Concepts of energy use of municipal solid waste

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Abstract: The introduction highlights the technologies of converting the chemical energy of biomass and municipal waste into various forms of final energy (electricity, heat, cooling, new fuels) as important in the pursuit of a low--carbon economy, especially for energy and transport sector. The work continues to focus mainly on gasification as a process of energy valorization of the initial form of biomass or waste, which does not imply that other methods of biomass energy use are not considered or used. Furthermore, the article presents a general technological flowchart of gasification with a gas purification process developed by Investeko S.A. in the framework of Lifecogeneration.pl. In addition, selected properties of the municipal waste residual fraction are described, which are of key importance when selecting the technology for its energy recovery. Significant quality parameters were identified, which have a significant impact on the production and quality of syngas, hydrogen production and electricity generation capacity in SOFC cells. On the basis of the research on the waste stream, a preliminary qualitative assessment was made in the context of the possibility of using the waste gasification technology, syngas production with a significant share of hydrogen and in combination with the technology of energy production in oxide-ceramic SOFC cells. The article presents configurations of energy systems with a fuel cell, with particular emphasis on oxide fuel cells and their integration with waste gasification process. An important part of the content of the article is also the environmental protection requirements for the proposed solution.

Introduction

Conversion technologies of the chemical energy of biomass and municipal waste to various forms of final energy use (electricity, heat, cooling, new fuels) are considered important in the pursuit of a low-emission economy, especially in terms of energy and transport. The consequence of the diversity of this class of substances is the technological differentiation of the conversion processes. This applies to both the methods of refining the substrates as well as the energy generation technologies. This study focuses mainly on the gasification as a process of energy valorization of the initial form of biomass or waste, which does not mean that other methods of energy use of biomass are not considered and applied. Biomass and waste can be combusted in steam boiler installations in large power plants (usually fluidized-bed boilers and classic condensing power plants) and in small power plants. In the latter case, in many studies (Thilak et al. 2011, Huang et al. 2013, Maraver et al. 2013, ZT Lian et al. 2010, Al-attab et al. 2015, Dong et al. 2009, Sipilä et al. 2005) cogeneration systems (electricity, heat) and trigeneration systems (electricity, heat, cooling) are considered.

Syngas produced from the gasification of MSW (or biogas in the case of biological conversion) may be injected and combusted in engines and installations enabling higher efficiency in the generation of electricity, heat and fuels. Reciprocating engines, gas turbines and fuel cells can be used in installations for the energetic use of syngas. In specific solutions, it is also possible to generate hydrogen to be utilized in other installations, e.g. in the transport sector. The general concept of organization of the installation for the energy use of biomass and waste is shown in Fig. 1.

Specific solutions depend on the type of input substances (substrates), gasification technologies used, treatment processes and energy systems. If the final useable energy is electricity, then in the simplest case the energy installation will be an autonomous gas turbine, a reciprocating engine or a fuel cell. In all these cases, technologies make it possible to produce heat, which will always be a rational solution. The use of a high-temperature fuel cell enables the construction of hierarchical systems with a gas turbine (Fryda et al. 2008, Rajesh et al. 2012, Di Carlo et al. 2013, Fortunato et al. 2016, Radenahmad et al. 2020). Trigeneration systems including an engine module and a cooling system are also analyzed (Puig-Arnavat et al. 2013). In specific solutions, the biomass gasification installation can be integrated with other energy systems (reciprocating engines, ORC systems, Stirling engines

(Salehi et al. 2019, Bartela et al. 2019). The issues of system operation modeling: biomass gasification – oxide cell are discussed in many studies, incl. Rajesh et al. 2009, Colpan 2009, Colpan et al. 2010, Wongchanapai et al. 2012, Kupecki et al. 2017. The analysis includes the impact of the gasification method and other values on the cell characteristics and the efficiency of the entire installation. The analyses carried out by Colpan et al. 2010 for three gasifying agents: 1. air (gas composition – mole fractions: $xCH_4 = 0.14\%$, $xH_2 = 11.22\%$, $xCO = 8.16\%$, $xCO_2 = 12.95\%$, $xH_2O = 22.68\%$, $xN_2 = 44.84\%$), 2. oxygen-enriched air (0.28%, 15.74%, 1.40%, 16.37%, 28.80%, 27.41%), 3. steam (2.15%, 43.37%, 27.38%, 8.98%, 18.12%, 0.00%) show that the highest efficiency of electricity generation was obtained from steam gasification (approx. 50%). Similar values of efficiency were obtained by Suranat Wongchanapai et al. 2012, who analyzed the effect of

the vapor stream ratio in relation to the biomass stream, the temperature of the medium at the inlet of the cell, the degree of recirculation at the anode and the degree of fuel use on the efficiency of the installation. Striving to achieve synergistic effects leads to a technological complication, while the final decision requires an economic analysis. An important new direction in the development of technologies for the energy use of biomass and waste is the search for the optimal integration of their gasification installations with the production of hydrogen using wind and solar energy. Typically, this class of technology targets the production of methane, methanol and other fuels. The processes can be arranged according to the general diagram shown in Fig. 2.

There are three main modules in the technological system: biomass island, electrolysis and hydrogenation. A biomass island can have a different technological structure, and in the
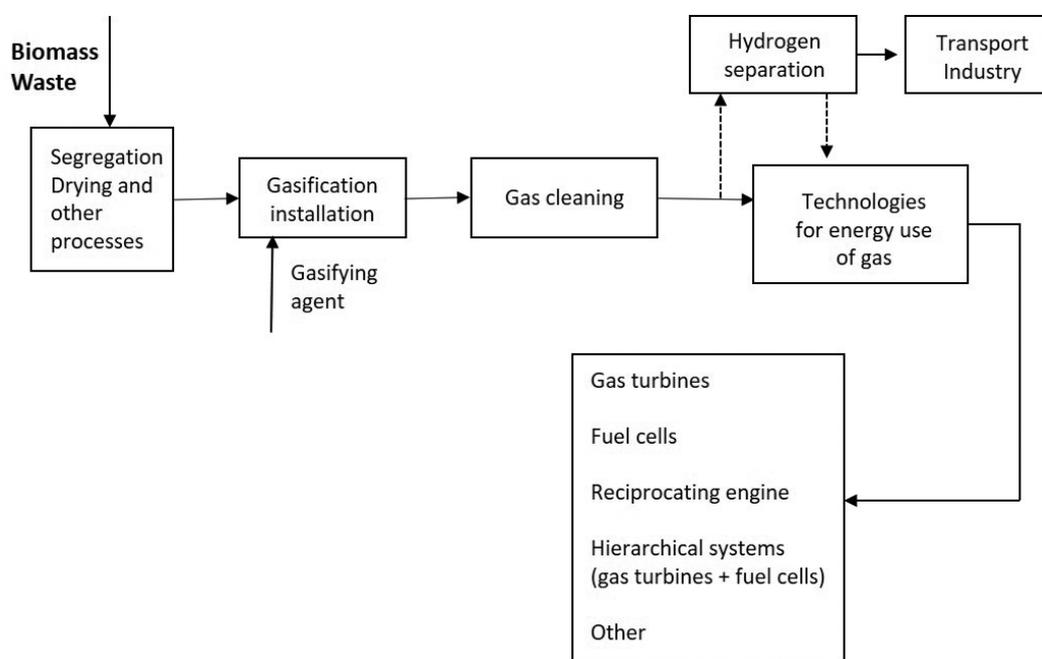
Fig. 1. General diagram of the energy use modules subjected to the biomass and waste gasification process
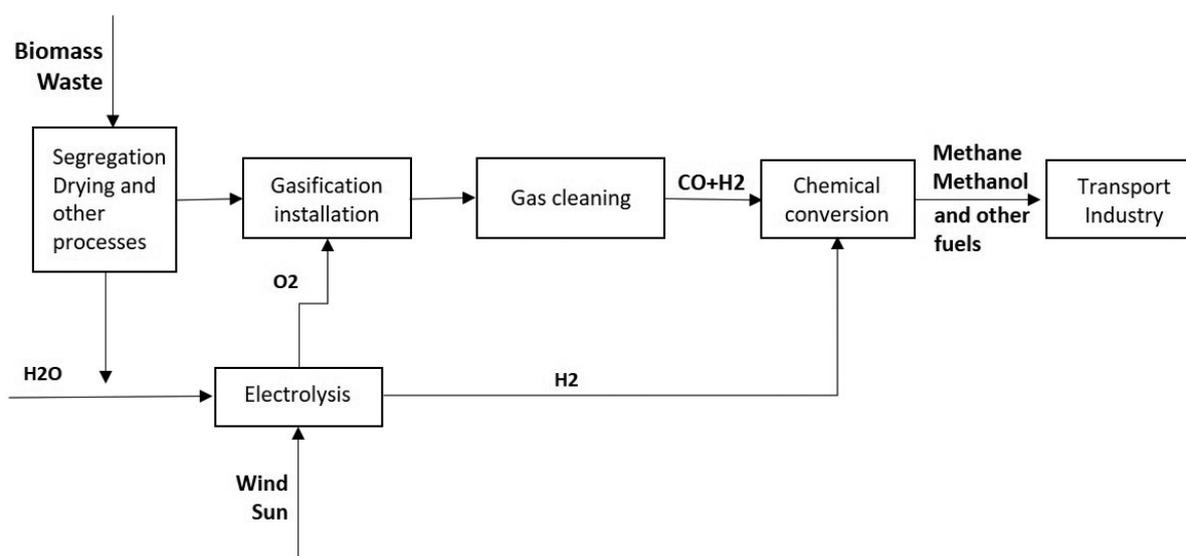
Fig. 2. General technological structure of integration of waste and biomass gasification with hydrogen generation and fuel production

simplest solution it can include a boiler (usually fluidized bed) for combustion of biomass in a steam power plant (power plant or combined heat and power plant), where the carbon dioxide can be separated and then fed to the hydrogenation module. There are many possibilities of additional technological coupling with the electrolysis process, such as supporting the preparation of water or steam for the electrolysis process, supporting the operation of a high-temperature electrolysis, optimal use of process heat generated in various installation modules. The introduction of the gasification process significantly expands the technological possibilities of coupling all processes occurring in the hydrogen and other fuel generation system. This leads to greater thermodynamic efficiency of the installation, although it may lead to increased capital expenditure. Regis et al. 2019, Götz et al. 2016, Uebbinga et al. 2019, Mathiesen et al. 2015 in their works, analyze various solutions falling within the general technological diagram shown earlier in Fig. 2.

Biomass is considered as a source of carbon dioxide in the methanation process. The methanation problem is dealt with in the work of Uebbing et al. 2019, and the issues of an energy system fully based on renewable sources are discussed in the work of Mathiesen et al. 2014. Regis et al. 2019 presents thermodynamic analyzes of three technological options for gas conversion from biomass gasification to synthetic natural gas (SNG, 20 bar), compressed synthetic gas (CNG, 250 bar) and liquefied natural gas (LNG). They differ in the type of electrolyzer used (PEM or SOE) and in the method of integrating the methanation reactor with other modules of the installation. The oxygen from the electrolysis process was used in the gasification process. When using a ceramic electrolyzer, the conversion efficiencies, defined using the heat of combustion of end products, were respectively 81.8% for SNG, 81.0% for CNG and 78.5% for LNG, while the use of a polymer electrolyzer gives lower efficiency values of 64.9% (SNG) and 64.4% (CNG). For this class of polymer electrolyzer, the conversion options to LNG have not been tested. The given

efficiency values should be regarded as the maximum ones, because the modeling process does not take into account all types of losses (although there is a potential to improve the organization of heat management). The differences between the efficiency values supporting the use of high temperature electrolyzers (SOE) result mainly from the higher process efficiency for SOE and better thermal integration of this class of electrolyzers with the methanation module. A study published by Götz et al. 2016 contains a comparison of various options of Power-to-Gas technology, pointing to the importance of this process in the energy transformation. The main criteria are low Capex, high conversion efficiency and flexibility.

General characteristics of the waste management model in terms of the gasification process

The waste management system introduced on 1 July 2013 by changes to the law on cleanliness and order in the commune is based on installations for mechanical and biological treatment of municipal waste, where the basis is the waste sorting process and the most effective separation of streams for further management or disposal. The model of waste management along with the assumptions of its integration is shown in Figure 3.

This system cannot be classified as fully integrated, because it does not provide a systemic solution to the management of material fractions that must be recycled. There are still no specialized waste treatment installations for material recovery, but the biggest problem is the lack of an effective management of the over-sieve (energetic) fraction in energy conversion (recovery) facilities. It is currently the biggest problem of the implemented waste management system due to the significant deficit of thermal waste treatment plants in Poland. The municipal waste stream directed to the mechanical-biological treatment plants undergoes the standardization process by separating it into bio and mineral fractions (0–80 mm), and the remaining waste stream (> 80 mm), after prior separation of material fractions, is the over-sieve fraction with quite
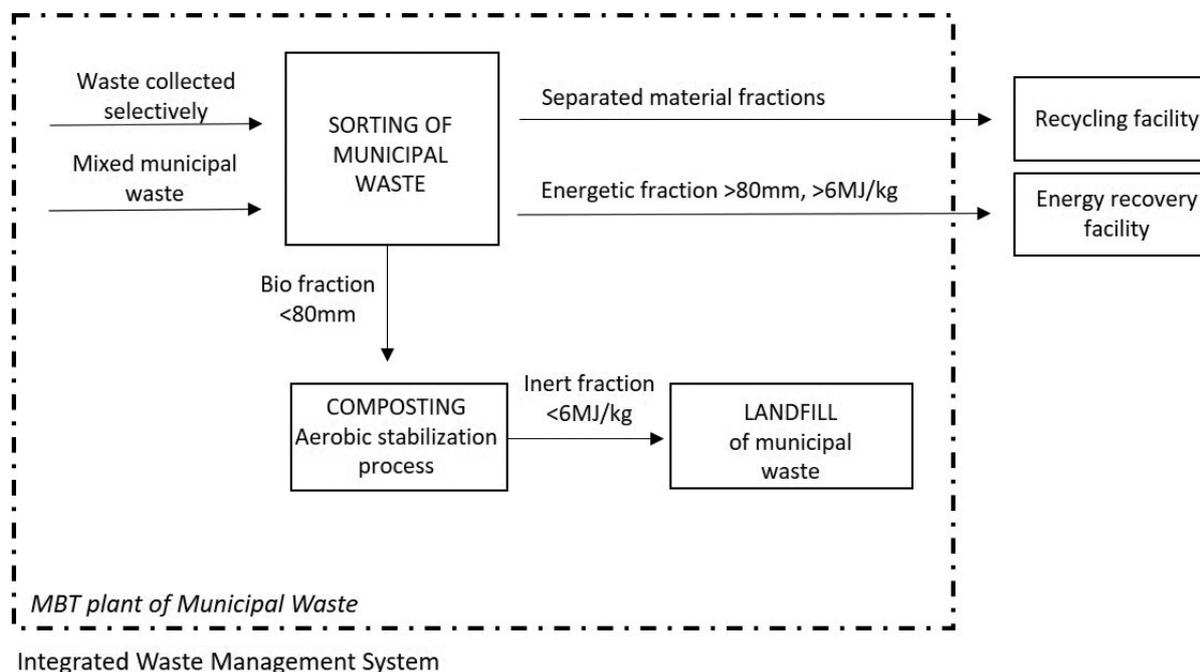
Fig. 3. Waste management model

stable fuel properties in the span of four seasons (Primus and Rosik-Dulewska, 2018). Therefore, assuming a safe and at the same time real value of the share of the over-sieve fraction in the mixed municipal waste stream, delivered to the Regional Municipal Waste Processing Installations (RIPOK) at the level of 35–45%, it is estimated to be around 4 million Mg/year (Ściążko and Nowak, 2017, Primus and Rosik-Dulewska 2018). Nevertheless, it should be emphasized that the quantity and quality of the separated stream of the over-sieve fraction depend not only on the type, quantity and quality of the delivered waste, but also on the technical standards of the sorting plant's equipment, as well as on market conditions and the demand for material intended for recycling and energy recovery. Quantitative and qualitative fulfillment of the above criteria of the discussed fraction has a positive effect on its energetic properties (Primus and Rosik-Dulewska 2018).

Technical conditions for waste gasification and syngas production

Waste gasification is conditioned by technical and environmental requirements in order to maintain high environmental protection standards. The provisions of the IE Directive (Integrated Emission 2010/75/EU, 24.11.2010) introduced a conditional exemption from technical requirements for thermal waste treatment for gasification and/or pyrolysis technologies, which, however, remained obligatory for waste incineration plants.

The provisions of the directive indicate that the special provisions on incineration of waste do not apply to gasification installations, provided that the gases resulting from the incineration process are cleaned to such an extent that they will not cause more pollutants than when burning natural gas. These conditions have also been transposed to the national legislation, which gives a real chance for the development of gasification technology for the over-sieve fraction of waste due to the possibility of obtaining high energy efficiency of

the process in small distributed energy systems based on low-power cogeneration systems up to 1 MWe.

Through gasification technology and use of thermal waste treatment conditions, it is possible to search for a configuration with power systems using syngas as a fuel, where the main goal will be to achieve high efficiency of electricity production as a local source of renewable energy (RES). LIFECOGENERATION.PL plant located in the R&D Center of INVESTEKO S.A. in Świętochłowice is intended for energy management of the over-sieve fraction of municipal waste and sewage sludge using the gasification process and highly efficient production of electricity and heat in cogeneration. The plant is divided into 3 technical segments, and consists of 4 basic technological modules responsible for individual production functions, namely: module 1 is used for mechanical processing, mixing and thickening of solid fuel from the over-sieve fraction of municipal waste and dried sewage sludge (the effect is a molded fuel intended for gasification in a gasifier), module 2 is gasification and syngas production, module 3 is the process of "deep" cleaning of syngas, and module 4 is a cogeneration system for the production of electricity and heat. The described installation is equipped with a continuous measurement of the quality of cleaned syngas, prior to its injection into the cogeneration installation, and a continuous flue gas monitoring system for emissions of carbon monoxide, nitrogen oxides, sulfur dioxide and dust. In terms of power supply, the plant was designed and built in explosion-proof version of class 2, equipped with all the required protections.

Thus, the presented waste gasification technology also has great potential for the construction of technological structures displayed in Figures 1 and 2. A simplified schematic diagram of the waste gasification installation is shown in Fig. 4.

The above technological flowchart includes a co-current gasification reactor with a fixed bed and rotary bottom ash collection. The reactor is based on the design used in biomass gasification, but it must be adapted to the increased content of
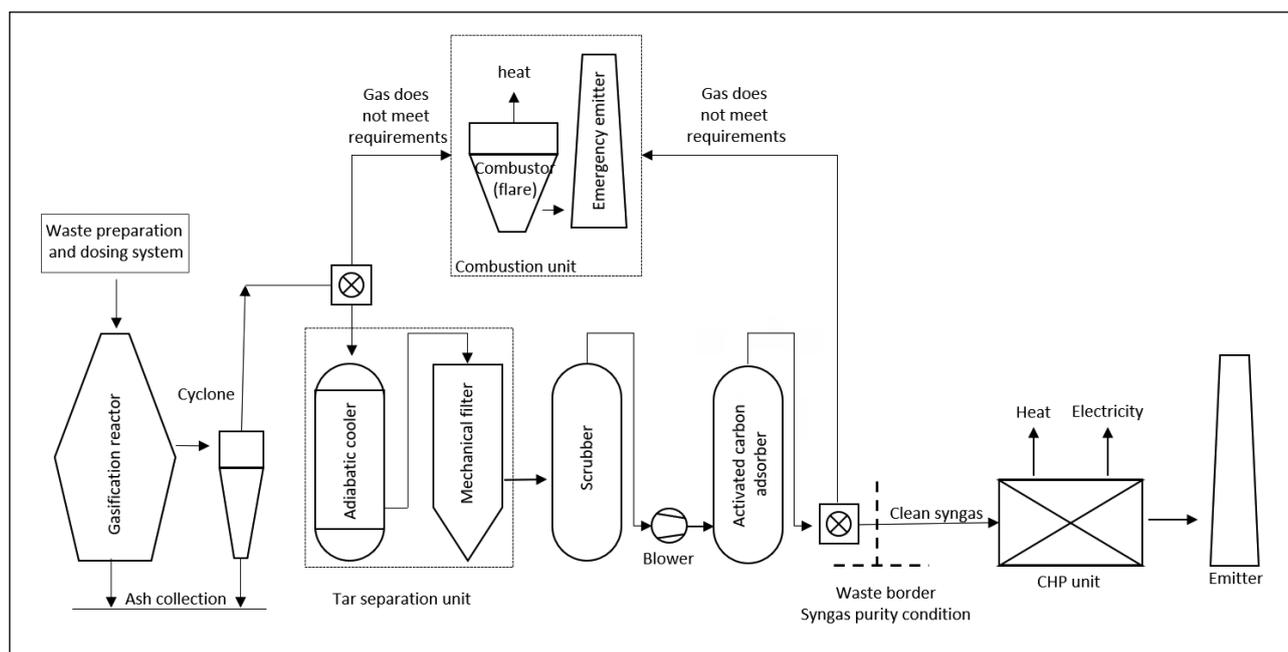
Fig. 4. General technological flowchart of gasification with the gas cleaning process
(own study based on the Lifecogeneration.pl technology)

post-reaction ashes due to the significant share of the mineral substance in the residual fraction constituting the fuel input for gasification. Air is used as a gasifying agent, which is heated in two stages in the syngas/air exchanger and in the internal exchanger of the reactor. Such an arrangement allows to increase the energy efficiency of the gasification process. The temperature of the gasification process does not exceed 1000°C, effectively reducing the flow of organic matter and consequently, the formation of slag. Basic parameters of raw syngas: calorific value – 5 MJ/Nm³; tar content – 2–3 g/Nm³; dust content – up to 10 g/Nm³. Additional data are presented in Table 1.

Due to the above-mentioned environmental requirements resulting from the IE directive related to the thermal conversion of waste in gasification technology, the physicochemical composition of the municipal waste residual fraction stream and the technical requirements of the applied technique for the transformation of chemical energy into other types of energy, the process of syngas purification becomes of key importance. The syngas cleaning unit in the discussed installation includes the following devices (Table 2):

- dust removal cyclone (pre-separation of solid particles before cooling),
- syngas/air exchanger, also performing the role of a preliminary tar removal,
- adiabatic cooler,
- mechanical filter system with a granular bed (coarse and fine),
- alkaline scrubber (counter-current absorber),
- activated carbon adsorber.

The task of the syngas/air exchanger is to pre-cool the syngas and to separate the heavier gas tars, the vapors and aerosols which are lifted from the reactor chamber together with the flowing syngas. The tars condensate at temperatures below 300°C. An additional function of the exchanger is to heat the process air supplied to the gasification chamber.

Wet gas cleaning in an alkaline scrubber eliminates contamination of chlorine, fluorine, bromine and their compounds. The system is also highly effective in cleaning gas from sulfur compounds (mainly hydrogen sulphide). Other contaminants, such as organic acids, ammonium compounds, silanes and alkali metal vapors, will also be absorbed by the liquid droplets in the scrubber.

An extensive syngas cleaning system from dust and tars, consisting of a cyclone and tar remover (preliminary stage) and granular filters, a scrubber and an adsorber with activated carbon (thorough cleaning stage) is characterized by a high total efficiency of separation of gas-dust pollutants from syngas.

In the course of the gasification process, the formation of dioxins and furans is limited, as the gas passing through the reduction zone reaches a temperature in the range of 900–1000°C (with stoichiometric oxygen deficiency), which limits their formation. Secondary formation of dioxins and furans may take place at the temperature of 450–200°C, in particular when halogenated syngas is kept at this temperature,

Table 1. Composition of syngas from gasification of the residual fraction of municipal waste in a co-current reactor (gasifying agent – air) (Own study based on the Lifecogeneration.pl technology)

Nr	Components	Volume share (%)
1	Hydrogen	25
2	Carbon monoxide	16
3	Methane	2
4	Nitrogen	44
5	Carbon dioxide	10
6	Water (steam)	3

Table 2. Possible configurations of syngas cleaning systems (Own study based on the Lifecogeneration.pl technology)

No	System/apparatus	Removed contamination	Characteristics of the process
1	Dust cyclone	Dust	Dust removal with dimensions greater than 60 μm
2	Syngas/air exchanger	heavy gas tars	preliminary tar removal and the first stage of heating the process air
3	Adiabatic cooler	Light tars	Water injection and rapid condensation of tars in order to prepare them for separation
4	Mechanical filter system	dust and tar with metal compounds	Mineral or ceramic bed with regeneration
5	Alkaline scrubber	chlorine and sulfur compounds, residues of tars and degassing waters, dust, organic acids, ammonium compounds, silanes, alkali metal vapors	Counter-current absorber with filling. Sorption medium – soda lye solutions.
6	Adsorber with activated carbon	tar, dust and micro-droplets, metal vapors, mercury, volatile organic compounds, dioxins and furans	Adsorber with a cartridge replacement system or a parallel system with a regeneration system

in an environment with high share of oxygen, for a longer period of time (Wielgosiński 2020). After passing through the adiabatic cooler, syngas is dynamically cooled down to the temperature of 120°C. The continuously flowing gas will gradually lower its temperature by going through the subsequent cleaning stages, where in the alkaline absorption process (with high efficiency) chlorine compounds which are the triggers of dioxin and furan formation in an oxygen atmosphere are removed. Due to this sequence of the process, the possibility of their formation during the combustion of syngas is limited. The treatment of syngas should also take into account the process of cooling, condensing and collecting water from the syngas stream, so as to ensure an appropriate level of calorific value and meet basic quality requirements when it is intended for energy use. Precipitated tars and rinse waters obtained during syngas cooling may be:

- used for energy purposes in the technological system by returning them to the gasification process (dosing in the pyrolysis zone),
- used in the petrochemical industry as an intermediate,
- neutralized.

Selected properties of the residual municipal waste in the context of fuel cell use

The qualitative characteristics of the residual fraction of municipal waste are of key importance when choosing a technology for its energy recovery. The diagram (Fig. 4) indicates that gas is combusted in a reciprocating engine. According to Fig. 1, this is not the only possibility of its energy recovery. On the basis of previous research and evaluation of this waste stream, it was possible to perform an additional preliminary qualitative assessment in the context of the possibility of producing hydrogen and its further use for energy purposes. The analysis was carried out with an attempt to use the waste gasification technology, syngas production with a significant share of hydrogen and also in combination with the technology of energy production in solid oxide fuel cells (SOFC).

In the indicated direction of the management of the residual waste fraction, significant quality parameters (energy and pollutant content) should be identified, which have a significant impact on the production and quality of syngas, hydrogen production and electricity generation capacity in SOFC. The basic parameters include calorific value, heat of combustion and the content of hydrogen, carbon, ash, sulfur,

chlorine, which are based on own research and are presented in Table 3.

In addition to the above-mentioned indicators, important is also the share of heavy metals, especially mercury and alkali metals, which condense at temperatures of 500–700°C, and act as a condensation nuclei for the tars during the waste gasification and syngas treatment. The indicated basic parameters of the energy fraction of municipal waste and their relative qualitative stability in annual terms suggest that they can be considered a good fuel for syngas production in the gasification process.

Configurations of fuel cell energy systems
Solid oxide fuel cell

The data contained in tab. 1 show that the gas generated in the gasification process of the residual fraction of municipal waste contains H_2, CO, CO_2 and CH_4. In the SOFC (Fig. 5), H_2 and CO are oxidized in the anode electrochemical process, according to the reaction (Chmielniak and Chmielniak 2020).

Anode:

$$aH_2 + bCO + O^{2-} \rightarrow aH_2O + bCO_2 + 2(a+b)e^- \quad (1)$$
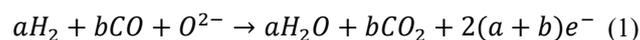
A reaction of the reduction takes place at the cathode:

$$\frac{1}{2}(a+b)O_2 + 2(a+b)e^- \rightarrow (a+b)O^{2-} \quad (2)$$
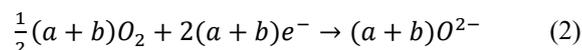
Combined reaction:
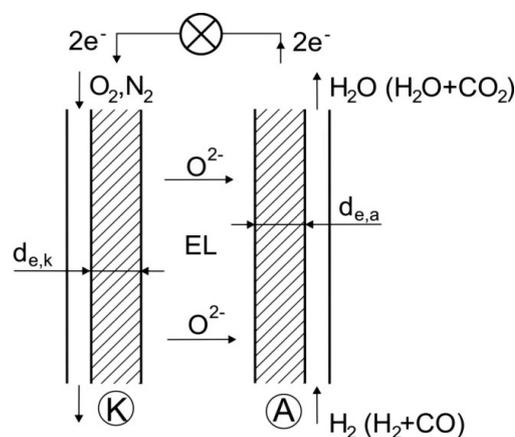
Fig. 5. Diagram of an SOFC

Table 3. Averaged qualitative parameters of the residual municipal waste from MBT plants
(Primus and Rosik-Dulewska 2018)

Nr.	Parameter	Unit	Season				Average
			Winter	Spring	Summer	Autumn	
1	**Calorific** value	MJ/kg	18,6	19,8	18,6	17,5	18,6
2	Heat of combustion	MJ/kg	19,9	21,2	20,0	19,0	20,0
3	**Hydrogen** content	%	6,3	6,5	6,6	6,6	6,5
4	Carbon content	%	46,6	48,9	47,2	48,2	47,7
5	Ash content	%	20,9	13,5	17,3	16,5	17,0
6	Sulfur content	%	0,5	0,2	0,2	0,3	0,3
7	Chlorine content	%	1,5	1,0	0,5	0,9	1,0

$$\frac{1}{2}(a + b)O_2 + H_2 + bCO \rightarrow aH_2O + bCO_2 \qquad (3)$$
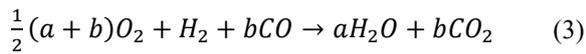
Solid oxide fuel cells are high-temperature cells. The working temperature is t = 800–1000°C. In classic solutions, the electrolyte is zirconium oxide (ZrO_2) with an admixture of Y_2O_3 (8–10 mol/%). Instead of yttrium oxide, the use of cesium dioxide (CeO_2) and Gd_2O_3 (Gd – gadolinium) are also considered. The anode is formed by the porous structure of $NiZrO_2$ (porosity 20–40%). The cathode is made of $La_{1-X}Sr_X MO_3$ oxides (M may be manganese or cobalt). The porosity is of the same order as in the anode, X ranges from 0.1 to 0.15. The effect of pressure follows from the Nernst equation. The same equation shows that the theoretical potential decreases with temperature. In real cells, due to the decrease in ohmic resistance losses (especially in the range of 800–1000°C), the voltage increases with the temperature increase. The temperature increase above 1000°C does not lead to any significant changes in that resistance, therefore the working temperature is now assumed to be 900–1000°C. Out of many possible technological solutions, tubular cells and monolithic (plate) cells are tested. The main advantages are:

- high dynamics of reaction
- possibility of internal fuel reforming
- good efficiency (efficiency 50–70% (HHV))
- no need for any precious metal catalyst
- generation of large amounts of high-temperature heat (possibility of building hierarchical systems).

The operating temperature has a significant impact on the basic characteristics of the cell (voltage-current characteristics). With the temperature increase for a given current density, the cell operating voltage increases. However, with increasing temperature, the current density corresponding to the maximum power decreases. The issues of modeling their characteristics for various operational states are discussed, among others, in works by Kupecki 2018, Zhang et al. 2005, Menon et al. 2012, Mauro et al. 2011, Andersson et al. 2010 [2–7]. The main problem of gas utilization from waste gasification in fuel cells is the sensitivity of the SOFC anode to sulfur poisoning. The conducted experimental work shows the acceptable concentration of H_2S at the level of several (4–7 ppm) (e.g. Rasmussen and Hagen 2010). However, there are no clear conclusions. New anode materials are sought to reduce the influence of sulfur compounds on the degradation of cell characteristics and service life (Radenahmad et al. 2020). The most important immediate goals to be achieved are to increase the lifetime of modules under real operating conditions with acceptable degradation to more than 50,000 hours, to improve operational flexibility, and to reduce the investment costs to less than USD 2,000 per kW.

Integration of the fuel cell with the waste gasification process

Fig. 6 shows one of the possible connection diagrams of a biomass gasification installation with a high-temperature fuel cell. The cell is fed with purified synthesis gas. Prior to its introduction to the cell's anode, it is additionally heated in the heat exchanger (HE) to the cell operating temperature. In specific solutions, recirculation is used to maintain the proper anode temperature.

The products from the anode and cathode processes are burnt in the combustion chamber (B). Combustion products are used to heat the air directed to the cathode and to heat up the gasifying agents. Fig. 6 additionally shows the option of preparing and using steam as a gasifying agent. According to the diagram shown in Fig. 2, synthesis gas can be a substrate in fuel generation for the transport sector. The process is usually supported by hydrogen generated in the electrolysers. The production of fuels intended for the transport sector is often assisted by the generation of hydrogen in electrolysers to improve the quality of the fuels. It seems that currently, in order to control the energetic utilization of the over-sieve fraction, it is important to check the efficiency of the systems shown in Figures 6 and 7. In order to obtain high energy effects it is required to optimize the thermal management of the entire installation. Figure 7 shows the development of the
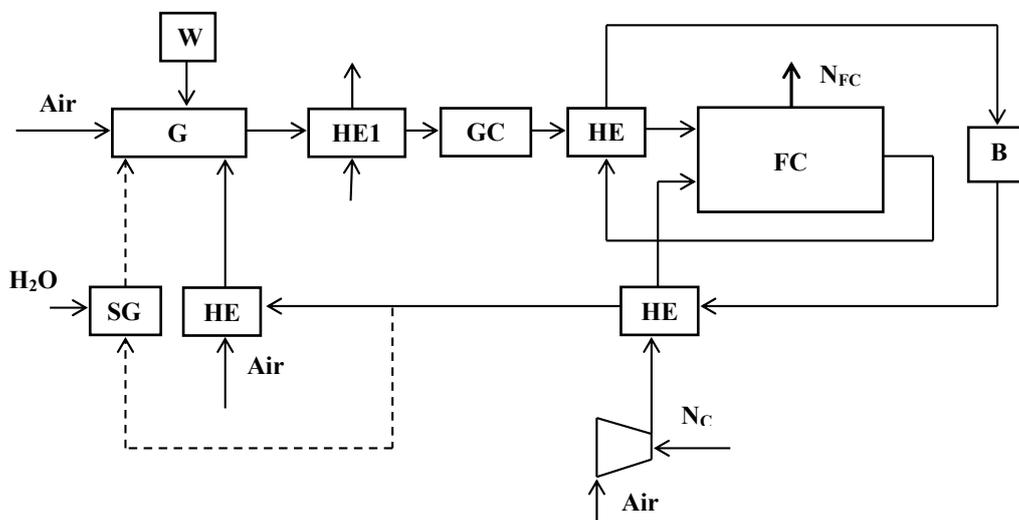
Fig. 6. Flowchart of the waste gasification installation integrated with a high-temperature fuel cell.
W – Waste, HE – Heat Exchangers, G – Gasifier, GC – Gas Cleaning, FC – Fuel Cell (SOFC), B – Burner,
SG – Steam Generator, N_{FC} – Fuel cell power, N_C – compressor driving power

system with a gas turbine. In this way, we obtain an energy hybrid system, more complex in terms of energy, but allowing us to obtain higher energy efficiency. Apart from the systems shown in Figures 6 and 7 in (Colpan 2009), the fuel cell system and a steam turbine is considered. The choice of technological structure depends on the stream size of the available waste, the gasification technology used and the structure of the final forms of energy.

Environmental protection requirements

The use and development of waste gasification technology in various energy systems, including combined high-efficiency cogeneration systems, depends on the purity of the generated gas and its energetic utility properties. The main advantage of systems integrated with a high-temperature fuel cell is their high efficiency of electricity generation, wide availability and gradation of power, and acceptable investment expenditure.

Gasification techniques are becoming more and more popular not only due to the possibility of obtaining high energy efficiency but also due to the reduction of pollutant emissions.

In the case of gasification of waste, including the over-sieve/residual fraction, neither the current EU nor national regulations regulate the requirements for pollutant emission, apart from standardizing the emissions from natural gas combustion. Due to the fact that the regulations on the emission of pollutants from the waste gasification process in installations meeting the condition of art. 42 of the IE Directive should be related directly to the emission standards for natural gas combustion installations, four basic pollutants will be subject to standardization: dust, sulfur dioxide, carbon monoxide and nitrogen oxides calculated as nitrogen dioxide. Moreover, the provisions of the IE directive introduced a conditional exemption from the technical requirements for thermal waste treatment for waste gasification or pyrolysis technologies, which are mandatory for waste incineration processes. An exemption in this respect is also possible only if the functional properties of the produced gas, intended for energy purposes, are similar to the parameters of natural gas (Primus and Rosik-Dulewska 2018, 2019). However, it is easier and more effective to clean the raw (synthetic) gas. According to Skorek and Kalina 2005, the main advantages of the gas treatment technique for the environment are:

- much smaller gas stream to be processed in relation to the flue gas stream generated from combustion processes,
- easier removal of hydrogen sulphide from synthetic gas than removal of sulfur dioxide from flue gas, enabling achievement of the efficiency of reducing sulfur compounds emissions at the level of 99%,
- high efficiency in removing heavy metals, mercury and chlorine compounds by combining wet cleaning processes with activated carbon adsorption.

Nevertheless, bearing in mind the aspect of environmental protection and technological conditions of the gasification process, in many cases the requirements for thermal waste treatment installations should be referred to.

Summary

Considering the significant amounts of over-sieve fraction (30–45% of the mixed municipal waste stream entering the RIPOK facilities) with good fuel properties, this potential should be used for the production of electricity and heat, using various highly efficient technologies for their conversion, including gasification. The type of gasification process (air gasification, steam gasification, oxygen gasification) determines, among other things, the scale of integration of this process with gas utilization technologies (reciprocating engine, fuel cell, gas turbine). The selection of an oxide fuel cell will, on the one hand, guarantee higher efficiency of electricity generation and, on the other hand, it will speak for
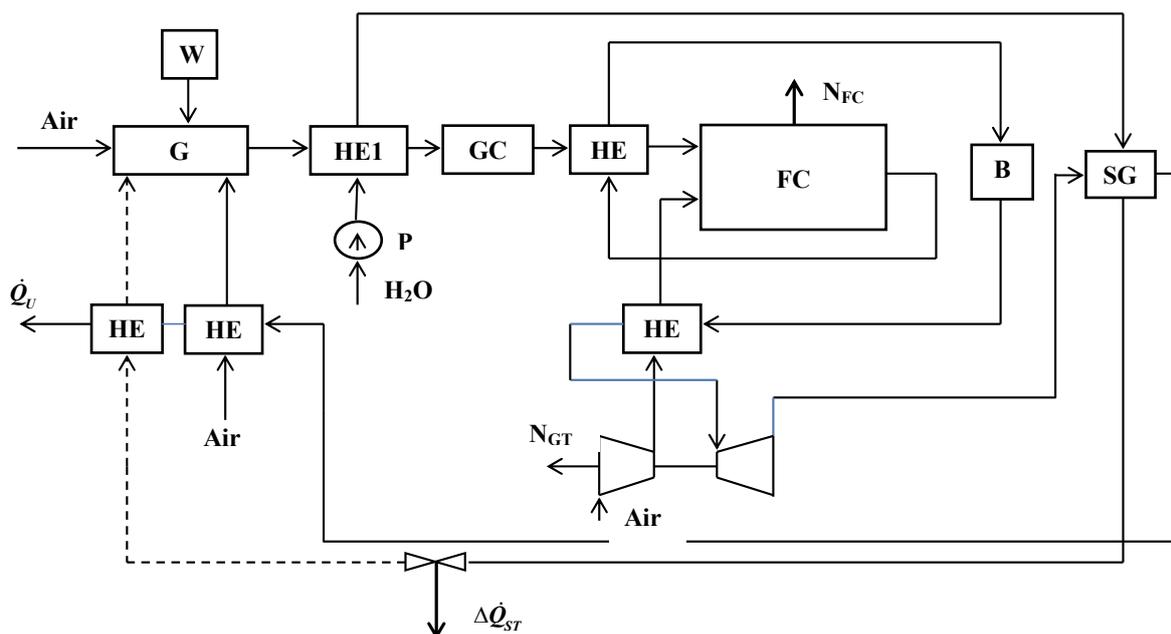
Fig. 7. Flowchart of a waste gasification installation integrated with a high-temperature fuel cell and a gas turbine. W – Waste, HE – Heat Exchangers, G – Gasifier, GC – Gas Cleaning, FC – Fuel Cell (SOFC), B – Burner, SG – Steam Generator, N_{FC} – Fuel cell power, P – Pump, N_{TG} – Gas Turbine Power, $\Delta\dot{Q}_{ST}$ Excess steam heat source, $\dot{Q}_U$ – Heating heat

a high-temperature method of gas treatment and will require gas with the required purity for use in the cells. The choice of the energy conversion method of the obtained synthesis gas is determined by many technological, economic and environmental aspects. The economic analysis should take into account additional investment costs related to the complexity of the technological installation and the method of its operation. Taking into account the use of solid fuels from municipal waste, which are financially attractive, and considering the increasing price of electricity generated from other sources, it is necessary to adopt these technological solutions based on cells with good development prospects. The literature quoted in the article shows that much attention is paid to the search for material solutions, mainly for the anode, reducing the risk of poisoning the ceramic cell with sulfur compounds, and thus extending the possibilities of using this class of cells in biomass and waste gasification installations without the need for very deep desulphurization of synthesis gas . However, this does not exclude other ways of using synthesis gas for energy purposes, but in each case the final choice, taking into account all environmental and market restrictions and legal solutions, will be determined by the economic analysis. The selection of the best solutions for energy systems with waste gasification requires a lot of research and development to prepare demonstration installations of different power. This is an important stage for the market dissemination of integrated waste gasification

systems, also in the configuration with fuel cells. One of such examples is the installation of gasification of municipal waste Lifecogeneration.pl.

The plant was built on a semi-technical scale and has a research and demonstration function. It is located within the premises of the Research and Development Center in Świętochłowice. The processing capacity of the plant is 300 kg/h of waste. The plant is integrated with a cogeneration system based on a GUASCOR reciprocating engine equipped with a generator of 304 kWe nominal electricity power and of 414 kWt nominal thermal power. The research work conducted in the course of start-up tests confirmed the possibility of developing this technology in the proposed configuration that meets the requirements of the IE directive and national waste gasification regulations. The conducted research work also defined the directions of further research for the development of this technology. The main research areas should focus on

- stabilization of the gasification process in the context of fuel charge variability,
- development of techniques and design of gas generators as a function of maximizing the share of hydrogen in syngas,
- development of thermal and catalytic cracking techniques of carbon chains as a function of minimizing the share of condensing tars in syngas,
- selection of optimal syngas purification techniques,
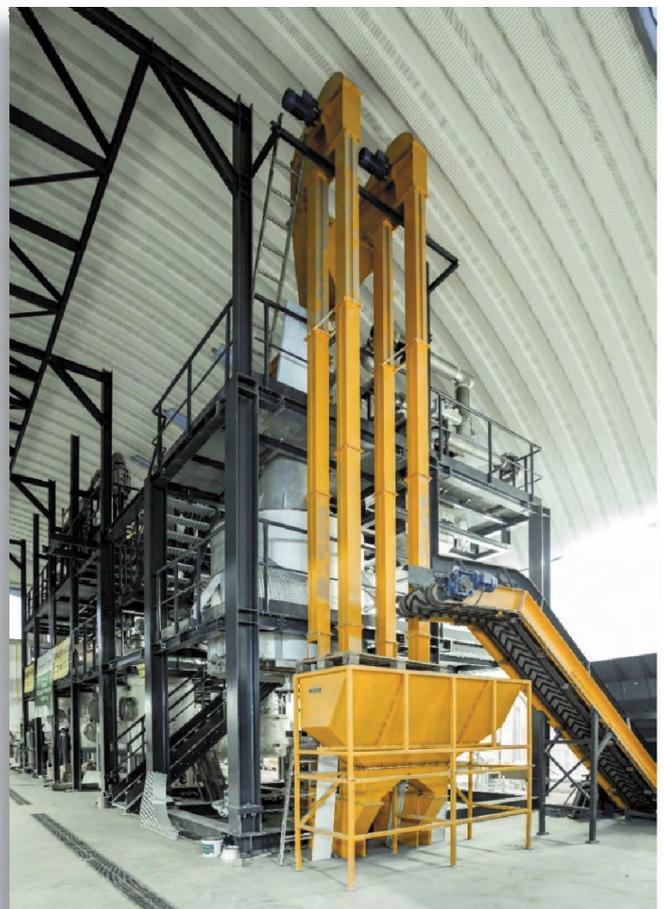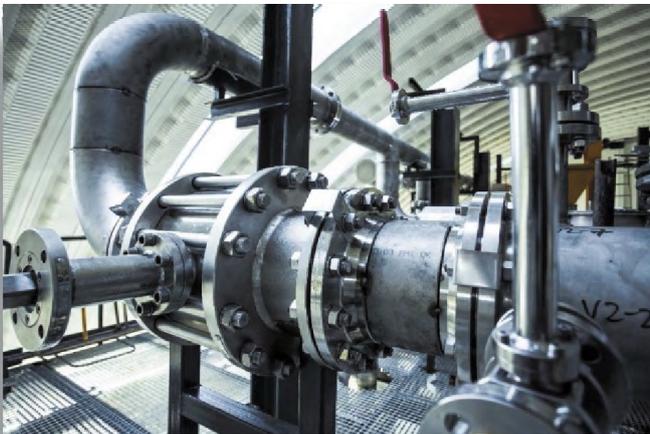
Fig. 8. Waste gasification plant erected within the framework Lifecogeneration.pl project

● development and further integration of systems as a function of operational safety of processes,

The development of the above technical areas and further integration will allow for the standardization of the process and, consequently, an increase in the quality stability of the syngas. This will enable the use of a wider range of techniques for its energetic use, including the possibility of integrating the gasification system with fuel cells.

References

Al-attab, K.A. & Zainal, Z.A. (2015). Externally fired gas turbine technology: A review. *Applied Energy*, 138, pp. 474–487, DOI: 10.1016/j.apenergy.2014.10.049

Andersson, M., Yuan, J. & Sunden, B. (2010). Review on modeling development for multiscale chemical reactions coupled transport phenomena in solid oxide fuel cells. *Applied Energy*, 87, pp. 1461–1476, DOI: 10.1016/j.apenergy.2009.11.013

Regise, A., Muller, C., Schmid, M., Colomar, D., Ortloff, F., Sporl, R., Brisse, A. & Graf, F. (2019). Innovative power-to-gas plant concepts for upgrading of gasification bio-syngas through steam electrolysis and catalytic methanation. *Energy Conversion and Management*, 183, pp. 462–473. DOI: 10.1016/j.enconman.2018.12.101

Bartela, Ł., Kotowicz, J. & Dubiel-Jurga, K. (2018). Investment risk for biomass integrated gasification combined heat and power unit with an internal combustion engine and a Stirling engine. *Energy*, 150, pp. 601 – 616. DOI: 10.1016/j.energy.2018.02.152

Chmielniak, T. & Chmielniak, T.M. (2020). Energetyka wodorowa, s. 378. PWN, Warszawa.

Colpan, C.O., Hamdullahpur, F., Dincer, I. & Yoo, Y. (2010). Effect of gasification agent on the performance of solid oxide fuel cell and biomass gasification systems. *I. J. of Hydrogen Energy*, 35, pp. 5001–5009. DOI: 10.1016/j.ijhydene.2009.08.083

Colpan, C.O. (2009). Thermal Modeling of Solid Oxide Fuel Cell Based Biomass Gasification Systems, Department of Mechanical and Aerospace Engineering Carleton University Ottawa, Ontario, Canada, (Thesis).

Di Carlo, A., Borello, A. & Bocci, E. (2013). Process simulation of a hybrid SOFC/mGT and enriched air/steam fluidized bed gasifier power plant, *I.J.of Hydrogen Energy*, 38, pp. 5857–5874. DOI: 10.1016/j.ijhydene.2013.03.005

Dong, L., Liu, H. & Riffat, S. (2009). Development of small-scale and micro-scale biomass fuelled CHP systems – a literature review. *Appl Therm Eng.*, 29, pp. 2119–26. DOI: 10.1016/j.applthermaleng.2008.12.004

Integrated Emission Directive no. 2010/75/UE 24.11.2010.

Fortunato B., Camporeale, S.M., Torresi, M. & Fornarelli, F. (2016). A Combined Power Plant Fueled by Syngas Produced in a Downdraft Gasifier, *Proceedings of ASME Turbo Expo*, GT2016-58159, V003T06A023. DOI: 10.1115/GT2016-58159

Fryda, L., Panopoulos, K.D. & Kakaras, E. (2008). Integrated CHP with autothermal biomass gasification and SOFC–MGT. *Energy Conversion and Management*, 49, pp. 281–290. DOI: 10.1016/j.enconman.2007.06.013

Götz, M., Lefebvre, J., Mörs, F., McDaniel Koch, A., Graf, F., Bajohr, S., Reimert, R. & Kolb, T., (2016). Renewable Power-to-Gas: A technological and economic review. *Renewable Energy*, 85, pp. 1371–1390. DOI: 10.1016/j.renene.2015.07.066

Huang, Y., Wang, Y.D., Rezvani, S., McIlveen-Wright, D.R., Anderson, M., Mondol, J., Zacharopolous, A. & Hewitt, N.J. (2013). A techno-economic assessment of biomass fuelled trigeneration system integrated with organic Rankine cycle. *Applied Thermal Engineering*, 53, pp. 325–331. DOI: 10.1016/j.applthermaleng.2012.03.041

Kupecki, J. (2018). Modelling, Design, Construction, and Operation of Power Generators with Solid Oxide Fuel Cells, s. 261. Springer.

Kupecki, J. (2018). Selected problems of mathematical modeling of solid oxide fuel cell stacks during transient operation, p. 133. Wyd. Instytutu Technologii Eksploatacji. (in Polish)

Kupecki, J., Skrzypkiewicz, M., Wierzbicki, M. & Stepien M. (2017). Experimental and numerical analysis of a serial connection of two SOFC stacks in a micro-CHP system fed by biogas. *I.J. of Hydrogen Energy*, 4, 2, pp. 3487–3497. DOI: 10.1016/j.ijhydene.2016.07.222

Lian, Z.T., Chua, K.J. & Chou, S.K. (2010) A thermoeconomic analysis of biomass energy for trigeneration. *Applied Energy*, 87, pp. 84–95. DOI: 10.1016/j.apenergy.2009.07.003

Maraver, D., Sin, A., Royo, J. & Sebastián, F. (2013). Assessment of CCHP systems based on biomass combustion for small-scale applications through a review of the technology and analysis of energy efficiency parameters. *Applied Energy*, 102, pp. 1303–1313. DOI: 10.1016/j.apenergy.2012.07.012

Mathiesen, B.V., Lund, H., Connolly, D., Wenzel, H., Ostergaard, P.A., Moller, B., Nielsen, S., Ridjan, I., Karnoe, P., Sperling, K. & Hvelplund, F.K. (2015). Smart Energy Systems for coherent 100% renewable energy and transport solutions. *Applied Energy*, 145, pp. 139–154. DOI: 10.1016/j.apenergy.2015.01.075

Mauro, A., Arpina, F., Massarotti, N. (2011). Three – dimensional simulation of heat and mass transport phenomena in planar SOFCs. *I. J. of Hydrogen Energy*, 36, pp. 10288–10301. DOI: 10.1016/j.ijhydene.2010.10.023

Menon, V., Janardhanan, V.M., Tisher, S. & Deutschmann, O. (2012). A novel approach to model the transient behaviour of solid – oxide fuel cell stacks. *J. of Power Sources*, 214 pp. 227–238. DOI: 10.1016/j.jpowsour.2012.03.114

Primus, A. & Rosik-Dulewska, C. (2018). Fuel potential of the over-sieve fraction of municipal waste and its role in the national model of waste management. Zeszyty Naukowe Instytutu Gospodarki Surowcami Mineralnymi i Energią PAN, 105, pp. 121–134. DOI: 10.24425/124382. (in Polish)

Primus, A. & Rosik-Dulewska, C. (2019). Integration of energy and material recovery processes of municipal plastic waste into the national waste management system. Polityka Energetyczna Energy Policy Journal, 22, 4, pp. 129–140. DOI: 10.33223/epj/114741

Puig-Arnavat, M, Bruno, J.C. & Coronas, A. (2014). Modeling of trigeneration configurations based on biomass gasification and comparison of performance. *Applied Energy*, 114, pp. 845–856. DOI: 10.1016/j.apenergy.2013.09.013

Kempegowda, R.S., Assabumrungrat, S. & Laosiripojana, N. (2009). Integrated CHP System Efficiency Analysis of Air, Mixed Air – Steam And Steam Blown Biomass Gasification Fuelled SOFC, Proc.of the IASIED International Conf. Modelling, Simulation, and Indentification. October 12–14, 2009, Beijing, China

Nikdalila, R., Azad, A.T., Saghir, M., Taweekun, J., Bakar, M.S.A., Reza, M.S. & Azad, A.K. (2020). A review on biomass derived syngas for SOFC based combined heat and power application. *Renewable and Sustainable Energy Reviews*, 119, 109560. DOI: 10.1016/j.rser.2019.109560

Rasmussen, J.F.B. & Hagen, A. (2011). The effect of H_2S on the performance of SOFCs using methane containing fuel. *Fuel Cell*, 10, pp. 1135–1142. HAL Id: hal-00576976

Salehi A., Mousavi, S.M., Fasihfar, A. & Ravanbakhsh, M. (2019). Energy, exergy, and environmental (3E) assessments of an integrated molten carbonate fuel cell (MCFC), Stirling engine and organic Rankine cycle (ORC) cogeneration system fed by a biomass-fueled gasifier. *I.J. of Hydrogen Energy*, 44, pp. 31488–31505. DOI: 10.1016/j.ijhydene.2019.10.038

Skorek, J. & Kalina, J. (2005). Gas cogeneration systems; Wydawnictwo Naukowo-Techniczne; Warszawa, 2005 r. (in Polish)

Sipilä, K., Pursiheimo, E., Savola, T., Fogelholm, C.J., Keppo, I. & Pekka A. (2005). Small Scale Biomass CHP Plant and District Heating. Vtt Tiedotteita . Research Notes 2301, Valopaino Oy, Helsinki, 2005. http://www.vtt.fi/inf/pdf/tiedotteet/2005/T2301.pdf

Ściążko, M. & Nowak, W. (2017). Municipal waste gasification technologies. Nowa Energia 1. technologie_zgazowania_odpadow_komunalnych_1.pdf (cire.pl)

Thilak, N., Iniyan, R.S. & Goic, R. (2011). A review of renewable energy based cogeneration technologies. *Renewable and Sustainable Energy Reviews*, 15, pp. 3640–3648. DOI: 10.1016/j.rser.2011.06.003

Uebbinga, M., Liisa, M., Rihko-Struckmanna, K. & Sundmachera, K. (2019). Exergetic assessment of CO_2 methanation processes for the chemical storage of renewable energies. *Applied Energy*, 233–234, pp. 271–282. DOI: 10.1016/j.apenergy.2018.10.014

Wielgosiński, G. (2020). Thermal waste conversion, Nowa Energia; Racibórz 2020 r. (in Polish)

Wongchanapai, S., Iwai, H., Saito, M. & Yoshida, H. (2012). Performance evaluation of an integrated small-scale SOFC--biomass gasification power generation system. *Journal of Power Sources*, 216, pp. 314 – 322. DOI: 10.1016/j.jpowsour.2012.05.098

Zhang W., Croiset, E., Douglas, P.L., Fowler, M.W. & Entchev, E. (2005). Simulation of a tubular solid oxide fuel cells stack using Aspen Plus™ unit operation models. *Energy Conversion and Management*, 46, pp. 181–196. DOI: 10.1016/j.enconman.2004.03.002