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Small Scale Gasification Application and Perspectives in Circular Economy

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Abstract **– Gasification is the process converting solid fuels as coal and organic plant matter, or biomass into combustible gas, called syngas. Gasification is a thermal conversion process using carbonaceous fuel, and it differs substantially from other thermal processes such as incineration or pyrolysis. The process can be used with virtually any carbonaceous fuel. It is an endothermic thermal conversion process, with partial oxidation being the dominant feature. Gasification converts various feedstock including waste to a syngas. Instead of producing only heat and electricity, synthesis gas produced by gasification may be transformed into commercial products with higher value as transport fuels, fertilizers, chemicals and even to substitute natural gas. Thermo-chemical conversion of biomass and solid municipal waste is developing as a tool to promote the idea of energy system without fossil fuels to a reality. In municipal solid waste management, gasification does not compete with recycling, moreover it enhances recycling programs. Pre-processing and after-processing must increase the amount of recyclables in the circular economy. Additionally, end of life plastics can serve as an energy feedstock for gasification as otherwise it cannot be sorted out and recycled. There is great potential for application of gasification technology within the biomass waste and solid waste management sector. Industrial self-consumption in the mode of combined heat and power can contribute to sustainable economic development within a circular economy.**

Keywords – Circular economy; gasification; municipal solid waste; refuse derived fuel; syngas

1. INTRODUCTION

The escalating energy consumption, demographic boost and spreading of industrialization during the last decades has led to increased concern on environmental issues such as threats to lack of sufficient energy capacities and negative influences on climate. Extensive use of fossil fuels are still dominating, however, new ways of applying alternative fuels such as wind, solar, geothermal, tidal, waste and biomass recovery have become more efficient and popular. Combustion of the mass, whatever it is, still provides the most easily extractable kind of energy. Increasing higher demand for power supply with more efficient energy conversion technologies that produce energy from cheap and abundant fossil and renewable fuels while reducing CO_2 emissions is crucial. For fossil fuel technologies a lot of innovation has led to the development of chemical looping combustion, direct power extraction, pressure gain combustion and other technologies that provide significant improvements of efficacy and lessen negative environmental effects [1].

Hence industrial production provides goods and the end of life cycle dominantly is waste after the use of material, in the context of a circular economy there appeared a number of technologies that provide efficient solutions for waste and biomass reduction while recovering energy. Among

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thermo-chemical treatments of waste and biomass, pyrolysis and gasification are attractive solutions; gasification provides release of syngas usable for internal combustion engines.

The World Bank accounts about 4 gigatons of all types of waste worldwide annually. Cities alone generate approximately 1.5 gigatons of solid waste. This amount is estimated to reach 2.4 gigatons by 2025. Emerging economies will double waste generation over the next 25 years [2]. Currently, 75 % of this waste is disposed and only 25 % recycled.

Conventional combustion process converts solid organic materials including waste and biomass to energy and generates electrical power. Gasification and pyrolysis both provide options for refuse derived fuel (RDF) and recover potential. These conversion processes recover and generate energy, and in some cases valuables, e.g., such as methanol. Both are not new technologies nevertheless are rather new to the market. The use for recovery of energy from waste is a relatively new domain. Waste combustion has generally been applied on energy recovery in processes for municipal solid waste (MSW) and RDF, with few exceptions where electrical power and methanol were produced [3], [4]. No stable market, however, exists for those products, trading through bourse markets they are virtually absent on the worldwide scale. RDF itself is produced by sorting process, weight-based and size separated and shredded MSW. The constant size distribution and composition is achieved through the sorting and preparation process; the result mainly consisting of high calorific waste fractions: textiles and rubber (10–15 % wt.), plastics (20–30 % wt.), paper and cardboard (50–60 % wt.). Use of high calorific waste fractions leads to relatively stable industrial conditions and much better homogeneity which, in turn, leads to higher quality of resulting gas in comparison with MSW [4]–[6]. Nowadays thermal treatment of RDF is proceeded in plants specifically dedicated for this purpose, also together with MSW in co-combustion facilities [7], [8]. During recent years RDF gasification in fluidized bed reactors applying sub-stoichiometric oxygen concentrations gained wider acceptance because of the greater potential of energy recovery and lower production of emissions (NO_x and SO_2) compared to incineration [8]–[10]. Giugliano et al. [11] talks about higher operating costs with this waste management technology. Waste facilities are regional and local which means that large waste-to-energy (WtE) plants are not the best solution if not enough feedstock is available around. Therefore efficient, mobile and smaller-scale plants for county-type communities might be of particular interest. Regardless of scale, these facilities create byproducts that create residual materials, the most abundant of which is bottom ash (BA), which takes 10–20 % wt. of the feedstock (e.g. [12]). In Denmark, The Netherlands and France, the reuse of BA as aggregate amendment material in construction industry is commonly practiced if the residues present suitable properties. Elsewhere BA is mostly landfilled as a non-hazardous waste due to absence of specific legislation regulating conditions for its utilization [12]. The same problem shall be solved using pyrolysis and gasification plants. Toxic components as metals pose concerns but reuse of BA mitigates environmental effects.

Tars and chars as well as carbonaceous solid particles are other substances that area created as residuals particularly during the gasification process which is a distinct method of thermal treatment.

Studies have been conducted to address leaching behaviour of contaminants from MSW bottom ash used in construction (e.g. [13]–[15]).

Beneficial utilization of RDF from thermal treatment BA as a fine aggregate in concrete and cement blends, landfill cover construction propose high compressive strength in specific application scenarios [16]–[22] analyzed and pinpointed problems raised by leaching of heavy metals, salts, geotechnical incompatibilities and other problems related to BA reuse applications. Thermal treatment is a promising technology, improving material and energy recovery from waste, however unsolved issues are slowing the implementation of gasification and pyrolysis technologies in a set of often used tools for energy recovery in a circular economy approach.

This paper is reviewing the small plant perspectives in gasification and alternatives of gasification residual potential reuse.

2. GASIFICATION TECHNOLOGIES

Gasification reactors and design of those has been a subject of discussion in research for more than a century over which different scale configurations were achieved [23].

Classifications are different: based on agent (oxygen gasifiers, air-blown gasifiers, steam gasifiers), heat source (auto-thermal or direct ones as well as allo-thermal or indirect gasifiers, pressure and design [24]. Common type gasifiers for biomass gasification are fluidised bed gasifiers, and of them the most common are bubbling and circulating fluidised bed items. Heat may be added directly by injection of air, indirectly through heat exchanger, or with a fluidisation medium that works as a heat carrier among reactors. Those are good as for stationary use and suitable for medium to large scale installations. Cyclone is commonly a part of installation for the removal of particulates. The gas has relatively high (800–900 °C) temperature, containing alkaline vapours [25]. Twin-bed gasification consists of two fluidised-bed reactors where biomass enters the first reactor, then is gasified with steam, but char is taken to the second reactor in order to be oxidized with air for heat performance [26].

Oil, phenols, tar, other liquids of devolatilization are decomposed into hydrogen (H_2), carbon monooxide (CO) as well as tiny amounts of light hydrocarbons. Ash is melted into vitreous inert slag. Fine fuel is delivered as dry or slurry mass through lock hopper system and slurry pumps. Slurry feed makes additional water supply in a syngas with a higher H_2 to CO ratio, therefore lowering gasifier thermal efficiency. The feeding system must be accurately adjusted for process parameters. Life of machinery is shorter due to high temperatures [27], [28]. Over the total, 20 % are fluidised-bed systems, 75 % are fixed-bed downdraft, 2.5 % are updraft, and 2.5 % are of various other designs [29].

2.1. Syngas and Feedstock

Gasification creates syngas, mixture of carbon monoxide, hydrogen, and carbon dioxide through oxidation reactions between 550–1600 °C depending on the design and parameters [30]. The waste size should be sorted, separated and mass reduced to achieve necessary quality and gain material that often is known as refuse-derived fuel (RDF). There are different types of RDF [31], also the composition and quality of RDF may vary a lot. Syngas contains other trace gases as hydrogen sulfide, methane, carbonyl sulfide, ammonia, as well as gases in trace amounts. Tar (i.e., condensable hydrocarbons) reduce efficiencies and promote corrosion [30]. Ciferno and Marano [32] have provided a description of how syngas composition varies depending on content of MSW. Franco et al. [33] give an example of syngas composition during gasification of wood. Three types of equipment are typical for gasification [34]: fixed-bed, entrained-flow, fluidized-bed gasifiers. Fixed-bed gasifiers are fed with air or oxygen at the bottom, but feedstock is provided at the top, thereby feedstock material may have comparatively large sizes of particles (pieces), but syngas is at relatively cool temperature. Entrained-flow gasifiers feed gas and feedstock at top, are fast reactive and of small size, although syngas exits very hot thereby there is a necessity to cool it. Fluidized-bed gasifiers mix gas and feedstock particles well, the reaction type is intermediate. Fluidized-bed gasifiers are good for biomass gasification, however other types may be used. Another is plasma reactor with temperatures of 1500–5000 °C that is capable of handling variations in absolutely all parameters like moisture content, particle size, and components [30]. Gasification systems process feedstock and create byproducts of dense materials like bottom ash; in the case of plasma gasification – vitrified slag. Syngas has great potential, e.g., ethanol may be manufactured [35]. Two kinds for production of ethanol from syngas are catalytic conversion and fermentation [36]. Subramani and Gangwal [37] have reviewed catalytic reactions, that may be performed with different kinds of heterogeneous and homogeneous catalysts at ∼300 °C, which is the temperature required to creation byproducts. Bacterial fermentation in a liquid at ∼40 °C is rather slow, nevertheless produces ethanol with higher selectivity. Ethanol production via gasification and fermentation averages 96.45 gal/tonne. There were 21 U.S. companies with demo or pilot gasification, 17 – with full-scale processes under development/construction in 2013. The same report [37] gives capacities of 300–750 tonne of feedstock/day, but Griffin and Schultz [38] provide data on 2000 tonne/day. When coal gasification or thermal treatment of biomass facilities exist close to a community, organic fraction MSW may be used in concert with RDF for co-firing [39]. Options of gasification are turning the negative value MSW into energy through the use of incomplete combustion [40]. It may be used as syngas in many applications: synthesis of chemicals and fuels, direct combustion as well as electricity generation [41].

2.2. Biomass Gasification

Biomass gasification is a good alternative because: (1) biomass is easily available, (2) it is relatively cheap, (3) there are no tremendously high capital investments necessary, (4) technology is relatively simple [42], [43]. Fixed and fluidized beds are mostly abundant, suspension gasifier is developed for finely divided coal [44], [45].

Fixed-bed gasifiers are mainstream and are exploited to generate syngas. Large-scale (higher than 10 MW) are used industrially [46]. Small-scale (lower than 10 MW) are mainly for decentralized use and manufacturer needs [47]. They are classified as downdraft, updraft, cross-draft [48].

In an updraft one, the biomass is fed from the upper part of the gasifier. It is dried at the top and passes through the pyrolitic zone, where volatiles, tar and char are the decomposition components. In a downdraft – biomass and air enters the down part. This type gasifier has 4 zones drying, pyrolitic, oxidative and reduction zones. Partial cracking of formed tars happens and thus gas with a low content of tars forms. Gas contains particulate tars (approximately1g/Nm^3) but most are combusted therefore this type of gasifier is ideal if clean gas is required as the result [49].

Among biomass combustion technologies, fluidized beds have good flexibility in terms of efficiency. Its advantage over fixed-bed ones is defined temperature which is accomplished by using fine material where air circulates, fluidizing the bed [50]. Two main types are in current use of fluidized-bed gasifiers: circulating fluidized bed and bubbling bed. Third type is circulating bed gasifier in pilot scale [51]. Selection of a system depends on scrutinized analysis of feedstock (both chemical and physical), quality of gas and operational features [52]. High plant costs makes fluidized-bed gasification economic if 5–10 MW scale is planned. Fixed bed gasifiers are best in small-scale stations with gas turbines. The fixed-bed gasifier plants are simpler [23], [43].

2.3. Catalytic Biomass Gasification

Biomass gasification is one of the possible alternatives for renewable energy and is considered to be a tool to reduce the greenhouse gas (GHG) emissions because life cycle of biomass confirms CO_2 neutrality [50]. However, the product gas quality and the formation of by-products are still the problems that need to be solved for commercialization. The product gas quality is affected by many factors such as catalyst, reactor type and gasifying agent type. The product gas quality can be improved to some extent by use of catalyst in the gasification. Thus, the catalytic gasification is considered to be a promising method to enhance the product gas quality [53]. The research interest in catalytic gasification has grown considerably due to tar elimination and removal of unwanted product to ensure economic viability. Catalyst effectively remove or reduce the tar, achieve desired gas ratio, have longer active life and resist sintering, reduces costs [53], [54]. Primary catalyst promote combustion, carbonation, methanation and reduce tar formation – organic compounds volatilize into gases [54], [55]. Other, secondary catalysts are placed in the downstream reactor and are involved in the formation of hydrocarbon and methane [56], [57]. A cleaner process may be achieved during the cleaning of the syngas. In fact, although gasification as a process has been known for decades, its control was a problem for researchers and manufacturers. Nowadays quality of process may be elaborated through efficient modelling [29].

2.4. Plasma Gasification

Plasma gasification is a multi-stage process starting with feed inputs of everything from waste to coal and plant matter, including hazardous wastes. First of all, valuables are sorted out for recycling, then material is dried, second step is gasification itself via plasma torches in an air-controlled reactor. The process leads to the breakdown of carbon-based materials into gases and liquid slag forming from inorganic matter. The temperature applied is extremely high and leads to the complete hazardous material complete disarrangement. Afterwards the recovered gas is cleaned-up and the gasses are scrubbed of impurities to form a clean fuel that is recycled back via heat exchangers into the system. Finally electricity, chemicals, hydrogen and polymers are gained. Plasma torches burn at temperatures close to the surface temperatures of the Sun approaching 5500 °C and destroy any materials found on Earth with the exception of nuclear waste. Plasma torches cause organic and carbonaceous materials to vaporize into gas, but non-organic materials are transformed into vitrified glass [58].

3. MUNICIPAL SOLID WASTE AS SUSTAINABLE ENERGY RESOURCE

Municipal solid waste give plethora of opportunities taking into account economics and environmental aspects. Incineration, anaerobic digestion, gasification, and fermentation are counted under commercially successful development and may be compared in different aspects.

The importance of economic and environmental aspects in waste to energy processes are comprehensively covered in Wiedinmyer et al. [59], mentioning that 40 % of worldwide MSW is openly burned and constitutes for up to 64 % of the worldwide emissions for particular substances.

Comparisons among the four methods mentioned depend on the analyses performed and the assumptions made. For instance, emissions per production of ethanol are different than for fermentation and gasification if one considers the base level. Incineration produces 6.6 times more electricity than Anaerobic Digestion for 3.6 times more feedstock, however Gasification produces more ethanol compared to Fermentation. There also may be considered the total amounts of feedstock processed that change costs for treatment of residual. Hereby range is following – Fermentation, Anaerobic Digestion, Gasification, allowing for more opportunities for the remaining MSW. Incineration create a lot of ash streams, Anaerobic Digestion is the only to improve processes of emissions from the baseline. The facility is inside the community not requiring any logistics. Methane and VOC emissions are reduced for all the alternatives, PM is decreased except for incineration. CO_2 emissions show mixed results, where Gasification and Incineration provide increased CO_2 pollution. The alternatives without burning the feedstock lead to CO_2 emission reductions. Residuals are in all cases, however, many opportunities exist for industrial ecology to recycle [60].

3.1. Economics of Waste Gasification Solution

Economic analysis among different energy sources have been performed, e.g., the breakeven prices calculated for natural gas in order to compare with solar energy driven gasification.

In a global perspective, natural gas prices in Japan averaged 18.08$ GJMg, in Germany 10.45$ GJ/Mg, 8.97$ GJ/Mg in the UK [61]. The main reason is low extraction of these countries themselves and relying on imports. Thus prices are high enough to make RDF gasification feasible, especially in the EU where environmental benefit and remediation pricing is crucial. Monetization of environmental costs in combination with economic benefits according to EU Directives is advantageous to investors to promote these technologies, even when we speak about plasma gasification [62]. The costs and calculations involves discussion among many stakeholders and partners: large-scale projects carry higher organizational risks and require more capital. Willingness to risk more carrying more expenses with opportunities to cash out larger profits later are evaluated versus uncertainty surrounding large alternative energy projects. Further research must expand knowledge on potential GHG and improve carbon credit pricing to lower emissions rather than to do it formally. Tax rate and bond yield reduction might reduce costs for technologies. If policies would be organized, that couple the production credit policy with environmental policy methods, cost savings and reduction of capital investments may boost the alternative energies including gasification and lower price for the technologies [40].

First plasma gasification pilot projects appeared in Japan to transform waste, sludge, and auto-shredder residuals to energy. Companies in Japan and Canada have also achieved success in pilot and numerous commercial attempts [58]. The economics of waste gasification need to have recycling of inert materials: metal and glass which decline efficiency of gasification process, however plasma is capable to melt them. Higher value is in products such as high-quality plastic and paper – certain plastics earn €195 per tonne, some sorts of paper give €53 per tonne. It is obvious that distinct waste may be recycled, but then good sorting and separation is important [58].

Hereby plasma gasification products are few: syngas as alternative energy, inert vitrified glass for construction industry.

Processing of industrial waste as incinerator ash or batteries will provide less syngas but more metal alloys, but, for instance medical waste processing in plasma gasification will provide lower amounts of inorganic byproducts but more syngas. Separated metal alloy can be traded via a commodity-based pricing system.

3.2. Gasification Process and Residuals

Gasification is a thermochemical process where carbon containing material at high temperatures and in presence of oxygen, carbon dioxide, steam, hydrogen, air is converted into a gas (syngas). The key advantage is the opportunity of converting a solid material into a gas with keeping 70–80 % of the chemical energy through process [63]. Besides the producer gas may be used in many applications [64]–[66]. If biomass gasification advantages are widespread and available relatively cheap, however negatives aspects of biomass gasification is that it produces tars, particles and char [67]. Tars are pollutants of producer gas, and are the main hurdle for commercial implementation of this technology [63], [67], [68]. Tars include polycyclic aromatic compounds (PAHs) that are solid at room temperature and cause several technical problems [55], [67]–[70]. Carbonaceous particles wear out engines [71]. Concentrations may reach 3–10 % wt of the biomass feedstock [72], that determine chemical composition and physical properties [73].

Char is a carbon containing solid material formed during gasification. Often char and ashes are collected together [70], [74]. The ash content may reach high values [75].

3.3. Biochar

One gasification product is biochar, it may be used as a soil amendment for climate change mitigation and improve soil biota functional redundancy, increase organic carbon stability, reduce N_2O emissions, facilitate soil formation and favour water circulation as well as rhizosphere microbiome including support of the soil pH buffering capacity [75]. The understanding of biochar's role in soil provide valuable information about soil remediation process and contact with contaminants [76]–[79].

Char properties limit its application possibilities [80]. Gasification chars are dense (specific surface area <70 g/m^2), thus their application possibilities are limited.

Among the mentioned wastes formed during gasification, char may find applications as fuel [81], domestic charcoal, activated carbon [82], in agriculture [83], [84], for further thermochemical processing of waste [85], [86]. Contaminations with trace elements may significantly reduce its application possibilities [87], [88] therefore studying possible sustainable use is of high importance [89].

3.4. Hazard Tests of the Gasification Residuals

A very important issue is to study is leaching from waste thermal treatment bottom ashes, chars and tars, by taking into account pH and other aspects. Thermal treatment (incineration, pyrolysis and gasification) for the feedstock may use various wastes. Column percolation test as well as more different types of batch tests are used for modelling aimed at identifying of main mechanisms of contaminant possible spreading to environment due to the leakage from ash. Leaching tests provide information related to pH dependence, L:S ratio and differences in mineralogy.

Recently, granulation of waste material has received attention as well as their applications as construction materials and others (e.g. [90]–[93]). Natural aggregates compared to gasification residuals contain lower concentrations of potentially harmful compounds (e.g., heavy metals) that may be leached and present hazards to the environment and public health [94].

4. EXERGY ANALYSIS OF GASIFICATION AND SUSTAINABLE ENERGY PRODUCTION

Exergy analysis concept combines energy, environment and sustainable development approaches [95], [96], and identifies possibilities for process improvement through evaluation of process alternatives [97], [98]. Biomass-gasification exergy analysis provides insight of process improvement potential [99], [100]. Several studies [100]–[102] are dedicated to exergy analysis of different kinds of biomass in comparison to coal gasification. Exergy analysis has shown higher exergy efficiency for steam/air use in process [95].

CO_2-enhanced gasification of biomass feed demonstrates high efficiency [103].

Small-scale co-generation installation can operate on biomass, municipal waste and dried sewage sludge, agricultural residue, as well as other fuels providing enough calorific values.

Several attempts to analyze various environmental and combined economic aspects were done [104]. The electrical energy obtained from biomass gasification process was supported by green certificates and production of energy in CHP with yellow certificates (small CHP <1 MW).

The economic efficiency of the specified CHP plant usually is based on the production economy calculations. Economic efficiency (NPV) analysis was performed in [105], [106] and showed the value of the investment based on rate of return, equipment life, risk of the investment and the time when the revenue will be reached. The Internal Rate of Return (IRR) was calculated as an indicator to determine cash flows and risks.

Positive NPV means that the investment is profitable, and the minimum required IRR for an investment in the energy sector in Poland is equal to 2.8 % [104], but 11 % is a much more common assumption [107]. These economic studies in Poland as a reference country have shown that installation is more profitable when electricity and heat were produced for self-consumption instead of being sold on the market. Payback time is not less than eight years and should be noted that installation fits very well with European energy policies, especially in the area of decentralised power generation. Moreover, such a CHP installation is most suitable in isolated and rural areas, especially for small farms or horticultural businesses, thus electricity and heat can be efficiently utilised in combination. Increased biowaste production is a concern and creates adverse effects on the local and natural environment therefore one may expect much larger financial support (in the form of adequate regulations and policies, e.g., in the EU) allowing transformation of biomass wastes into energy. Also environmental benefit arising from using a system is the contribution made towards reducing greenhouse gas effects and help to reach Paris 2016 targets [104].

5. Conclusions: Future Research Trends for Closing the Industrial Loop of Waste Thermal Treatment Methods

Gasification converts various feedstock including wastes to a syngas that differs from incineration. Future research should be designed to study gasification products for recovery of metals like in plasma gasification. Thermo-chemical conversion of biomass is becoming a tool to develop energy systems without fossil fuels. Especially large amounts of industrial biowaste can be processed through gasification and create possibilities to use local resources in the bioeconomy. In the near future biomass and carbon contained waste recovery will have a positive influence on the economy, welfare and sustainability. One specific problems of power supply in sparsely settled areas or for industrial applications as alternative to capital intensive grid development may be solved through the boost of gasification in a combination of micro-grid development when conducted in an efficient CHP mode. Gasification is not only not a competitor to recycling, it actually serves to enhance recycling programs. Pre-processing and after-processing must increase the amount of recyclables in a circular economy. Additionally, a lot of end of life plastics, wood residue and paper can be good, high energy feedstock for gasification as otherwise this mass cannot be sorted out and recycled.

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