates electricity surpluses, it might be good idea to consume them with energy available under the prosumer scheme. Additional capital expenditures for the electric boiler installation (3 000 PLN excl. VAT) are included in the calculations. The model layout of Scenario 3 is presented in Fig. 12.

3 Results and discussion

Simulation in energyPRO provided results for the analysed scenarios. The output values such as, electricity consumption, fuel consumption as well as operating costs were calculated for each considered energy production unit. The annual heat and electricity production profiles generated for each scenario allowed for

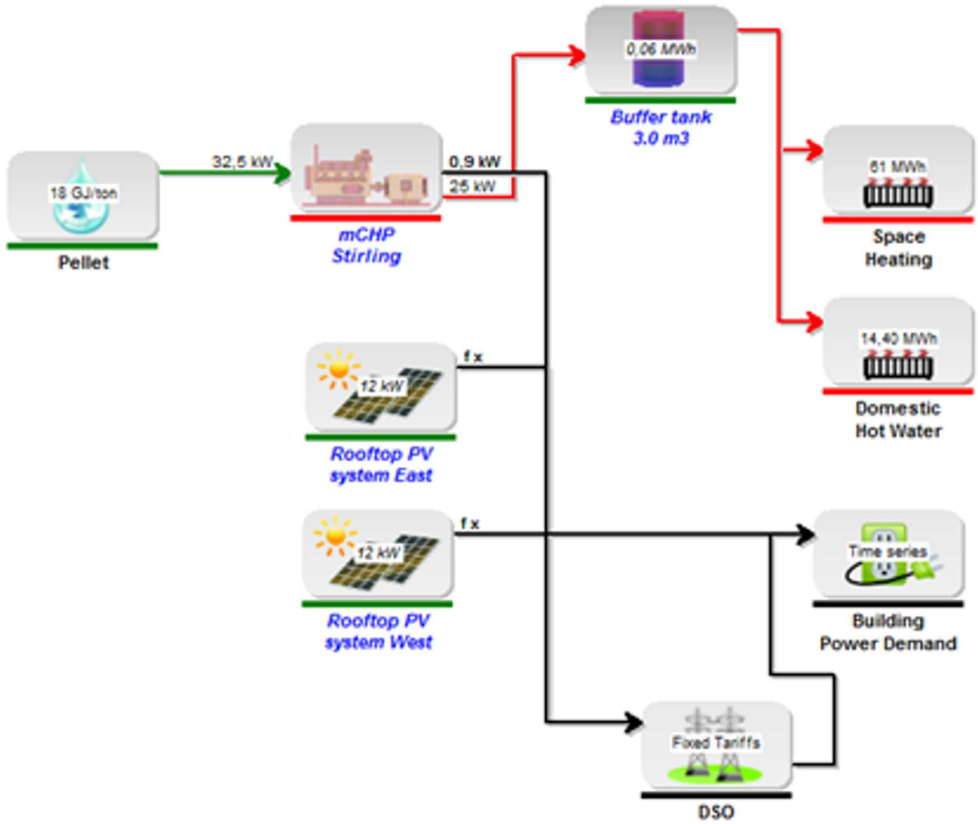

Figure 11: Graphical representation of Scenario 2 model in energyPRO.

comparison between the electricity/heat production and consumption (Figs. 14–16). While the electricity production profiles are comparable in both scenarios (Fig. 14, and 16), the heat demand is covered differently (Figs. 13 and 15). In Scenario 2, the total heat demand is covered only by the BIOmCHP. In Scenario 3, the electric boiler covered the heat demand in summer and during the non-availability periods of the BIOmCHP.

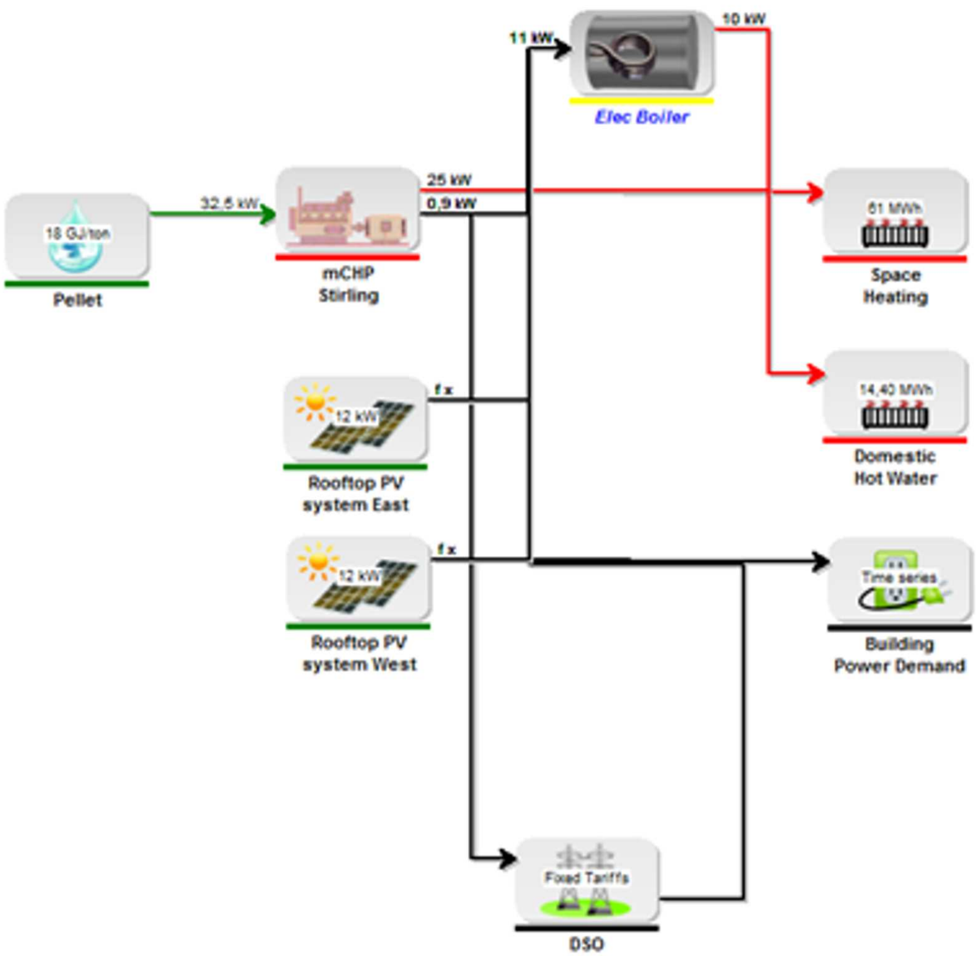

Figure 12: Graphical interpretation of Scenario 3 model in energyPRO.

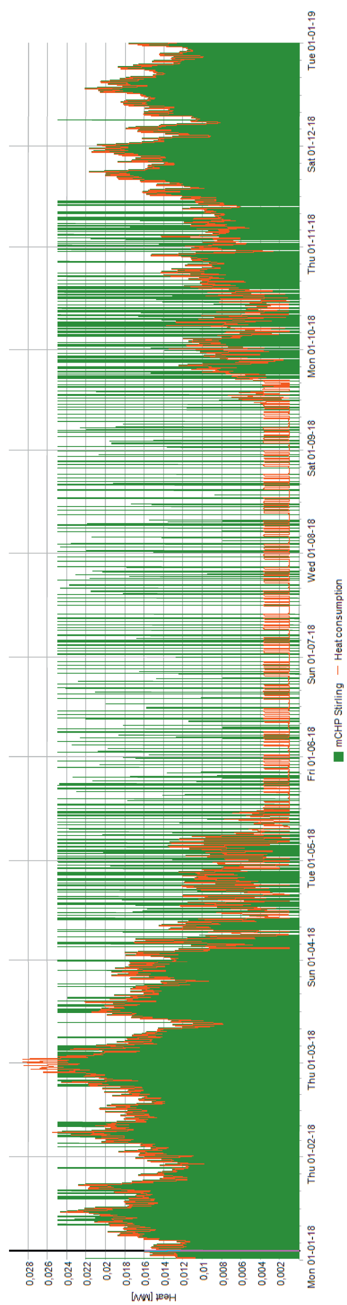

Fig. 13. Annual heat demand *vs.* production – Scenario 2.

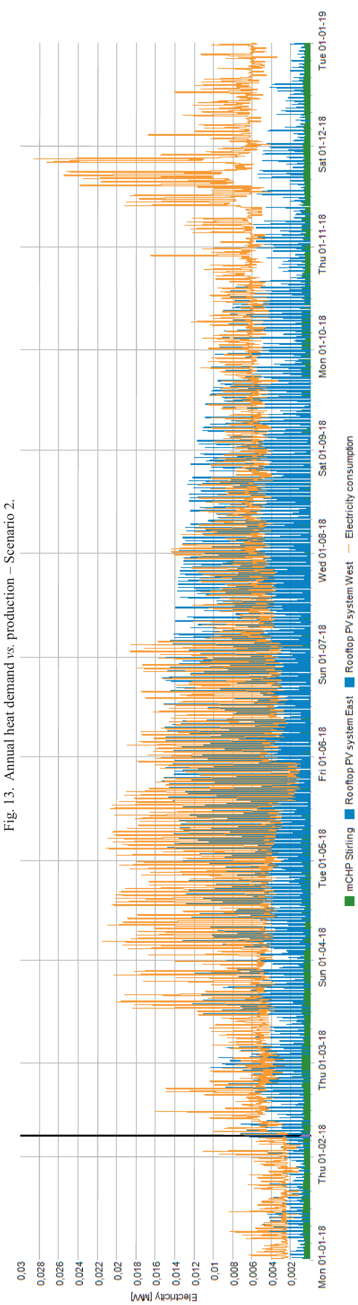

Fig. 14 . Annual electricity demand *vs.* production – Scenario 2.

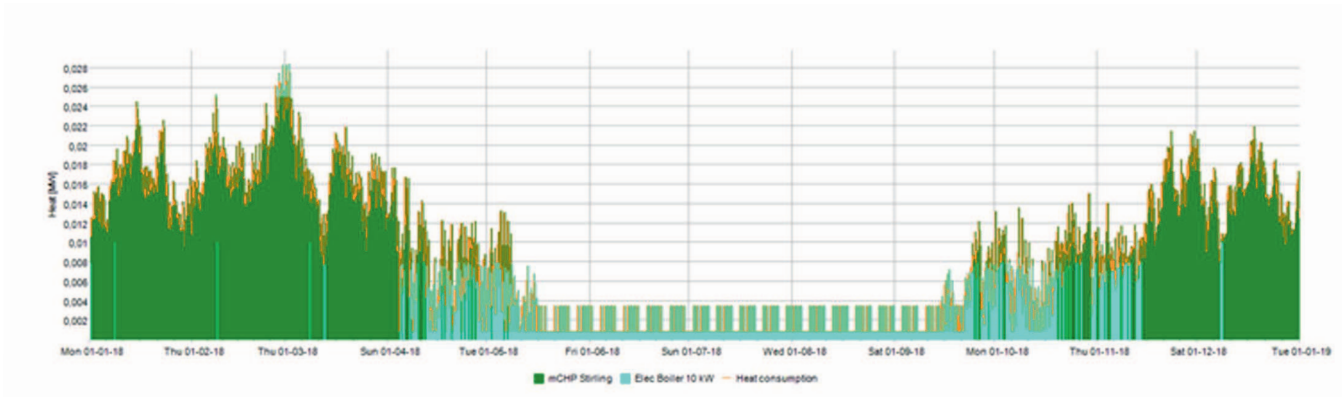

Fig. 15. Annual heat demand *vs.* production – Scenario 3.

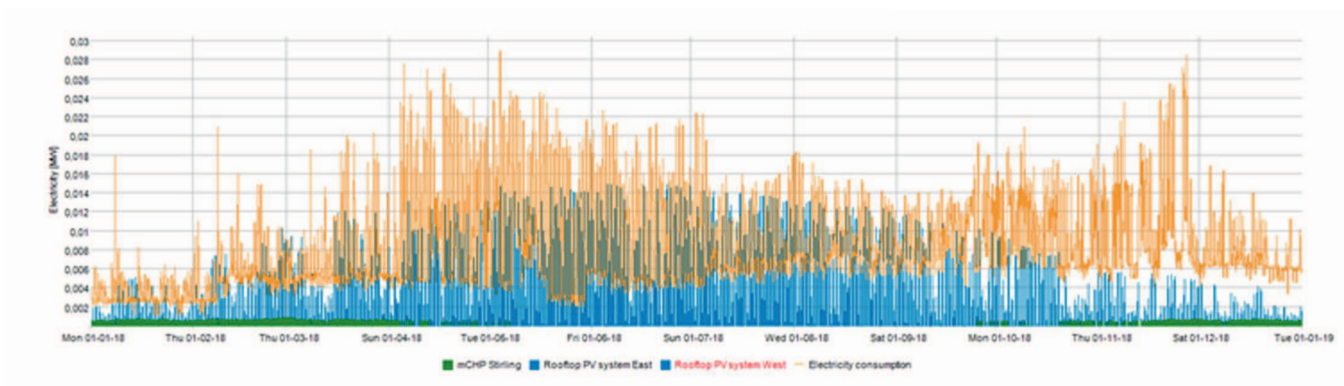

Fig. 16. Annual electricity demand *vs*. production – Scenario 3.

3.1 Energy conversion

Table 5: Annual energy conversion performance.

General	Unit	Scenario 1	Scenario 2	Scenario 3
Heat demand	MWh	75.4	75.4	75.4
Electricity demand	MWh	60.9	60.9	60.9
Electricity produced by the energy units	MWh	0	25.2	24.7
Electricity consumed by the energy units	MWh	0	0	13.2
Exported electricity	MWh	0	1.3	0.5
Peak exported power	MW	0	0.012	0.008
Imported electricity	MWh	60.9	37	50
Peak imported power	MW	0.029	0.028	0.028
Energy unit: Oil boiler				
Fuel consumption	dm^3	8714.3	0	0
Fuel consumption	MWh	88.6	0	0
Heat production	MWh	75.4	0	0
Operating hours	h	8760	0	0
Full load operating hours	h	2356.2	0	0
Energy unit: mCHP Stirling				
Fuel consumption	ton	0	20.3	15.2
Fuel consumption	MWh	0	101.5	76
Heat production	MWh	0	77	63.3
Electricity production	MWh	0	3.3	2.8
Operating hours	h	0	4765	4323
Full load operating hours	h	0	3662.9	3153.2
Energy unit: rooftop PV system East				
Electricity production	MWh	0	10.8	10.8
Operating hours	h	0	4897	4897
Full load operating hours	h	0	898.5	898.5
Energy unit: rooftop PV system West				
Electricity production	MWh	0	11.1	11.1
Operating hours	h	0	4637	4637
Full load operating hours	h	0	928.8	925.5
Energy unit: elec boiler 10 kW				
Heat production	MWh	0	0	12
Electricity consumption	MWh	0	0	13.2
Operating hours	hours	0	0	4492
Full load operating hours	h	0	0	1202.4
Fuel consumption: EkoTerm oil				
Fuel consumption	dm^3	8714.3	0	0
Fuel consumption	MWh	88.6	0	0
Fuel consumption: pellet				
Fuel consumption	ton	0	20.3	15.2
Fuel consumption	MWh	0	101.5	76

Calculations in modelling software package return various values regarding energy conversion in considered scenarios, ordered by implemented technologies (so called energy units). Electricity and heat productions for each unit are calculated, as well as fuel consumption of each fuel type. These values are basis for further economic calculation.

3.1.1 Heat production

The actual total heat demand is covered by the oil boiler in the reference Scenario 1 (Fig. 17), as there is no minimum output set for this energy conversion unit. The annual oil consumption is calculated at 8714 dm^3. In Scenario 2, where buffer tank is applied, the BIOmCHP unit delivers enough heat to cover all the heat demand, including losses. The unit modulates heating power between the nameplate and minimum capacities. Excess heat is stored in the buffer tank (Fig. 18). Pellets consumption amounts to 20.3 Mg. Scenario 3 shows that without the buffer tank, the BIOmCHP unit can work only to its minimum heat capacity of 8 kW and then turns-off. The deficiency in the heat demand is covered by the electrical boiler (Fig. 19). The electrical boiler delivers 12 MWh out of the annual total of 75.4 MWh, which represents the share of almost 16%. Pellet consumption amounts to 15.2 Mg.

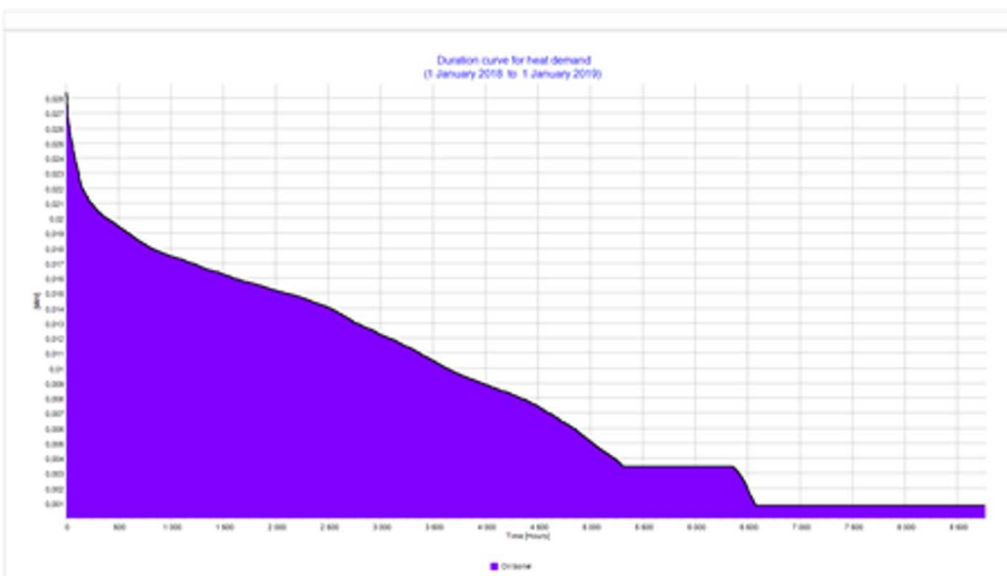

Figure 17: Heat production – reference scenario.

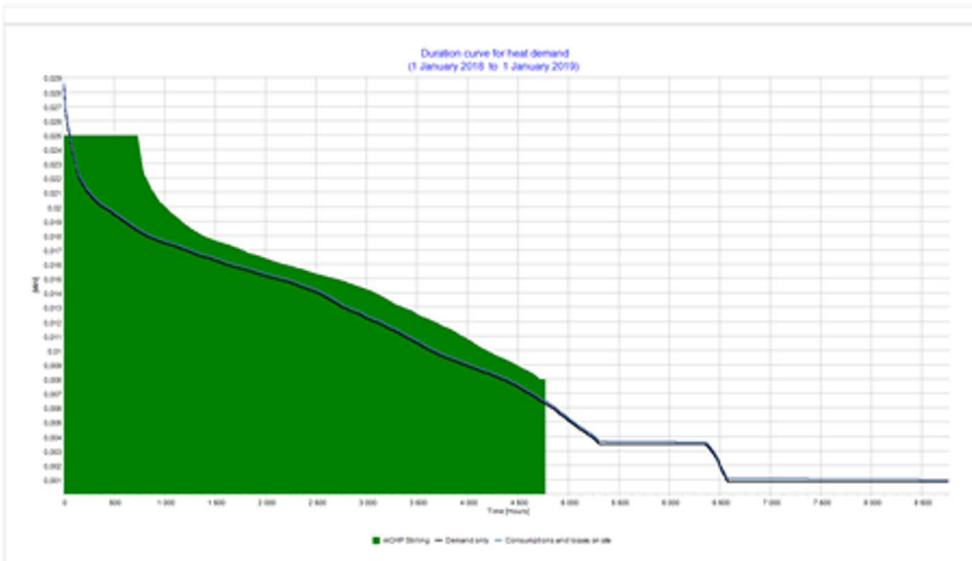

Figure 18: Heat production – Scenario 2.

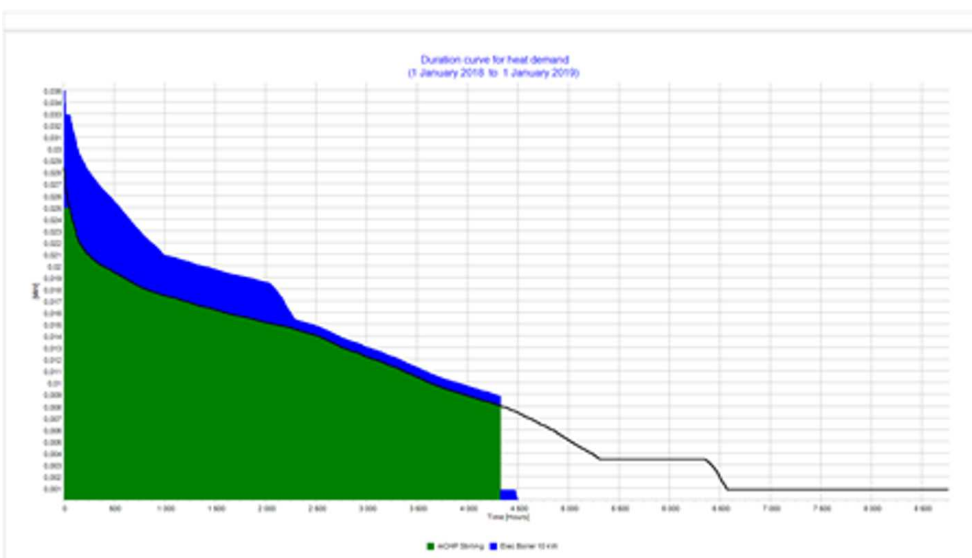

Figure 19: Heat production – Scenario 3.

3.1.2 Electricity production

Electricity production from the PV system is the same in Scenarios 2 and 3, and totals 21.9 MWh annually. The electricity production from BIOmCHP equals 3.3 MWh for Scenario 2 and 2.8 MWh for Scenario 3, which corresponds to 13.1% and 11.5% of the total electricity production, respectively. Surpluses (exported electricity) were not significant and reached only 1.3 MW in Scenario 2 and 0.5 MWh in Scenario 3. The reason for this is high electricity demand compared to the production capacity.

Figure 20 and 21 show the calculated electricity production from the BIOmCHP unit and from the PVs against the background of the demand curve in Scenario 2 and Scenario 3, respectively. Based on these results, the own consumption ratio can be calculated, as the ratio of the electricity generated and used on site to the total electricity generated. The own consumption ratio is 94.8% in Scenario 2 and 98.0% for Scenario 3.

The level of self-sufficiency (autarchy), that is defined as a ratio of directly used electricity generated on-site to the total energy consumed. The self-sufficiency ratio was estimated at 39.2% in Scenario 2 and 32.6% in Scenario 3. for the lower value of the ratio in Scenario 3 is caused by the electricity consumption by the electric boiler.

The results show that BIOmCHP runs for 4 765 hours a year in Scenario 2 and 4 323 hours in Scenario 3 (Tab. 5). These values correspond well with the 10-year lifetime for the LFPSE (50 000 h).

As the electricity production depends on the coolant temperature provided to the LFPSE, low-temperature heating systems, such as, floor heating, could further improve the amount of electricity delivered from BIOmCHP. On the other hand, this could imply implementation of a condensing flue gas heat exchanger and higher investment costs.

Further calculations could be done with higher records resolution (e.g. 1 minute instead of 1 hour) to better asses the correlation between momentary PV system production and heat demand covered by the electric boiler. However, such calculations require higher computing power [5].

3.2 Economic viability

Using the results derived from the operational performance of the building and the energy units, the economic viability of the scenarios can be calculated. The investments with shorter payback times are preferred and may induce the decision of potential implementation. At best, the economic viability should be achieved

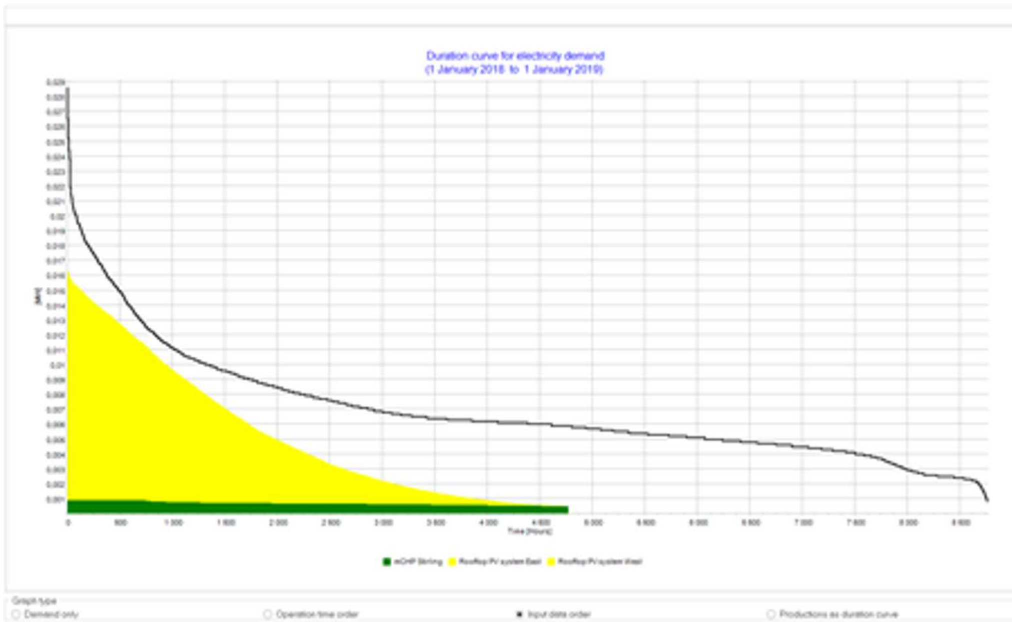

Figure 20: Electricity production – Scenario 2.

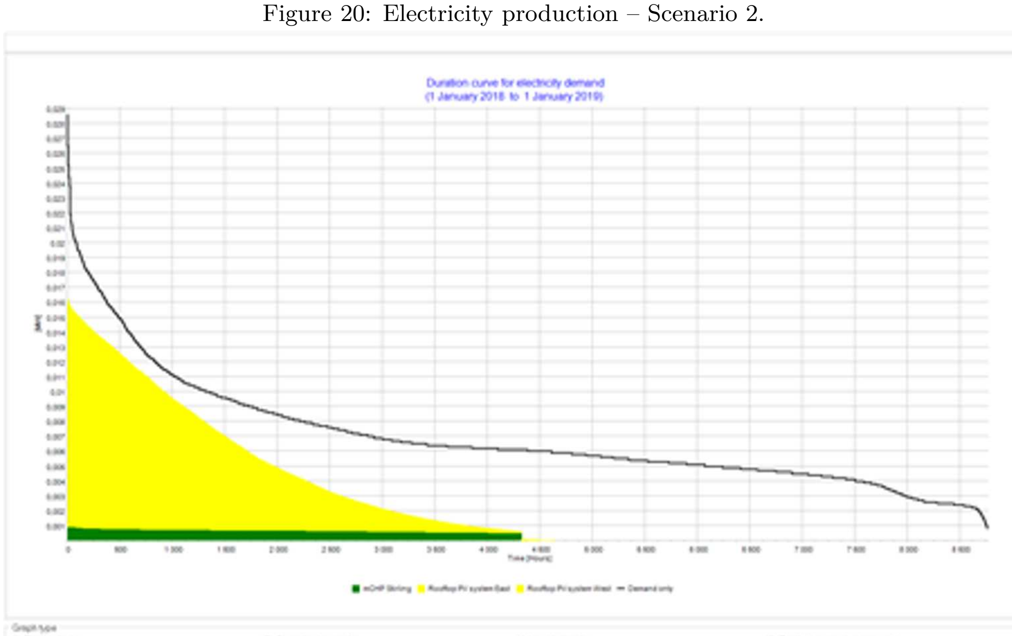

Figure 21: Electricity production – Scenario 3.

without any financial support.

In the simplified approach adopted in the present study, inflation, cash account surplus and debts interest rates as well as indexing prices were ignored.

Summary of the investments and operation expenditures is presented in Tab. 6 (all values in PLN, excl. VAT).

Table 6: Investment and operation expenditures for the scenarios.

Parameter	Reference (Scenario 1)	Scenario 2	Scenario 3
Revenues			
Own electricity consumption	0	10782	4935
Electricity surplus	0	398	168
Revenues Total	0	11180	5103
Operation expenditures			
Electricity purchases	27417	16635	22482
Fuel purchases	24400	15232	11405
Operation expenditures Total	51817	31868	33887
Net Cash from Operation	-51817	-20688	-28784
Investments			
BIOmCHP	0	47000	47000
Rooftop PV System	0	115200	115200
BoS	0	12000	3000
Total Investments	0	174200	165200

We can clearly see that the annual operation expenditures in Scenarios 2 and 3 are significantly smaller while compared with the reference Scenario 1 if the revenues from the own electricity consumption are included. The total difference is 31 129 PLN and 23 022 PLN, respectively.

Total investments are slightly higher in Scenario 2 in comparison with Scenario 3, as the buffer tank system is a bit more complicated to build than implementing the flow-through electrical boiler.

Because the electricity surpluses are insignificant, the prosumer scheme principles affect the actual situation only slightly. Assuming, that the given parameters do not change over the examined period of 10 years, the SPBT can be estimated. The results are presented in Fig. 22. The investment starts to return after 5.5 years in Scenario 2 and after 7.1 years in Scenario 3. It should be noted that these periods can be longer while considering broader economy context, but at the same time they can be easily offset by rising electricity prices and potential support schemes.

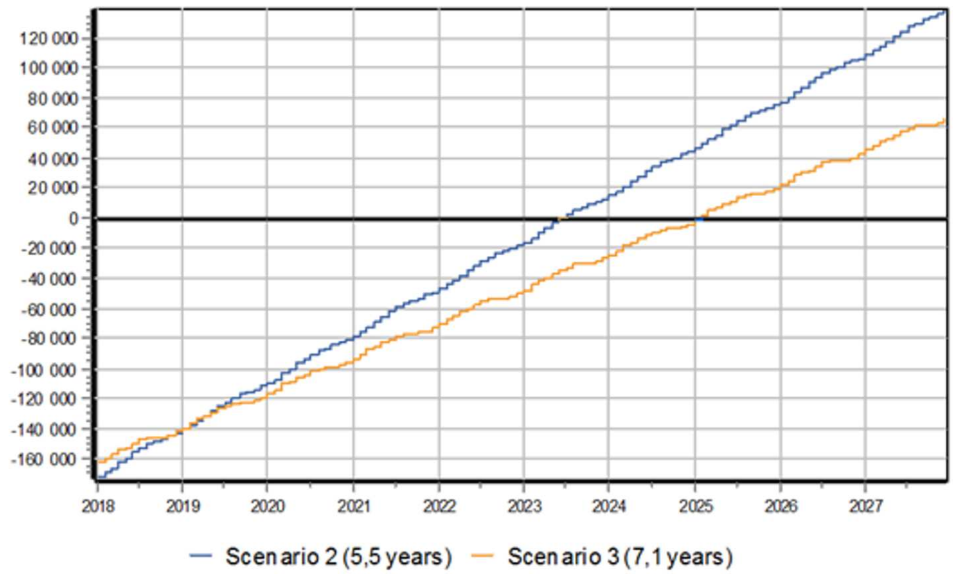

Figure 22: Payback times for the scenarios.

4 Conclusions

This paper evaluates feasibility of a concept microcogeneration biomass-fired unit based on a Stirling engine working together with a photovoltaic rooftop installation. The system is applied to a public building (forester's house), where electricity is delivered from the DSO grid and heating comes from an oil-fired boiler. A real electricity consumption profile was available.

The calculations proved, that replacing existing energy supply system for the building with BIOmCHP unit and PV shows payback times of 5.5 years or 7.1 years. As the fraction of electricity surpluses is very little, the impact of prosumer scheme is almost negligible.

Nevertheless the replacement of existing set-up is profitable. Application of buffer tank has positive impact for operation of the system. It allows for covering heat demand peaks, as well as cover heat demand while maintenance activities at the BIOmCHP are carried out.

Electricity generated by BIOmCHP in the range of 2.8–3.3 MWh per annum equals annual electricity demand of average household [5].

Scenario 3 with electrical boiler instead of buffer tank proved less economically effective despite lower investment costs. However, the advantage of this set up is, that electric boiler can act as back-up energy source. Impact of time zone tariffs for electricity can be further analysed.

Another element to be taken into account in further analysis, is the exchange of information between PV technologies, boiler regulator, heating system regulator, LFPSE module regulator and energy receivers. Balancing of generation and demand on "building level" e.g. by programming of dishwashers, washing machines, autonomous vacuum cleaners etc., LED, air conditioning etc. could further improve autarchy levels.

Connection of the system to district heating network could further improve both heat and electricity utilization [5].

Received in December 2018

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