We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,900
Open access books available

185,000
International authors and editors

200M
Downloads

Our authors are among the

154
Countries delivered to

TOP 1%
most cited scientists

12.2%
Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com



Chapter 6

Recent Trends in Gasification Based Waste-to-Energy

Muhammad Saghir, Mohammad Rehan and Abdul-Sattar Nizami

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.74487

Abstract

Addressing the contemporary waste management is seeing a shift towards energy production while managing waste sustainably. Consequently, waste treatment through gasification is slowly taking over the waste incineration with multiple benefits, including simultaneous waste management and energy production while reducing landfill volumes and displacing conventional fossil fuels. Only in the UK, there are around 14 commercial plants built to operate on gasification technology. These include fixed bed and fluidized bed gasification reactors. Ultra-clean tar free gasification of waste is now the best available technique and has experienced a significant shift from two-stage gasification and combustion towards a one-stage system for gasification and syngas cleaning. Nowadays in gasification sector, more companies are developing commercial plants with tar cracking and syngas cleaning. Moreover, gasification can be a practical scheme when applying ultra-clean syngas for a gas turbine with heat recovery by steam cycle for district heating and cooling (DHC) systems. This chapter aims to examine the recent trends in gasification-based waste-to-energy technologies. Furthermore, types of gasification technologies, their challenges and future perspectives in various applications are highlighted in detail.

Keywords: waste-to-energy (WtE), waste, gasification, fuel cell

1. Introduction

Anthropogenic activities associated with increasing global population, living standards, desire for better economic growth, energy demands, and global trade are some of the critical factors that inevitably lead to massive waste generation [1]. The environmental challenges associated with growing waste generation are further exacerbated by lack of waste planning and policy, poor waste management practices, open dumping of waste residues leading to pollution, low

IntechOpen

© 2018 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. CC BY

or no landfilling and cheap energy costs in some regions around the world. It is inevitable that waste generation cannot be eliminated to support the human development [2].

A study by International Solid Waste Association (ISWA) showed that annual global waste generation accounts for 7–10 billion tonnes in total, of which approximately 2 billion tonnes is made up of municipal solid waste (MSW). The typical waste is made up of 24% MSW, 21% industrial waste, 36% construction and demolition (C&D) waste, 11% commercial waste, and 5% arises from wastewater treatment. Only 3% of the total solid waste is used for energy production, and there is a considerable potential to use the remaining waste for energy recovery [3].

There is an increasing momentum to reduce, reuse and recycle the waste (3R's approach), but more efforts are required to minimize the environmental impacts of residual waste disposal. When the efforts to reduce the waste generation are exhausted, plastics, glass, paper, and metals are more attractive materials for reuse and recycling purposes. A vast quantity of mixed waste still remains that becomes a nuisance and thus destined to landfills if not left to decay naturally in the immediate environment [4]. Energy generation from residual waste provides an excellent waste management solution especially after all the waste management hierarchical efforts are made and when further waste recycling is not economically viable. These mixed waste streams, commonly known as residual waste, are heterogeneous, very complex to recycle and are well suited for waste-to-energy (WtE) application. After energy conversion, the remaining waste is reduced to a tiny fraction of the original volume, and the rest can be easily disposed of in the landfills.

Many factors influence the effectiveness and routes of energy recovery from waste. Awareness to greenhouse gases (GHG's) effects from increasing emissions of waste, access to conventional energy resources, waste management costs and practicality of WtE technologies are some of the key factors that influence the energy recovery from waste. For maximizing the resource efficiency of waste feedstocks, all efforts are made to manage the waste during its life cycle. A standard waste management hierarchy includes, prevention of waste generation, reduce, reuse and recycle, conversion to energy and disposal of remaining residues throughout the waste life cycle. This chapter aims to examine the recent trends in WtE, primarily based on gasification technologies with an ambition to produce clean energy and solve waste disposal issues.

2. Trends in waste management

Historically waste was an undesirable by-product of human development and was considered as a nuisance. However, rising or unstable conventional energy costs in some parts of the world, geopolitical instability of the supply and costs of conventional energy resources, increasing waste landfills costs, and reducing landfill capacities led to a change in the waste management strategies. As a consequent, the trends in waste management have shifted from waste dumping to waste disposal for the landfill, and from waste destruction by incineration to WtE generation. Therefore, waste is no longer an undesirable by-product but one of the very

profitable business in some developed countries due to its high potential for energy and resource recovery.

2.1. Waste types and composition

Waste is a general term and encompasses a wide range of materials originating from various sources associated with human development. Waste is heterogeneous in nature [5] and very troublesome to separate down to individual waste types. Readily separable waste streams are sorted and separated at a material recovery facility (MRF), and remaining residue waste that is complex and un-economical to separate is left for energy recovery. **Table 1** provides waste types and their sources that shows the diversity of waste materials in the MSW. Typical composition of MSW varies from country to country and can have high moisture content up to 50 w/w %.

2.2. Waste treatment options

As shown in **Table 1**, the diversity of materials in the waste and complexity of separation leads to a variety of waste treatment options. Since no single waste treatment option can address all types of waste, hence different waste types attract different treatments. Source segregation has made it possible to separate waste streams that can be destined for a waste treatment facility. For example, in an MRF or waste-based biorefinery, most of the readily separable waste streams are separated for reuse and recycling such as metals, plastics, glass, aggregates,

Source	Type	Composition
Municipal solid waste (MSW)	Residential	Food wastes, paper, cardboard, plastics, textiles, leather, yard wastes, wood, glass, metals, ashes, special wastes (e.g., bulky items, consumer electronics, white goods, batteries, oil, tires), household hazardous wastes, e-waste.
	Industrial	Housekeeping wastes, packaging, food wastes, wood, steel, concrete, bricks, ashes, hazardous wastes.
	Commercial & institutional	Paper, cardboard, plastics, wood, food wastes, glass, metals, special wastes, hazardous wastes, e-waste.
	Construction & demolition	Wood, steel, concrete, soil, bricks, tiles, glass, plastics, insulation, hazardous waste.
	Municipal services	Street sweepings, landscape & tree trimmings, sludge, wastes from recreational areas.
Process waste		Scrap materials, off-specification products, slag, tailings, topsoil, waste rock, process water & chemicals.
Medical waste		Infectious wastes (bandages, gloves, cultures, swabs, blood & bodily fluids), hazardous wastes (sharps, instruments, chemicals), radioactive wastes, pharmaceutical wastes.
Agricultural waste		Spoiled food wastes, rice husks, cotton stalks, coconut shells, pesticides, animal excreta, soiled water, silage effluent, plastic, scrap machinery, veterinary medicines.

Table 1. Types and sources of waste [2].

e-waste, and liquid waste [4–9]. Medical waste is sent for incineration with or without energy recovery with minimal ash residues left for landfilling [6, 8, 10]. Organic liquid waste such as waste cooking oils and fats are sent for conversion to biodiesel and glycerol [7, 9]. Food waste, wastewater, and some agricultural wastes are sent for anaerobic digestion (AD) to be turned into biogas and digestate [11]. Solid green waste is composted and turned into a standardized compost product for horticulture applications [12]. Most of the MSW can be incinerated [13] with or without energy recovery or can be subjected to advanced conversion technologies such as gasification [14, 15] and pyrolysis [16, 17]. Incineration of MSW has been practiced in developed and developing countries as an effective waste management solution, but it leads to toxic emissions [18, 19]. These emissions are produced when the waste residue is burnt at high temperatures that lead to the formation of toxic gases such as dioxins [20], furans, polycyclic aromatic hydrocarbons (PAH), oxides of sulfur, and nitrogen [21].

2.3. Waste-to-energy (WtE)

WtE is promising because most of the waste originates from urban and industrial areas, which are close to large urban populations and where there is a great need for energy. Waste treatment and energy conversion close to the waste source help to reduce transportation costs, provide energy locally, reduce transportation-related GHG emissions and can offset fossil fuel based GHG emissions by taking a large portion of energy from waste in the form of organic biomass waste. Another advantage is that since the WtE power plants can be built close to urban areas, this leads to a reduction in the electricity distribution losses, and there is a greater likelihood of using the waste heat from the plant for district heating and cooling (DHC) purposes. Waste management at local level further supports the concept of the circular economy where resource potential of the waste feedstocks is maximized. Another critical aspect that can partially be addressed by effective waste management is the Energy Trilemma; energy security, social equity and environmental impact mitigation [22]. Conversion of residual waste-to-energy is highly desirable because of environmental benefits and income generation from energy production and sales and gate fees [23] associated with the diversion of wastes from landfill, as can be seen in some developed regions such as the European Union (EU). Similarly, in some other countries like India, China, and Pakistan, it is an excellent option to divert waste from landfill for environmental benefits as well as displacing some fossil fuel based energy production.

3. Gasification of waste

Gasification was used during the Second World War to run engines on fuelwood. It was due to lower fossil fuel prices that lead to the demise of wood gasification. However, coal gasification is well known and is still used around the world. Gasification of waste feedstocks is no different in this, as they are hydrocarbons which are used to produce syngas. Gasification of waste is preferred over incineration because it provides a syngas product that can be used in many ways as opposed to hot combustion gases. Gasification provides a uniform quality syngas from a heterogeneous and complex residual waste. Gasification is the only option that

can provide multimodal products such as heat, power, cooling, gaseous and liquid fuels as well as chemicals [24, 25]. Moreover, gasification provides the feedstock flexibility with varying qualities. Gasification also enables to produce power efficiently with an excellent ability for integration with existing power production equipment such as steam cycle, gas turbines, and gas engines. As gasification can be deployed on a local level, thus it provides efficient DHC potential from waste heat by maximizing the energy conversion efficiency. Waste gasification is a precursor for large-scale biomass gasification, and it will enable the carbon capture and storage (CCS) that otherwise lead to harmful GHG's emissions.

There is a significant rise in urbanization that is commensurate with waste generation, thus waste energy through gasification became an obvious trend. Waste is attractive for energy recovery due to huge volumes produced in urban areas. However, waste is not uniform in quality, and its moisture content varies from season to season and between geographic locations. Waste gasification can also be integrated with biomass blending to deliver low carbon energy and chemicals. Gasification processes are extensively studied where researchers have tried to optimize the gasification conditions using thermal and catalytic treatments in order to enhance the gas quality by reducing the tar content in the syngas [26, 27], along with increasing the hydrogen content and reducing the processing steps to name a few. Furthermore, various studies have focused on the effect of gasifier types [28], effect of processing temperatures [29–31], effect of feedstock types and their particle sizes [31], effect of gasifying (oxidant) agents [30, 31], effect of the bed materials [32, 33], and combining gasification with other processes to enhance the process economics and efficiency. During gasification, various complex homogeneous and heterogeneous reactions take place; some of these are shown in **Table 2**.

Reaction	Heat of reaction (MJ/kmol)	Reaction name
Heterogeneous reactions:		
$C + 0.5O_2 = CO$	−111[a]	Char partial combustion
$C + CO_2 \leftrightarrow 2CO$	+172	Boudouard
$C + H_2O \leftrightarrow CO + H_2$	+131	Water-gas
$C + 2H_2 \leftrightarrow CH_4$	−75	Methanation
Homogeneous reactions:		
$CO + 0.5O_2 = CO_2$	−283	CO partial combustion
$H_2 + 0.5O_2 = H_2O$	−242	H_2 partial combustion
$CO + H_2O \leftrightarrow CO_2 + H_2$	−41	CO shift
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	+206	Steam methane reforming
Hydrogen sulfide (H_2S) and ammonia (NH_3) formation reaction:		
$H_2 + S = H_2S$	nr[b]	H_2S formation
$0.5N_2 + 1.5H_2 \leftrightarrow NH_3$	nr	NH_3 formation

[a]Negative sign indicates an exothermic reaction, and the positive sign indicates an endothermic reaction.
[b]nr = Not reported.

Table 2. List of reactions in gasification process [34, 35].

Gasification involves four different steps that are drying of feedstock, pyrolysis, oxidation, and finally the reduction [36]. These are further explained below.

Drying: Feedstocks with varying moisture content are dried in a drying process at temperatures above 100°C. In this step, no chemical reactions take place, and phase change between liquid water and vapor steam is the main cause of energy requirement in the drying process.

Pyrolysis: In this step, feedstock starts to decompose [37] in the absence of oxidant at elevated temperatures and vapors are released from the feedstock using primary reactions. The proportions of vapors and char produced are influenced by process conditions such as the heating rate and temperature. In addition, product distribution is also affected by feedstock composition and feedstock size.

Oxidation: At elevated temperatures and in the partially oxidized environment, heterogeneous reactions take place between oxidant and feedstock forming carbon monoxide (CO) and water vapor. Oxidation is influenced by the chemical composition of feedstock, type of oxidants (oxygen, steam, CO_2 or air) and operating conditions. This step is mostly exothermic and results in heat energy released for energy self-sufficiency to sustain the process heating needs.

Reduction: This is a net endothermic step during which high-temperature chemical reactions take place in the absence of oxygen. Various reactions between products of oxidation and char take place to form new hydrocarbons. Ash and some char are the by-products of this reaction step [36, 38, 39].

Gasifier selection involves a detailed understanding of different types of gasification systems and feedstocks. Selecting a gasifier type with an atmospheric or pressurized gasifier will have cost implications as pressurized systems tend to cost slightly more. Selecting between a fixed bed and fluidized bed gasifier system will be influenced by the scale of the process as well as the upstream and downstream processing requirements such as upstream air preheating for fluidized bed gasifier and downstream heavy air suction requirement for fixed bed gasifiers. Choosing between different oxidant types such as air, oxygen, steam or carbon dioxide (CO_2) will be influenced by capital costs, syngas product quality and its application. Using air as an oxidant is a cheaper option with regards to capital investment, but it may not give high calorific value syngas, and hence a compromise needs to be made during the selection process [40]. Syngas heating values have a huge influence when selecting a gasifier because syngas heating value ranges between 4 and 40 MJ/kg. End applications of syngas will dictate certain heating values, e.g., syngas for heating applications can be accepted with a low heating value gas whereas Fischer-Tropsch diesel and another chemical synthesis will require fairly high heating value syngas [41].

Various types of gasification system configurations exist that are preferred for various reasons; these are presented in **Table 3**. Most notably, they include (1) fixed-bed downdraft gasification where feedstock and syngas flow downward in a co-current direction, (2) updraft gasification where feedstock and syngas flow are in counter directions, and syngas flows upward in the gasifier, and (3) fluidized bed gasification involves a moving (catalytic or non-catalytic) bed material in addition to feedstock and oxidant. Fluidized bed gasifiers involve bubbling and circulating fluidized bed. In a bubbling fluidized bed gasifier, there is rapid mixing of feedstock and bed material by the oxidant, which leads to high heating rates and somewhat uniform distribution of temperature within the system [44]. Notable differences between the

Gasifier	Flow direction		Support	Heat source
	Fuel	Oxidant		
Fixed bed-Updraft	Descending	Ascending	Grate	Coal partial combustion
Fixed bed-Downdraft	Ascending	Descending	Grate	Volatile partial combustion
Fluidized bed-Bubbling	Descending	Ascending	None	Coal and volatile partial combustion
Fluidized bed-Circulation	Descending	Ascending	None	Coal and volatile partial combustion

Table 3. Types of gasifiers, fuel, and oxidant flow configuration [42, 43].

different types of gasifiers arise due to variations in bed support for feedstock material in the gasifier, direction of flow of material and oxidant and the heat supply and control in the gasification process. **Table 3** lays out the most common gasifier configurations [42, 43].

3.1. Differences between pyrolysis, gasification, and combustion

The main differences between pyrolysis, gasification, and combustion based on oxygen demand can be explained as below:

- In pyrolysis there is no air or oxygen allowed in the reactor with feedstock and the ultimate objective is to produce liquids (bio-oil) for further upgrading as a fuel, small quantity of char and syngas. Most of the energy in starting feedstock is condensed in a liquid that is a complex mixture of more than 300 compounds. It is red-brown in appearance with high acidity or low pH, high viscosity and lower calorific value in comparison to crude oil. It is a mixture of organic compounds such as carboxylic acids, alcohols, aldehydes, esters, ketones, sugars, phenols, guaiacols, syringol, furans, terpenes and other minor compounds [45, 46]. Bio-oil can be used as a fuel in diesel engines with some modifications or after blending with conventional diesel or as a fuel in furnaces; oil-fired boilers and turbines. Due to the characteristics of bio-oil, some improvements are necessary to enable its applications as a liquid fuel [45, 47–49].
- In combustion, the feedstock is completely combusted with excess air or oxygen, and hot combustion gases are produced. Heat produced during combustion is the end product and is used in boilers for steam generation to convert to power. The hot combustion gases are mainly made up of CO_2, water vapor, and nitrogen.
- In gasification, the feedstock is partially burned with limited oxygen or air, and fuel gas (syngas) with a calorific value greater than 4 MJ/m^3 is produced. This syngas is then further cleaned for other uses in boilers, engines, turbines, fuel cells and chemical synthesis. It is mainly composed of CO, CO_2, water vapor, hydrogen, nitrogen, and C_2H_n gases in varying concentrations [45]. Syngas (CO & H_2) is a precursor for the production of liquid fuel through Fischer-Tropsch (FT) synthesis process [50]. The gaseous product from gasification can be used in many different ways such as in heating applications (furnaces, boilers), power applications (gas engines, integrated gasification combined cycle (IGCC)) or in chemical synthesis through catalyst reactions for producing ammonia, hydrogen, FT hydrocarbons and methanol [51].

3.2. Trends in waste gasification

As highlighted earlier, MSW has vast variations in material composition, particle size, density, calorific value, contamination and ash and moisture content composition. Due to these variations in MSW, waste feedstock after sorting valuable components such as metals, plastics, and paper is standardized into solid recovered fuel (SRF) or refuse-derived fuel (RDF). This standardization has led to waste being a commodity and is sold in the international market. Also, to reduce transportation costs, SRF and RDF are pelletized to increase energy density. The international movement of waste is widespread among the EU countries [52]. The huge size of installed incineration capacity within EU attracts waste movement on the mass scale. In continental Europe, cement kilns are regularly co-fired with RDF as these facilities have sophisticated emissions cleaning equipment. However, due to Waste Incineration Directive, there is an increasing shift towards advanced conversion treatment such as pyrolysis and gasification within EU.

There is an increasing policy shift towards sustainable energy production at reduced carbon footprint. For example, the United Kingdom (UK) of Great Britain under its Climate Change Act 2008 committed to reducing its 80% of carbon emissions to 1990 level by 2050 [53]. The UK government has provided subsidies in the form of Renewables Obligation Certificates (ROC) for biomass waste utilization contained within the residual waste to support the low carbon energy production. This has created a big shift towards the UK becoming a market leader in WtE. There are currently 14 such WtE plants, mostly based on gasification technology, are operational in the UK alone, and much more are under construction [52].

3.3. Tars and their associated problems in gasification

Tars are defined by Milne et al. [54] as "the organics produced under thermal or partial-oxidation regimes (gasification) of any organic material are called "tars" and are assumed to be largely aromatic." Other researchers have described tars as a very complex mixture of aromatic and oxygenated hydrocarbons having a molecular weight higher than that of benzene of [55–57]. Benzene and other heavier molecular weight compounds are present in pyrolysis bio-oil, and their presence in syngas tends to cause problems. As previously said, intermediate pyrolysis is based around the concept of encouraging secondary reactions between the evolved vapors from biomass and resulting char. Some tars present in the bio-oil can have their molecular weight up to 500 Daltons [58]. The presence of these very high molecular weight tars in bio-oil and syngas lead to incomplete combustion when these fuels are used. High molecular weight tars act as promoters of high viscosity, and limit the atomization of the fuel, and cause blockages in fuel pipes and injector lines by condensation [45, 54, 59].

Tar levels as reported by Milne et al. [54] exhibit a wide range of various gasification processes. For example, updraft gasifier tar content in the raw syngas is reported between 1 and 150 g/m^3. Whereas, in a downdraft, it is 0.04–6 g nominally, and in the fluidized bed gasifiers it is 0.1–23 g/m^3. Milne et al. [54] also reported various tar tolerance levels from various authors in the syngas for multiple applications such as for engines, turbines, fuel cells, and compressors. It is

imperative to bring the tar levels in the syngas as low as possible to avoid associated problems in the downstream processing equipment.

4. Types and applications of gasification systems

Numerous researchers are looking into alternative ways to make use of low-grade biomass and wastes by avoiding the need even to produce bio-oils while still pyrolyzing and gasifying these materials [59–68]. One such system is the Viking gasifier [61] that is a two-stage process to crack the tars thermally. This system works by a screw pyrolysis system that produces hot vapors and char at a temperature of 500–600°C at the top of the gasifier to be partially oxidized and tar fractions to be broken down into syngas. The char from the pyrolysis unit is transferred into fixed bed of the gasifier to act as a tar cracking unit where further tar cracking occurs. This system is reported to have a nominal tar content in syngas as low as 15 mg/m^3. Tar sampling has been performed in various stages of this process in another study [1, 59–68], which shows a progressive decrease in tar levels starting from the pyrolysis stage to partial oxidation to gasification stages and decreasing to 5 mg/m^3 tar levels.

4.1. Fluidized bed gasifiers

Fluidized bed gasifiers are used for commercial applications >5 MW as they are only economical at large scale as compared to downdraft gasification that is economical up to 5 MW maximum. Such systems consist of a vessel with an air distributor nozzle assembly at the bottom of the vessel. Feedstock enters the bed and finely ground bed material is fluidized by air or oxidizing agent. The temperature of the bed in the gasifier is regulated by the air/feedstock ratio within 700–900°C. Biomass is thermally broken down into gaseous compounds, and char is produced. The hot char and fluidizing bed material cause further reactions to break long-chain hydrocarbons or tars into syngas components. Thus, a syngas product with very low tar content is produced with tar content less than 3 g/Nm^3.

Advantages of fluidized bed gasifiers include uniform syngas product composition, uniform temperature distribution throughout the gasifier, rapid heat transfer between the feedstock, bed material, and oxidant. It is also possible to achieve high conversion efficiency and low tar content in the syngas. The effectiveness of tar removal can be further enhanced by using catalytic bed materials such as olivine, dolomite, and other industrial nickel-based catalysts. Disadvantages include problems with low ash melting point materials and large bubble size bypassing the bed [43]. Examples of these gasifiers include Royal Dahlman [69] bubbling fluidized bed gasifier and Gussing circulating fluidized bed gasifier [70].

4.1.1. Type 1 gasifier

Two-stage close coupled gasification/combustion is used within the fluidized bed reactor with a multi-level injection of air. Primary air/oxygen injection in gasification level and secondary air injection is used in the combustion level for complete combustion of gases. Hot gases

exiting the reactor are fed into a steam generator to produce steam which then drives a steam turbine to generate electricity. Minimal gas cleaning takes place in this type of gasifier configuration. This process layout suits steam turbines and usually have low overall efficiency up to 20%. Example include Energos process [71] where the objective is to reduce capital costs of downstream gas cleaning equipment.

4.1.2. Type 2 gasifier

This kind of gasifier is usually better equipped as compared to type 1 gasifier. After waste feedstock entry into gasifier, air or oxygen is introduced to run the gasifier for converting waste into syngas. There is catalytic fluidized bed environment to crack tars, and the resulting syngas is then cooled to 400°C and hot filtered and then combusted in the boiler to produce steam for electricity generation using a steam turbine. The excess heat is also recovered and used in district heating system. An example of this system is a Lahti gasification process [72].

4.1.3. Type 3 gasifier

Only this type of gasifier can deliver the future promise of meeting the need of syngas utilization for multi-modal products. This is due to the ultra-clean and tar-free syngas it can produce through various syngas tar cracking and polishing stages. In this type of gasifier setup, the waste feedstock is fed into the fluidized bed gasifier where oxygen or air/steam react with it in the presence of a catalyst bed such as dolomite or olivine to produce syngas. After removing solids through hot gas filtration, thermal tar cracking is performed by oxygen injection to raise the temperature (1200°C) of the syngas. The higher calorific value of the syngas is maintained as nitrogen input through the air is kept minimal. The resulting syngas is then further cleaned and polished before being used either in the gas engine, gas turbine or in chemical synthesis. This syngas can be converted into Fischer Tropsch diesel, methanol or hydrogen. The tar free nature of syngas provides excellent future proofing potential for the product flexibility. The engine efficiency on this syngas can be as high as 35% [73], and with heat recovery or through methanation for synthetic natural gas (SNG) production, even higher efficiencies are easily achievable. An example of this system is Lurgi fluidized bed gasification system.

4.2. Plasma gasification

Plasma gasification is preferred for mixed waste such as MSW or hazardous waste (asbestos and radioactive) where high temperatures are used to produce syngas and a melt arising from inorganic species of feedstock. A distinctive feature of plasma process resides in its ability to produce very high temperatures that are not achievable with conventional gasification and combustion; these high temperatures help to reduce tars and convert all the organic material into syngas. Tar content as reported by Refs. [54, 74] is shown to be 1000 times less than that of auto-thermal gasification processes. Arc discharges obtain thermal plasmas from DC or AC current or through radio frequency or microwaves. Mostly DC plasma technology is preferred for waste gasification plasma processes. Plasma is formed by high energy from AC or DC sources through the plasma torch close to the bottom of reactor and fuels are gasified through the plasma flames. The oxygen demand in this process is small as compared to conventional

gasification as most of the thermal energy is coming from external energy source rather than through exothermic reactions between the fuel and oxygen. Oxygen is only used to convert the fuel into syngas [75]. Commercial scale examples of operating plants are Advanced Plasma Power and Alter NRG (Westinghouse) [76].

4.3. Waste gasification for fuel cell application

Although waste gasification plants are mostly feeding the syngas to turbine or engine for electricity, however, there is a significant interest in using the ultra-clean syngas in high-temperature solid oxide fuel cells (SOFC) [77]. This is because CO being the main constituent of the syngas does not poison the fuel cell electrodes as it happens to be in polymer electrolyte fuel cells. The interest is due to the high electricity conversion efficiency that can be achieved by using fuel cells. However, so far most of the development for fuel cell application is based on individual biomass feedstocks as opposed to mixed waste feedstocks. The sulfur poisoning of SOFC is one big hurdle that needs to be overcome for waste gasification. SOFC usually are tolerant to sulfur content in parts per billion (ppb) range. Nagel et al. [78] have studied the biomass integrated syngas fuel cell setup with an electrical power output of 1 MWe. In another development, Lobachyov and Richter [79] explored the integration of a biomass-fuelled gasifier to Molten Carbonate fuel cell (MCFC). With the trends of waste gasification leading to producing ultra-clean tar-free syngas, the quality of syngas permits to use it in high-temperature fuel cells. The need to clean the syngas with sulfur impurities down to ppb level is achievable through a separate sulfur removal process. Given the high electrical efficiency of fuel cells and excess heat available from such integrated system, it all lends to perfect combined heat and power (CHP) system through fuel cell application in urban areas [80].

4.4. In-situ oxygen separation from air for gasification

Separating oxygen from the air through pressure swing adsorption and cryogenic methods is all very well known for large-scale oxygen production. As the waste gasification is trending towards ultra-clean tar-free syngas with high calorific values, this demand can only be met by oxygen gasification rather than air. In all oxygen separation processes, the high costs of oxygen production are associated with high-pressure air, low-temperature cooling and or membranes. New techniques of oxygen separation from the air are emerging where oxygen can be separated using a ceramic ionic membrane separation at high temperatures [81]. Since gasification takes place at temperatures above 800°C, this has attracted a lot of interest from industry to generate in-situ oxygen while gasifying the feedstocks. This mixed ionic-electronic conducting (MIEC) technology is based on dense ceramic membranes to separate the oxygen from air at temperatures around 800–900°C [82]. Since these membranes are made up of ceramics, they can tolerate high temperatures and do not need electrodes for oxygen separation [83, 84]. These ion transport membranes (ITM) work on electronic conductivity principle that creates a short circuit that involves oxygen partial pressure gradient from high to low. Oxygen permeates from high partial pressure to low partial pressure side while the flux of electrons balances overall charge neutrality. Air

Products and Chemicals and Praxair have developed ionic transport based ceramic membranes driven by high process temperature. In an ideal environment, compressed air at 7–20 Bar is heated in-situ to the gasifier where heat is applied from the gasifier to enable electronic conductivity and oxygen transport from high partial pressure atmosphere to low-pressure atmosphere. Oxygen production in this way will only require compressed air at moderate to low pressures, and the remaining energy is supplied from gasifier process heat generated by exothermic reactions.

5. Conclusions

With increasing shift towards sustainable energy production, waste gasification is certainly providing multiple solutions such as sustainable waste management and clean energy production. In Europe, district heating schemes are now regularly powered by combined heating and power (CHP) plants. Therefore, gasification to steam cycle experienced a shift towards ultra-clean syngas injection into CHP plant with heat recovery for district heating and cooling (DHC) systems. Moreover, there is a significant interest in high-temperature fuel cell applications of syngas with heat recovery after the emergence of solid oxide fuel cells (SOFC). As the carbon capture and storage is becoming high on the strategic agenda, the use of oxygen during gasification is becoming the norm. Therefore, emerging research into ceramic ionic transport membranes (ITM) to produce high purity oxygen for gasification at elevated temperature is leading the way into the new market.

Author details

Muhammad Saghir[1], Mohammad Rehan[2] and Abdul-Sattar Nizami[2]*

*Address all correspondence to: nizami_pk@yahoo.com

1 European Bioenergy Research Institute (EBRI), Aston University, Birmingham, UK

2 Centre of Excellence in Environmental Studies (CEES), King Abdulaziz University, Jeddah, Saudi Arabia

References

[1] Rehan M et al. Waste to biodiesel: A preliminary assessment for Saudi Arabia. Bioresource Technology. 2018;**250**:17-25

[2] Hoornweg D, Bhada-Tata P. What a Waste: A Global Review of Solid Waste Management. Urban Development Series Knowledge Papers. World Bank. Report no. 15. March 2012

[3] ISWA: International Solid Waste Association. Austria: ISWA Report 2015; 2015. p. 37

[4] Jambeck JR et al. Plastic waste inputs from land into the ocean. Science. 2015;**347**(6223): 768-771

[5] Nizami AS et al. Developing waste biorefinery in Makkah: A way forward to convert urban waste into renewable energy. Applied Energy. 2017;**186**(2):189-196

[6] Miandad M et al. Effect of plastic waste types on pyrolysis liquid oil. International Biodeterioration & Biodegradation. 2017;**119**:239-252

[7] Shahzad K et al. Biodiesel production potential from fat fraction of municipal waste in Makkah. PLoS One. 2017;**12**(2):e0171297

[8] Rehan M et al. Effect of zeolite catalysts on pyrolysis liquid oil. International Biodeterioration & Biodegradation. 2017;**119**:162-175

[9] Nizami AS et al. The potential of Saudi Arabian natural zeolites in energy recovery technologies. Energy. 2016;**108**:162-171

[10] Ouda OKM et al. Waste to energy potential: A case study of Saudi Arabia. Renewable and Sustainable Energy Reviews. 2016;**61**:328-340

[11] Khan MD et al. Effect of co-substrates on biogas production and anaerobic decomposition of pentachlorophenol. Bioresource Technology. 2017;**238**:492-501

[12] Waqas M et al. Resource recovery of food waste through continuous thermophilic in-vessel composting. Environmental Science and Pollution Research. 2017. DOI: 10.1007/s11356-017-9358-x

[13] Sadef Y et al. Waste-to-energy and recycling value for developing integrated solid waste management plan in Lahore. Energy Sources, Part B: Economics, Planning, and Policy. 2015;**11**(7):571-581

[14] Eghtedaei R et al. Co-gasification of biomass and municipal solid waste for hydrogen-rich gas production. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2017;**39**:1-6

[15] Materazzi M, Lettieri P, Taylor R, Chapman C. Performance analysis of RDF gasification in a two stage fluidized bed–plasma process. Waste Management. 2016;**1**:256-266

[16] Miandad R et al. Influence of temperature and reaction time on the conversion of polystyrene waste to pyrolysis liquid oil. Waste Management. 2016;**58**:250-259

[17] Miandad R et al. Catalytic pyrolysis of plastic waste: A review. Process Safety and Environmental Protection. 2016;**102**:822-838

[18] Malakahmad A et al. Assessment of carbon footprint emissions and environmental concerns of solid waste treatment and disposal techniques; case study of Malaysia. Waste Management. 2017

[19] Morin NA et al. The presence and partitioning behavior of flame retardants in waste, leachate, and air particles from Norwegian waste-handling facilities. Journal of Environmental Sciences. 2017

[20] Akele ES, Tarekegn MM. Assessment of dioxin and furan emission levels and management practices in Addis Ababa, Ethiopia. Journal of Health and Pollution. 2017;**7**(15):85-94

[21] Gatti MG et al. Human biomonitoring of polycyclic aromatic hydrocarbonsand metals in the general population residing near the municipal solid waste incinerator of Modena, Italy. Chemosphere. 2017;**186**:546-557

[22] Miandad M et al. Plastic waste to liquid oil through catalytic pyrolysis using natural and synthetic zeolite catalysts. Waste Management. 2017;**69**:66-78

[23] Nizami AS et al. Waste biorefineries: Enabling circular economies in developing countries. Bioresource Technology. 2017;**241**:1101-1117

[24] Prins MJ, Ptasinski KJ, Janssen FJ. From coal to biomass gasification: Comparison of thermodynamic efficiency. Energy. 2007;**32**(7):1248-1259

[25] Rauch R et al. Biokerosene production from bio-chemical and thermo-chemical biomass conversion and subsequent Fischer-Tropsch synthesis. In: Biokerosene. Springer; 2018. pp. 497-542

[26] Erakhrumen AA. Biomass gasification: Documented information for adoption/adaptation and further improvements toward sustainable utilisation of renewable natural resources. ISRN Renewable Energy. 2012;**2012**:8. Article ID 536417

[27] Wongsiriamnuay T, Kannang N, Tippayawong N. Effect of operating conditions on catalytic gasification of bamboo in a fluidized bed. International Journal of Chemical Engineering. 2013;**2013**:9. Article ID 297941

[28] Gómez-Barea A, Leckner B. Modeling of biomass gasification in fluidized bed. Progress in Energy and Combustion Science. 2010;**36**(4):444-509

[29] Ciferno JP, Marano JJ. Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production. US Department of Energy. National Energy Technology Laboratory; 2002

[30] Rapagna S, Latif A. Steam gasification of almond shells in a fluidised bed reactor: The influence of temperature and particle size on product yield and distribution. Biomass and Bioenergy. 1997;**12**(4):281-288

[31] Mohammed M et al. Air gasification of empty fruit bunch for hydrogen-rich gas production in a fluidized-bed reactor. Energy Conversion and Management. 2011;**52**(2):1555-1561

[32] Mahishi MR, Goswami D. An experimental study of hydrogen production by gasification of biomass in the presence of a CO_2 sorbent. International Journal of Hydrogen Energy. 2007;**32**(14):2803-2808

[33] Hanaoka T et al. Hydrogen production from woody biomass by steam gasification using a CO_2 sorbent. Biomass and Bioenergy. 2005;**28**(1):63-68

[34] Ahmad AA et al. Assessing the gasification performance of biomass: A review on biomass gasification process conditions, optimization and economic evaluation. Renewable and Sustainable Energy Reviews. 2016;**53**:1333-1347

[35] Doherty W, Reynolds A, Kennedy D. The effect of air preheating in a biomass CFB gasifier using ASPEN Plus simulation. Biomass and Bioenergy. 2009;**33**(9):1158-1167

[36] Demirbas A. Biomass gasification for power generation in Turkey. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2006;**28**(5):433-445

[37] Bridgwater AV. Renewable fuels and chemicals by thermal processing of biomass. Chemical Engineering Journal. 2003;**91**(2):87-102

[38] Maschio G, Lucchesi A, Stoppato G. Production of syngas from biomass. Bioresource Technology. 1994;**48**(2):119-126

[39] André RN et al. Fluidised bed co-gasification of coal and olive oil industry wastes. Fuel. 2005;**84**(12):1635-1644

[40] Gañan J et al. Energy production by means of gasification process of residuals sourced in Extremadura (Spain). Renewable Energy. 2005;**30**(11):1759-1769

[41] McKendry P. Energy production from biomass (part 3): Gasification technologies. Bioresource Technology. 2002;**83**(1):55-63

[42] Couto N et al. Influence of the biomass gasification processes on the final composition of syngas. Energy Procedia. 2013;**36**:596-606

[43] Bridgwater AV, Evans G, Teknik D. An Assessment of Thermochemical Conversion Systems for Processing Biomass and Refuse. Harwell: Energy Technology Support Unit; 1993

[44] Rampling T, Gill P. Fundamental Research on the Thermal Treatment of Wastes and Biomass: Thermal Treatment Characteristics of Biomass. Vol. 208. Harwell Laboratory, Energy Technology Support Unit; 1993

[45] Hossain A, Davies P. Pyrolysis liquids and gases as alternative fuels in internal combustion engines – A review. Renewable and Sustainable Energy Reviews. 2013;**21**:165-189

[46] Zhang Q et al. Review of biomass pyrolysis oil properties and upgrading research. Energy Conversion and Management. 2007;**48**(1):87-92

[47] Veses A et al. Production of upgraded bio-oils by biomass catalytic pyrolysis in an auger reactor using low cost materials. Fuel. 2015;**141**:17-22

[48] Bridgwater A. Principles and practice of biomass fast pyrolysis processes for liquids. Journal of Analytical and Applied Pyrolysis. 1999;**51**(1):3-22

[49] Bridgwater AV. Review of fast pyrolysis of biomass and product upgrading. Biomass and Bioenergy. 2012;**38**:68-94

[50] Lam SS et al. Progress in waste oil to sustainable energy, with emphasis on pyrolysis techniques. Renewable and Sustainable Energy Reviews. 2016;**53**:741-753

[51] Center, B.E. Biomassenergycentre.org.uk. Retrieved on, 2012. pp. 02-28

[52] Unknown. Residual Waste Infrastructure Review; 2017. p. 22

[53] Climate Change Act 2008. Chapter 27 of 2008. United Kingdom. 2016. Available from: http://www.legislation.gov.uk/ukpga/2008/27/pdfs/ukpga_20080027_en.pdf

[54] Milne TA, Abatzoglou N, Evans RJ. Biomass Gasifier "Tars": Their Nature, Formation, and Conversion. Vol. 570. Golden, CO: National Renewable Energy Laboratory; 1998

[55] Maniatis K, Beenackers A. Tar protocols. IEA bioenergy gasification task. Biomass and Bioenergy. 2000;**18**(1):1-4

[56] Suzuki T, Ohme H, Watanabe Y. Alkali metal catalyzed carbon dioxide gasification of carbon. Energy & Fuels. 1992;**6**(4):343-351

[57] Devi L, Ptasinski KJ, Janssen FJ. Pretreated olivine as tar removal catalyst for biomass gasifiers: Investigation using naphthalene as model biomass tar. Fuel Processing Technology. 2005;**86**(6):707-730

[58] Brage C, Yu Q, Sjöström K. Characteristics of evolution of tar from wood pyrolysis in a fixed-bed reactor. Fuel. 1996;**75**(2):213-219

[59] Al-Rahbi AS, Onwudili JA, Williams PT. Thermal decomposition and gasification of biomass pyrolysis gases using a hot bed of waste derived pyrolysis char. Bioresource Technology. 2016;**204**:71-79

[60] Lu Q, Li W-Z, Zhu X-F. Overview of fuel properties of biomass fast pyrolysis oils. Energy Conversion and Management. 2009;**50**(5):1376-1383

[61] Gassner M, Maréchal F. Thermodynamic comparison of the FICFB and Viking gasification concepts. Energy. 2009;**34**(10):1744-1753

[62] Henriksen U et al. The design, construction and operation of a 75kW two-stage gasifier. Energy. 2006;**31**(10):1542-1553

[63] Neumann J et al. Production and characterization of a new quality pyrolysis oil, char and syngas from digestate – Introducing the thermo-catalytic reforming process. Journal of Analytical and Applied Pyrolysis. 2015;**113**:137-142

[64] Brandt P, Larsen E, Henriksen U. High tar reduction in a two-stage gasifier. Energy & Fuels. 2000;**14**(4):816-819

[65] Wu C, Williams PT. Hydrogen production by steam gasification of polypropylene with various nickel catalysts. Applied Catalysis B: Environmental. 2009;**87**(3):152-161

[66] Milhé M et al. Autothermal and allothermal pyrolysis in a continuous fixed bed reactor. Journal of Analytical and Applied Pyrolysis. 2013;**103**:102-111

[67] Tumiatti V. A flexible three-stage thermochemical conversion process; 2015

[68] Malkow T. Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal. Waste Management. 2004;**24**(1):53-79

[69] Dahlman. Gasification. 2017 [29/09/2017]

[70] Kraft S, Kirnbauer F, Hofbauer H. CPFD simulations of an industrial-sized dual fluidized bed steam gasification system of biomass with 8MW fuel input. Applied Energy. 2017; **190**:408-420

[71] Energos. [29/09/2017]. Available from: http://www.energos.com/energos-technology/the-process/

[72] Energia, L. Kymijarvi II Power Plant. [cited 2017]. Available from: https://www.lahtigasification.com/

[73] Evans G. Targeting New and Cleaner Uses of Wastes and Biomass Using Gasification. Loughborough: Energy Technologies Institute; 2017

[74] Fabry F et al. Waste gasification by thermal plasma: A review. Waste and Biomass Valorization. 2013;**4**(3):421-439

[75] Yoon SJ et al. Hydrogen and syngas production from glycerol through microwave plasma gasification. International Journal of Hydrogen Energy. 2013;**38**(34):14559-14567

[76] Power, A.P. Our Technology; 2017 [29/09/2017]

[77] Rokni M. Thermodynamic analyses of municipal solid waste gasification plant integrated with solid oxide fuel cell and Stirling hybrid system. International Journal of Hydrogen Energy. 2015;**40**(24):7855-7869

[78] Nagel FP, Schildhauer TJ, Biollaz SM. Biomass-integrated gasification fuel cell systems–part 1: Definition of systems and technical analysis. International Journal of Hydrogen Energy. 2009;**34**(16):6809-6825

[79] Lobachyov KV, Richter HJ. An advanced integrated biomass gasification and molten fuel cell power system. Energy Conversion and Management. 1998;**39**(16):1931-1943

[80] Panopoulos K et al. High temperature solid oxide fuel cell integrated with novel allothermal biomass gasification: Part I: Modelling and feasibility study. Journal of Power Sources. 2006;**159**(1):570-585

[81] Badwal SP, Ciacchi FT. Ceramic membrane technologies for oxygen separation. Advanced Materials. 2001;**13**(12–13):993-996

[82] Liu S, Gavalas GR. Oxygen selective ceramic hollow fiber membranes. Journal of Membrane Science. 2005;**246**(1):103-108

[83] Hashim S, Mohamed A, Bhatia S. Oxygen separation from air using ceramic-based membrane technology for sustainable fuel production and power generation. Renewable and Sustainable Energy Reviews. 2011;**15**(2):1284-1293

[84] Breeze P. Power Generation Technologies. Newnes; 2014

IntechOpen

IntechOpen