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Review Article

COMBINED SYSTEMS OF ENERGY GENERATION − A CHARACTERISATION AND CLASSIFICATION

Jan Gilewski[1], Jerzy Montusiewicz[2]

[1] Elektroprojekt S.A., Lublin, Poland, e-mail: bjgilewski@o2.pl

[2] Institute of Computer Science, Lublin University of Technology, Nadbysrtrzycka 36b, 20-618 Lublin, Poland, e-mail: j.montusiewicz@pollub.pl

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ABSTRACT
The study presents issues concerning technical solutions of combined systems of energy generation which can be used primarily in low-level power plants, installed in various types of public utility sites. A detailed description is given of selected ways of powering combined energy generation systems, presenting conceptual outlines of their operation and information on their advantages, disadvantages and applications. The following systems are introduced: gas-steam, back-pressure steam turbine, extraction-condensing steam turbine, gas turbine, gas microturbine, Stirling engine, fuel cells and internal combustion piston engine. Moreover, the study addresses economic aspects of energy generation in combined systems, discussing different methodologies of cost calculation, including the one used by the European Union. The article also gives a detailed review of piston engine combined-system aggregates available in the Polish market. Type series of associated systems designed for low-power appliances are shown, produced by Polish and foreign companies such as Viessmann, Centrum Elektroniki Stosowanej CES, H. Cegielski – Poznań, KWE Technika Energetyczna, TEDOM Poland or the EPS System.

Keywords: Combined Heat and Power (CHP), combined energy generation, cogeneration systems.

INTRODUCTION

The basic energy carriers such as electricity, heat and cold are produced, both in Poland and in the world, mainly as a result of thermal processes using the chemical energy contained in solid, liquid or gaseous fuels. Such energy technologies should fulfil the following technical-ecological and economic specifications [1]:

- be characterised by the greatest efficiency in energy processing,
- possess the most advantageous indices of economic profitability, i.e. have a short time of investment return and ensure a high profit value,
- have the least conceivable negative influence on the environment, i.e. emit a minimum of toxic dusts, gases, noise and waste, using in the process as little water as possible.

The realisation of the above-mentioned goals depends both on the kind of technology of electricity and heat production that we use (e.g. application of combined or separate systems) and the type of fuel used (e.g. solid, liquid or gaseous).

Combined systems of energy generation using gas module engines are regarded as distributed generation systems. There is no firmly grounded and generally accepted terminology in this regard. According to the CIGRE 37-23 Working Group (WG 37-23) [2] distributed generation refers to power sources from 50 to 100 MW whose construction is not centrally planned. Such sources are not subject to central disposition of power, although in most cases they are part of the distribution network. In Poland the power limitation of distributed generation systems to 150–200 MW results from their influence on the course of operation of the distribution network of no more than 110 kV. In practice there are examples of combined systems which are never part of the distribution network and are entirely autonomous systems. This is the situation on boats and ships [3], where the entire energy produced is divided into driving, electric and heating energy.

The notion of combined systems is broader than that of cogeneration systems. The latter produce two types of energy, e.g. electricity and heat, whereas the former can have more energy factors.

Considering the information prepared by the CIGRE 37-23 Working Group [2], the definition of combined systems could be generalised. Thus they are small systems of distributed generation of nominal power of up to 150 MW, or systems attached directly to distribution networks, or ones localised directly in the consumer's electric energy network behind the metering and billing system, which produce electricity from original energy (e.g. chemical one) in association with the generation of heat or cold.

The basic task of combined systems is to meet the energy demand of both community and industrial consumers. Such systems, known as CHP ones (Combined Heat and Power), belong to the most efficient technologies of distributed power engineering and bring numerous technological and ecological advantages. The electricity produced in such systems can be used in a building in its entirety or be partly sold to other consumers. On the basis of catalogue data analysis it is worth mentioning that the general efficiency of a combined system may reach 90%, while that of a power plant only between 30 and 40%.

Users of combined systems include:
- public utility sites (hotels, office blocks, shopping centres),
- sports centres (sports halls, swimming pools and skating rings),
- educational centres (universities, schools),
- industrial plants of diverse specialty,
- health service sites (hospitals, out-patient wards, sanatoriums),
- community sites (clusters of single- and multi-family housing, waste treatment plants), etc.

TECHNICAL ASPECTS OF COMBINED SYSTEMS

A description of different technical solutions of combined systems is given, among other places, in Kiciński and Lampart [4], as well as in reference [5, 6, 7, 8]. The authors present selected solutions for those systems which can be used in CHP-type arrangements.

Today there are many different kinds of technological solutions of combined systems:
- gas-steam systems,
- with back-pressure steam turbines,
- with extraction-condensing steam turbines,
- with gas turbines,
- with gas microturbines,
- with Stirling engines,
- with fuel cells,
- with internal combustion piston engines,
- and others (meeting the criterion of simultaneous generation of electricity and heat and/or cold).

Gas-steam systems

Combined gas-steam systems serve the generation of heat and electricity in a system of a gas machine (gas turbine) and a steam machine (steam turbine). In gas-steam systems there is an interrelation of the thermodynamic circuits of a gas turbine and a steam turbine via the exhaust waste heat utilised in the heat recovery boiler. Due to this arrangement a hybrid system of increased efficiency is created, combining a high-temperature circuit realised in a gas turbine with a low-temperature steam circuit [9]. A diagram of the working of a cogeneration gas-steam heat and power plant is shown in Figure 1.

Two types of gas-steam heat and power plants can be distinguished:
- systems working in an open circuit – the closure of the gas fuel circuit takes place via the surrounding atmosphere (air);

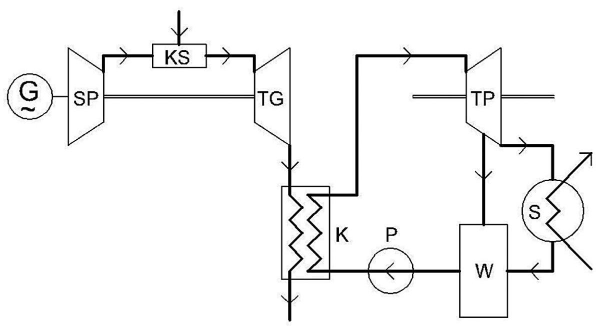

Fig. 1. Outline of a cogeneration gas-steam heat and power plant (with a gas turbine and a heat recovery boiler); G – power generator, SP – air compressor, KS – combustion chamber, TG – gas turbine, K – recovery boiler (steam exchanger), TP – steam turbine, S – condenser, W – heat box (reservoir), P – circulation pomp

- systems working in a closed circuit – in such a system a constant amount of working factor (gas exhaust) keeps circulating.

In view of their high investment costs, in Poland combined gas-steam systems are only used in industrial installations and low-level power industry electrical engineering, in which they reach capacity between 20 and 200 MW. Cogeneration systems with gas-steam turbines combine the advantages of gas and steam systems, which causes an increase in the difference of the exit process temperatures (steam) compared to the entrance process (gas exhaust), which in turn raises the thermal efficiency of the whole system.

Systems with a backpressure steam turbine

A cogeneration system with a back-pressure steam turbine is an example of a cogeneration system of power industry electrical engineering. Such a system has a back-pressure turbine working in a close circuit, supplied by decompressed overheated steam produced in a boiler. Having come through the turbine the steam passes to the exchanger, where it gives off its excess heat to heat up the water in the heating network. A diagram of a cogeneration system with a back-pressure turbine is shown in Figure 2.

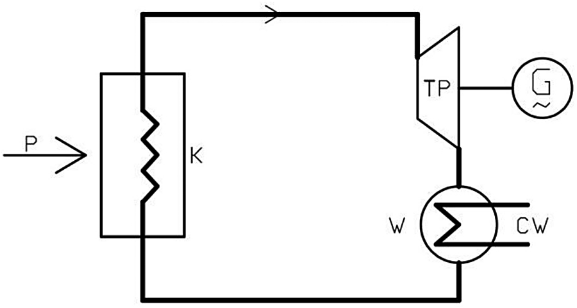

Fig. 2. Outline of a cogeneration heat and power plant with a back-pressure steam turbine; P – fuel, K – boiler, TP – steam turbine, G – power generator, W – condenser, CW – hot water [4]

Such a system is characterised by a simplicity of structure and a relatively low demand for water. A disadvantage is the high dependency between the electricity produced and the demand for heat and the exploitation of only high pressures in the production of electricity. Back-pressure turbines as cogeneration systems are characterised by high total efficiency. The steam obtained is used for technological and heating purposes. They are mainly applied in (power) industrial installations.

Systems with an extraction-condensing steam turbine

A cogeneration system with an extraction-condensing steam turbine works similarly to one with a back-pressure steam turbine, but differs by the presence of several heat extractions (several degrees of steam extraction) from the turbine as one goes towards the steam entrance. Such a solution ensures the exploitation of a wider scope of pressures and temperatures in electricity generation.

Just like cogeneration systems with a back-pressure turbine, systems with an extraction-condensing steam turbine are characterised by a high efficiency of the whole system. They are also mainly applied in (power) industrial installations in view of the high powers installed and the investment costs. A outline of a system with an extraction-condensing turbine is shown in Figure 3.

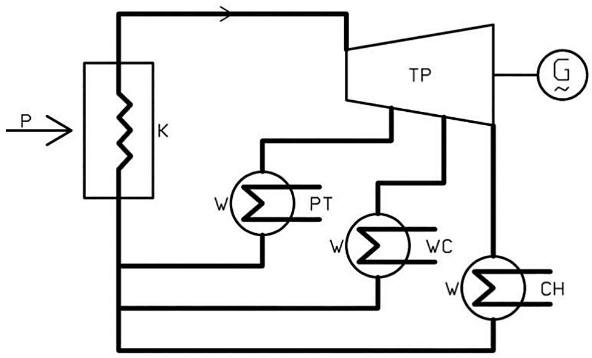

Fig. 3. Outline of a cogeneration heat and power plant with an extraction-condensing steam turbine; P – fuel, K – boiler, TP – steam turbine, G – AC generator, W – heat exchanger, PT – technological steam, WC – hot water, CH – cooling water [4]

Systems with a gas turbine

The basic elements of a cogeneration system with a gas turbine are: a compressor, a generator turbine (on a common shaft) and a combustion chamber between them. The driving energy is obtained from the exhaust of the gas burning in the combustion chamber. The exhaust drive a turbine, which in turn drives the generator and compressor. At the turbine exit we get the exhaust, which makes its way out (an open system) or pass through the heat exchanger (recovery boiler), from which heat is recovered (a closed system) (Fig. 4.)

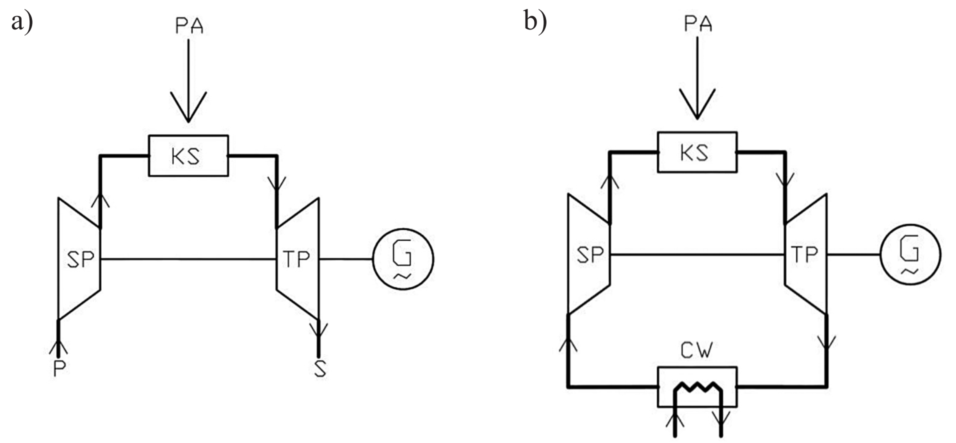

Fig. 4. Outline of a cogeneration heat and power plant with a gas turbine: a) open system, b) closed system; PA – fuel, KS – combustion chamber, TP – gas turbine, G – AC generator, SP – compressor, CW – low-temperature heat exchanger [1]

Systems with a gas microturbine

Systems with gas microturbines are gas turbosystems of small power. Their construction is similar to classical gas turbines except for slight differences. However, their capacity does not surpass a few hundred kilowatts.

Just as in a classical gas turbine, a gas microturbine is made up of [1]:
- mechanically and thermally connected one-step radial turbines and compressors;
- a regenerative exchanger between the compressor and combustion chamber, increasing the efficiency of the whole system;
- a high speed generator, together with a power-electronic converter system, allowing to adjust the parameters of the energy produced to the demands of the electric energy network.

The advantages of gas microturbines include:
- small overall dimensions,
- high efficiency of the whole system,
- reliability of operation and ease of use,
- low emission of pollutants,
- ability to supply different fuels (gaseous, liquid),
- ability to work in a grid or insular system.

Examples of applications:
- emergency power supply of public utilities such as offices, hospitals, etc.,
- as a source in distributed energy engineering.

Systems with a Stirling engine

Cogeneration systems with a Stirling engine use reciprocating heat engines with external combustion, which means that the working element – which is the piston moving in the cylinder – is supplied by energy from an external source. Since energy is passed to the system from outside it, it becomes possible to supply such an engine from an arbitrary source of heat. A source of heat can be the process of burning energetic fuel, but also concentrated solar radiation, geothermal energy, etc. At the basis of the operation of a Stirling engine lies continuous heating and cooling, that is continuous supply of potential difference of heat to the appropriate zones of the piston in the cylinder. A engine works in a closed circuit with any working gas, together with heat regeneration while keeping the gas volume constant (in Carnot's cycle). Despite the fact that the first copies of those engines were developed already in the 19th c., such systems found no general use, but are still within the interest of constructors and scientists.

Systems with fuel cells

Fuel cells are galvanic cells generating electric power from chemical energy on the basis of chemical fuel constantly supplied from outside. The mass flow of the fuel is correlated with the current cell load. In contrast to classical galvanic cells, electrodes take no direct part in electrochemical processes, only steer those processes, therefore their lifespan is theoretically limitless. The lifetime of the electrodes is limited by their structural stability, not chemical one.

In a fuel cell there occurs a direct transformation of chemical energy into electrical one without the mediation of heat and limits resulting from the application of Carnot's circuit, due to which a high efficiency of the whole process is achieved [10]. Just as ordinary galvanic cells, it contains two electrodes and electrolyte. The reacting substances (fuel and oxidant) are supplied non-stop. Apart from electrical energy, a product of a fuel cell's work is heat. The temperature achieved reaches around 200 ˚C (low-temperature cells) or 1000 ˚C (high-temperature cells) [11]. At present, both in the USA and in Europe, there are initiatives to commercialise the production of fuel cells as solutions of distributed cogeneration. Their capacity reaches some 200 kW. The greatest fuel cell systems achieve the capacity of 11 MW [12] and are used in power industry.

Systems with internal combustion piston engines

Cogeneration systems with piston engines are characterised by a wide range of rated power, modularity, low capital and investment costs and a short construction and installation time. They also feature a fast start, flexible keep-up with the load, high efficiency at partial load and high reliability. They can be used in objects of wide utility as emergency or peak-time sources, but they can also be put to sub-peak or even basic service, providing power, heat or even cold. Their fundamental flaws are pollution emitted into the atmosphere and noise emission.

Current production includes low-emission engines with spark ignition, powered by natural gas or biogas with a low degree of compression in relation to engines with compression ignition. Such engines are characterised by 60–80% of the power of diesel engines, which ultimately contributes to higher investment costs [11]. Yet when powered by natural or biogas, they have lower pressure in the cylinders and less bearing load, which as a consequence causes a lengthening of exploitation time. Figure 5 shows a outline of a cogeneration system using a piston combustion engine.

The basic cogeneration module using piston engines consists of:

- a system generating electricity (generator) and heat;
- electric safety system;
- auxiliary drives switchgear;
- installation of automatic oil refill;
- noise mufflers at exhaust and air exits;
- master control cabinet enabling monitoring and visualisation of the operating parameters;
- electricity network synchronisation system;
- emergency cooling system;
- soundproof enclosure.

A piston engine powered by natural gas, propane or biogas is placed on a common shaft with an asynchronous generator. The work of such a kit enables the production of electricity and heat. As a result of gas combustion the piston engine produces heat as an additional product of energy conversion. Silnik tłokowy zasilany gazem ziemnym, propanem lub biogazem posadowiony jest na wspólnym wale z prądnicą asynchroniczną. The work of such a kit enables the production of electricity and heat. As a result of gas combustion the piston engine produces heat as an additional product of energy conversion. This heat is received from the body of the engine and the exhaust expelled, then recovered by the heat exchanger circuits, added up and by a water or glycol system transmitted to the receptor. To achieve the assumed temperature of the water or glycol at the output of the module and for a stable op-

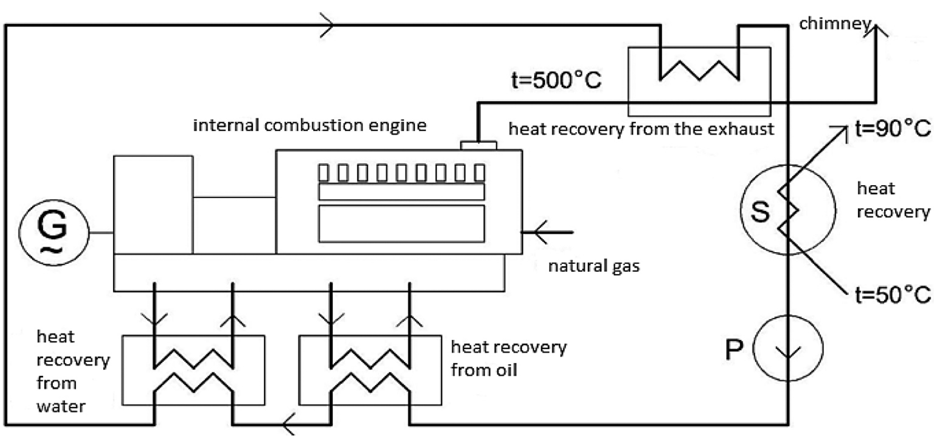

Fig. 5. Outline of a cogeneration circuit using an internal combustion piston engine: P – circulation pump, S – heat exchanger, G – electricity generator [13]

eration of the cogeneration system an auxiliary drives switchgear is used. This switchgear controls the valves of the emergency cooling system and continuously monitors the coolant:

- in the case of too hot water at the entrance to the cogeneration system, it redirects part of it to an additional cooling system;
- in the case of too cold water a by-pass is activated, warming it up to a designated temperature.

For CHP modules water parameters are assumed at 70 °C at input and 90 °C at outlet [9]. High temperature heat is obtained just from the flue gas at a temperature of 400–600 °C, while the heat obtained from cooling the engine block does not exceed 95 °C [14].

ECONOMIC ASPECTS OF COMBINED SYSTEMS

Calculating the cost of electricity and heat generation in combined systems in order to assess their economic competitiveness can be done by designating the unit cost of production, taking into account the entire period of its existence. The elements of the economic calculation of the combined technology of power generation are:

- investment costs;
- operating costs, understood as system servicing, current supervision, etc.;
- fuel costs;
- the costs of decommissioning at end of life.

In the literature one can find several methods to determine the unit cost of production of electricity and heat, including how this is to be understood in combined systems [11, 12, 15]. In [16] the authors consider the explores the effects of micro CHP systems for energy companies.

One of the criteria for selecting the most efficient design of electricity and heat generation is unit cost. According to the authors of paper [10] discounted long-term unit cost of production in the proposed systems of electricity generation in combined technology can be calculated from equation (1):

$$k_j = \frac{\sum_{t=0}^{n} I_t a_t + \sum_{t=0}^{n} K_t a_t - WM_N a_n}{\sum_{t=0}^{n} A_t a_t} \quad (1)$$

where: a_t – discounting factor $a_t = \frac{1}{(1+p)^t}$;

a_n – discounting factor of the last n-th year of analysis, $a_n = \frac{1}{(1+p)^n}$.

p – discounting rate, or the period of analysis including the period of the object's construction (b years) and operation (N, e.g. 30 years);

I_t – investment outlay in year t;

K_t – current operating costs (maintenance, renovation and fuel) in year t;

WM_N – object value in year N (final, as yet unamortised, value of fixed capital);

A_t – energy generated in year t;

„0” – base (zero) year, or the year of the first expense or the year of economic analysis.

A similar methodology for calculating the cost of production of electricity and heat in diffuse sources was applied by the European Commission in 2008 with the publication of a collection of documents under the title: „Second Strategic Energy Review – An EU energy security and solidarity action plan”. One of the documents it includes is: “Energy Sources, Production Cost and Performance of Technologies for Power Generation, Heating and Transport”. The method presented can calculate the equivalent unit cost of production of electricity and heat – see formula (2), [15]:

$$COE = \frac{SCI \cdot (1 + IDC) \cdot CRF \cdot}{8760 \cdot LF} + \frac{FOM}{8760 \cdot LF} + VOM + FC + CC + CTS \quad (2)$$

$$COE = \frac{SCI \cdot CRF}{8760 \cdot LF} + \frac{FOM}{8760 \cdot LF} + VOM + FC$$

where: 8760 – ratio equivalent to the number of hours per year;

COE – equivalent unit cost of electricity generation, € / (MW × h);

COH – equivalent unit cost of heat generation, € / toe;

toe – tonne of oil equivalent – energy equivalent to one metric tonne of crude oil with a calorific value equal to 10,000 kcal / kg;

SCI – individual investment in manufactured facility, € / MW or € / toe;

IDC – interest on capital expenditures during the construction of the facility;

CRF – equity installment (return on equity);

LF – annual utilisation of the capacity of the facility;

FOM – equivalent (for the time of operation) annual fixed operating costs, € / MW or € / toe;

VOM – equivalent unit variable operating costs , € / (MW × h) or € / toe;
FC – equivalent unit fuel costs, € / (MW × h) or € / toe;
CC – equivalent unit CO_2 emission costs, € / (MW × h);
CTS – equivalent unit costs of transport and storage of captured CO_2 € / (MW × h) (in the case of energy sources equipped with facilities for CO_2 interception and storage).

COGENERATION SYSTEMS USING PISTON ENGINES

Analysis of the parameters of the produced gas cogeneration units with piston engines reveals that:

- the largest amount of heat comes from the cooling system of the engine block and the circulation of lubricating oil cooling system;
- additional heat is recovered by cooling the exhaust gas;
- the amount of heat recovered from the engine cooling system, relative to the chemical energy of fuel, represents about 30%;
- the amount of electric power produced relative to the heat is distributed approximately half-in-half, with a slight advantage of the electric power over the thermal power;
- recovered heat is most commonly used for domestic hot water.

On the basis of analyses of selected manufacturers' data sheets it can be stated that systems associated with compression are currently available in a wide power range from about 400 kW to about 5000 kW of electrical power and heat. Therefore, such systems are used primarily where less heat output is needed. They also have limited capabilities in terms of steam generation, but have a higher round-trip efficiency (close to 90%) compared to combined systems based on a gas turbine.

Currently, the domestic market has several major suppliers of gas aggregate systems combined with piston engines, who offer units built with components from different manufacturers. Table 1 shows a list of selected suppliers and their products belonging to so-called small-scale energy appliances (5 KW to 5 MW [4]).

The features of the above systems include [19]:

- control system package;
- handling and visualisation of the functional processes and control by a PC and a touch terminal;
- the use of additional control functions (such as adjusting the gas pressure or heat generation);
- interconnection, supervision and control of the multiport systems via Ethernet;
- possibility to connect to a master control system;
- support of various communication protocols (e.g. Ethernet, Profibus DP, 3964R, Modbus RTU);

Table 1. List of firms producing type series of associated systems with combustion engines

Company	Modules offered
VIESSMANN Sp. z o.o [17]	Vitobloc 200 EM-18/36 … EM-401/549 (from 18 kWe/36 kWt to 401 kWe/549 kWt)
CES Sp. z o.o. [18, 19]	MTU Seria 400 (from 119 kWe/198 kWt to 420 kWe/504 kWt) MTU Seria 4000 (from 772 kWe/872 kWt to 1948 kWe/2156 kWt) MWM Seria TCG 2016 (from 400 kWe/428 kWt to 800 kWe/856 kWt) MWM Seria TCG 2020 (from 1200 kWe/1189 kWt to 2000 kWe/1977 kWt) MWM Seria TCG 2032 (from 3333 kWe/3206 kWt to 4300 kWe/4164 kWt)
H. Cegielski – Poznań S.A. [20]	module with motor WAUKESHA APG 1000 – 1002 kWe module with motor MWM TCG 2016 V12C – 600 kWe module with motor MWM TCG 2016 V16C – 800 kWe
KWE Technika Energetyczna Sp. z o.o. [21]	Jenbacher type 2 (J208) – 200-300 kWe Jenbacher type 3 (J312, J316, J320) – 500-1000 kWe Jenbacher type 4 (J412, J416, J420) – 1000-1500 kWe Jenbacher type 6 (J612, J616, J620, J624) – 2000-4500 kWe Jenbacher type 9 (J920) – 9,5 kWe
TETOM POLAND Sp. z o.o. [22]	Micro T7, T30, T50 (from 7 kWe/17,2 kWt to 48 kWe/91,0 kWt) Cento M50, T80, T100, T120, T160, T180, T200 (from 50 kWe/79,0 kWt to 200 kWe/239,0 kWt) Quanto D400, D580, D770, D1200, D1600, D2000 (from 400 kWe/456,0 kWt to 2000 kWe/2155,0 kWt)
EPS SYSTEM [23]	60 GA (41 kWe/72,8 kWt) 85 GA (57,8 kWe/99,5 kWt) 150 GA (111 kWe/170 kWt) 2500 GH (1151 kWe/1388 kWt) 4100 GH (1501 kWe/1840 kWt) 5300 GH (1927 kWe/2324 kWt)

- record of the history of operations and events in the database (from the period of 6 months);
- optional remote diagnostics system via ISDN;
- option to notify the operator via text messages / e-mail (reports, alarms).

An example of a large public utility site using combined generation with a 1.6 MW piston engine is the complex of buildings of Prince Charles Hospital in Brisbane, Australia. The system generates electricity and hot utility water and technological steam [24]. Another interesting example is the designing of combined generation aggregates for already existing office blocks in Sydney [25].

CONCLUSIONS

The article presents an overview of cogeneration systems used in distributed power generation as well as in power industry. Based on the analysis of existing design solutions one can make their basic division into those used in the power industry and in distributed networks. Due to more attention currently paid to environmental issues the boundaries of classical divisions are becoming blurred. At present application systems in power industry are mainly associated with high power ratings, while in distributed power – with low ratings (less than 1 MW, though some move this limit to the value of 5 MW [4]). Installed systems using gas and steam turbines are primarily used in power industry and are characterised by high power ratings – above 1 MW.

Cogeneration systems used in distributed power generation are selected taking into account the characteristics of the object supplied. In the case of power industry, systems supply the national electricity system, which has a relatively rigidly defined parameters and it is not possible to determine the parameters of individual loads received.

In Poland, public utilities are most commonly powered by cogeneration systems using piston engines.

The authors deal with the topic of the article in the context of the multicriterial optimalisation of the selection of combined generation systems with regard to the needs of powering a public utility site such as a hospital. Such systems can also be used for powering other utility sites, using – apart from electricity – technological heat, steam and technological cooling. Such a solution, apart from economic effects, can raise the power generation reliability ratio. Using several units of lower power can also raise the power generation flexibility on a yearly basis, depending on the energy needs of the site powered. Thus the designed associated technologies of energy generation should be characterised by the highest possible capacity, modular structure, scalability and the possibility of flexible enlargement. Further, they should display the most advantageous indices of economic return, low environmental impact through low emission of dust, gas, sewage and noise, as well as low water consumption.

Associated systems used in dispersed energy production are selected with regard to the load characteristics of the site powered. For an optimal choice, different criteria should be used and the whole process should be a multi-stage one. In the case of professional energy production the systems supply the national electricity generation system, characterised by relatively inflexible parameters and the lack of the possibility of specification of reception parameters. Power generation in public utility sites In Poland most often uses combined generation systems with piston engines in the power range of several kilowatts to several megawatts.

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