Potential uses of small cogeneration systems in prosumer systems

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Abstract. This paper presents potential uses of small combined heat and power systems, with the Laboratory of Cogeneration Systems (LoCS) at the Centre of Energy of the University of Science and Technology (AGH) used as an example, and research capabilities of the LoCS.

1. Introduction

Combined heat and power, also called cogeneration (Figure 1), is defined to be a combined generation of heat and power or mechanical energy in one production process. This process is carried out in one device or a system of connected devices [1]. Pursuant to directive 2004/8/EC, micro-cogeneration includes systems with installed power under 50 kWe. However, it is more and more the case that, when talking about systems with the smallest power output, what is meant are systems generating no more power than 15 kWe, since such units can be used in single-family houses, public buildings or in small businesses [2,3].

Figure 1. Comparison of combined heat and power and separate heat and power [4].

The idea of sustainable development and the climate policy lead to increased importance of distributed sources in the modern model of power generation. The term distributed generation is understood as facilities generating energy for own purposes of the user or supplying energy to the distribution network. These units are not subject to rules of central disposal and can be connected
directly to a low-voltage or medium-voltage network. Distributed systems can have power output from several kilowatts to a dozen or so megawatts [1,5-7]. Prosumer power industry is part of distributed generation which includes generation sources with the smallest power outputs. A prosumer is an entity who/which is a producer and a consumer of energy at the same time. The energy generated is used for own purposes of a prosumer and the possible production surplus is sold off the grid. One of the more important legal acts defining the support for distributed power generation is the Renewable Energy Sources Act dated 20 February 2015. It defines microsystems as sources of energy with a maximum electrical power output of 40 kWe or with a thermal power output not exceeding 120 kWt which can be connected to a power grid with a maximum rated voltage of 110 kV. The said Act also stipulates that a microsystem can only use renewable sources of energy. This, in turn, limits the number of potential investors, since the act does not provide for support for sources using low-emission fuels such as natural gas or LPG [8,9]. Nevertheless, the acts in force can contribute to the growth of installed power from small cogeneration systems installed in single-family houses or public buildings.

2. Small cogeneration systems in the LoCS at the Centre of Energy of AGH

The primary subject of research at the LoCS (Figure 2) is to determine optimum configurations of small, local micro-cogeneration systems which can be used for the purposes of individual supply of buildings with electricity, heat and also necessary utilities (cooling energy, domestic hot water, air for ventilation). The concept of a research and didactic laboratory of this type is an important element of fulfilment of future energy security criteria and environmental requirements connected with limiting the emission of CO₂ and other harmful substances. The laboratory addresses comprehensively the issues of small cogeneration based on different types of sources of energy and technologies for its processing. The scope of research conducted at the LoCS pertains not only to diagnosing of states and parameters of operation of individual thermal devices, but also to determination of optimum conditions of reception of the generated electrical and thermal power through an internal (in a building) and external (Smart Grid, electrical network) network, assessment of dynamic states, quality of energy, inertia and reliability of small CHP systems and their cooperation as part of a common network (under laboratory conditions).

![Figure 2. Diagram of the LoCS at the Centre of Energy.](image)

The laboratory infrastructure allows conducting research on the efficiency of cogeneration systems for various power and heat demand profiles, i.e. electricity generated by a generator can be supplied to
users, stored in batteries or sent to the grid. Similarly, heat collected from combustion gases or as a result of cooling of an engine can be stored in a buffer, supplied to receivers (heat exchangers), converted into other parameters or other form of energy.

The system at the LoCS consists of the following CHP units along with supporting systems and systems protecting the functioning of the LoCS (e.g. simulating states of loads and protecting against electrical and thermal overload):

- a cogeneration system based on an engine with an internal combustion chamber for natural gas – SenertecDachs; electrical power: 5.5 kW, thermal power: 12.5–15.5 kWt;
- a cogeneration system based on an engine with an internal combustion chamber for biodiesel – SenertecDachs;
- a cogeneration system based on a Stirling engine – SenertecDachs with a Stirling engine; electrical power: 1 kW, thermal power: 3–5.8 kWt;
- a cogeneration system based on a piston steam engine – Lion Powerblock with a steam engine; electrical power: 0.3–2 kW, thermal power: 3.5–16 kWt;

![Figure 3. Concept of operation of a CHP micro power station with an engine with an internal combustion chamber.](image)

The laboratory makes it possible to search for an optimum (with regard to efficiency) strategy of putting under load the individual components of a CHP system (with different configurations depending on the current state of activity of users). In periods of smaller electricity demand, the characteristics of the total efficiency of the CHP system will be analysed under conditions where it is put under load by devices distributing electrical and thermal energy. The equipment at the LoCS was selected in such a manner so as to constitute an important basis for the conducted research on micro-cogeneration systems with concentration of units most commonly used for generation of electrical energy and heat as well as new, small generation units which are being placed on the market and may be widespread in prosumer systems in the future. Thus, for instance, over a hundred years of development of internal combustion engines makes these systems well-developed, ensuring high efficiency of conversion of energy in the fuel. This leads to their very widespread use in many machines such as means of transport, generators or cogeneration systems. These engines also provide excellent dynamic properties at variable load and are available in broad range of power in contrast to other technologies. Thanks to this, they are widely used in all kinds of machines, from microdevices to ship drives [2,3].
Figure 4. Cogeneration systems: a) an engine with an internal combustion chamber for natural gas – SenertecDachs; b) Lion Powerblock with a steam engine; c) Stirling engine – SenertecDachs.

For micro-cogeneration units, high efficiency of internal combustion engines is one of their main advantages and that is why technologies using them are leading systems on the market for electrical power in the range of 1–5 kWe. These engines are able to work using natural gas as fuel thanks to which they can take advantage of well-developed infrastructure of supplies of gas in many countries. Other advantages of combustion engines used in cogeneration are low investment cost and easy maintenance. In turn, vibration, emission of noise and exhaust gases are the main disadvantages with regard to the use of these engines in single-family systems [7]. Compared to piston engines, Stirling engines can be supplied with various fuels. The most frequently used fuel is natural gas, albeit a Stirling engine can also be supplied with heat from a renewable/geothermal/waste source. External combustion allows greater control of the process of combustion as well as results in very low indices of emission of pollutants, low level of noise and high efficiency. What is more, the fact that combustion process products do not come in contact with moving parts of the engine improves durability of the device and reduces lubricating oil consumption. An external combustion engine is characterised by low price per unit of generated energy and high reliability. However, the use of expensive materials and complexity of the design make the price to installed power ratio almost two times higher than in the case of piston engines. They are also heavier than units with combustion engines with the same power. This is due to the necessity to use good heat exchangers which make it possible to transfer the heat from external heat sources to the working medium [7]. A cogeneration system based on a piston steam engine which converts thermal energy into mechanical energy and, further on, through a linear generator, into electricity. A technology taking advantage of steam generators, used for cogeneration of energy, has a commercial application. It is not a very widespread technology yet, but there are companies which offer such products. Among the leading companies in the area are: Spilling, Tenza, Lion Energy. As the only company, Lion Energy offers a solution of cogeneration of energy for the individual consumer – in the form of the Lion Powerblock. The device was designed to work in a prosumer system thanks both to its dimensions and its electrical power. This device allows one to satisfy completely heat demand of an individual user and, at the same time, satisfy 80% of electricity demand. Nonetheless, due to high unit costs of this type of device, it cannot compete with small combustion cogenerators, the work on increasing this type of devices requiring further research.

3. Tests of efficiency of the SenertecDachs cogeneration unit with an internal combustion chamber
The chemical energy of fuel supplied to the CHP unit was calculated according to the following formula:
\[ \dot{Q}_{\text{pal}} = \dot{m}_{\text{pal}} \cdot B \]  

(1)

where:
\[ \dot{m}_{\text{pal}} \] – fuel stream
\[ B \] – net calorific value of fuel oil

For the purposes of calculation of efficiency, the net calorific value of fuel oil was taken to be 43 MJ/kg.

Electrical efficiency was calculated using the measured value of active power:

\[ \eta_e = \frac{P}{\dot{Q}_{\text{pal}}} \]  

(2)

Thermal efficiency was calculated using the measured value of active power:

\[ \eta_c = \frac{\dot{Q}}{\dot{Q}_{\text{pal}}} \]  

(3)

Total efficiency of the cogenerator was the sum of electrical efficiency and thermal efficiency:

\[ \eta = \eta_e + \eta_c \]  

(4)

A cogeneration system based on an engine with an internal combustion chamber for biodiesel – SenertecDachs.

According to the manufacturer's data, the tested device achieves parameters shown in Table 1.

**Table 1.** Parameters of a CHP unit as given by the device's manufacturer.

| Technical data of the SenertecDachs HKA HR 5.3 system |
|-------------------------------------------------------|
| - power consumption (net calorific value) 20.5 kW     |
| - electrical power 5.5 kW                             |
| - thermal power without condenser 11.7 kW             |
| - thermal power with condenser 14.8 kW                |
| - maximum hot water supply temperature 83°C           |
| - maximum return temperature 70°C                    |
| - electricity generation efficiency 27%               |
| - efficiency of thermal energy generation with condenser 72% |
| - total efficiency (electrical and thermal) of up to 99% |
| - mode of operation of controllers: depending on the heat demand |
| - technical inspections every 2,700 hours of work      |
| - service life of devices of even up to 20 years       |

Tests were carried out for the following cases:
- cold start, i.e. for a start of the device with temperature equal to the ambient temperature;
- warm start, i.e. the device was turned off for 30 minutes after an hour of work at full load and then started again;
- the device was working in stable conditions at preset temperatures of buffers (30, 40, 50, 60°C).
Figure 5. Momentary electrical efficiency in the stable range of operation.

Figure 6. Momentary thermal efficiency in the stable range of operation.

The above graphs show that slightly better electrical efficiency during start-up was recorded in the case of the cold device (Figure 5), whereas, in the case thermal efficiency, the cogenerator behaved in a better way when starting after a short break (Figure 6). Larger differences in thermal efficiency had a decisive impact on the total efficiency. However, in the last minutes of measurement of efficiency of both start-ups, they get closer to each other achieving 86–89%.
Figure 7. Momentary total efficiency in the stable range of operation.

Figure 8. Momentary electrical efficiency in the stable range of operation depending on the thermal load.
Figure 9. Momentary thermal efficiency in the stable range of operation depending on the thermal load.

Figure 10. Momentary total efficiency in the stable range of operation depending on the thermal load.
In the case of the preset temperatures of reception, there are more visible differences in the achieved efficiencies. Thermal efficiency of the measurement at the lowest temperature exceeds the efficiency of the highest preset temperature by approximately 10% (Figure 10). There is a clear decrease in the total efficiency along with an increase in thermal load temperature. This is reflected on the graph of the total efficiency shown in Figure 10, especially in the case when electrical efficiencies do not exhibit dependency on the system temperature (Figure 8).

A summary of efficiencies achieved by the system was well presented in Figure 11 which took into account the average values of efficiency at a preset temperature. It can be concluded that the system achieved the efficiencies declared by the manufacturer. Nevertheless, it is necessary to point out that there was a considerable decrease in thermal efficiency as the temperature of reception of heat rose.

![Figure 11. Average values of efficiency during stable operation.](image)

4. Conclusion

Cost-effectiveness of the use of cogeneration systems depends mostly on the device cost and its operating time as the basic component. Operation of devices of this type requires constant reception of heat thanks to which the efficiency of a module in this mode is higher and thus the return on investment is faster. It is recommended that small cogenerators work as the basic heating components during the winter and be configured with adsorption refrigerators and produce cooling energy for air conditioning purposes during the summer. Thanks to such a solution, these systems can work more efficiently. To date, only systems with a piston engine have a price which allows return on investment in a shorter period of time than the expected service life of a device, provided that it works continuously. Too weak a scheme of support of systems running on natural gas in the form of funding for purchase and installation of a device makes systems with high initial costs, such as a steam engine or Stirling engines, uneconomic when using them in multi-family buildings. Cogeneration systems running on natural gas and based on piston engines are the only combined heat and power technology so far which is cost-effective when used in multi-family buildings. Other technologies seem to be an interesting prospect for prosumer energy generation, albeit high costs and insufficient support in the form funds for low-emission sources of energy hinder popularisation of the combined heat and power technology in multi-family residential housing. However, the observed upward trends in terms of the number of newly installed cogeneration modules prove strong interest in this technology and that is why the Centre of Energy at AGH, in response to market needs, founded the Laboratory of Cogeneration Systems where one can carry out a series of tests aimed at optimisation of operation of cogeneration devices and search for new technical solutions which can result in more efficient work of cogenerators.
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