Renewable and Sustainable Energy Reviews 81 (2018) 380–398

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Co-gasification and recent developments on waste-to-energy conversion: A review

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A R T I C L E I N F O

Keywords:
Biomass
MSW
Co-gasification
Synergy
Thermal conversion

A B S T R A C T

Biomass is currently seen as a promising renewable energy source, which can be sustainably utilized in the production of fuels and electric energy adding no carbon dioxide to the environment. Co-gasification has unveiled its potential amongst thermal techniques, as a result of the valuable products obtained, strengthening a solid position in the conversion of residues. Thus, the prevention of a complete depletion of non-renewable sources is supported and the effects of their utilization alleviated.

Extensive literature review was conducted and, few reports on co-gasification of biomass and wastes were found. In this context, this review addresses their thermal conversion, highlighting issues related to the equipment, operating conditions and physicochemical phenomena involved in such a complex process. Among other conclusions, the most important finding of this work was the synergy often encountered between the two feedstocks, proving co-gasification can overcome several of the individual gasification issues enhancing products quality and yields over biomass or wastes alone, and attesting its environmental-friendly character, with lower greenhouse gas emissions. It was also possible to depict some trends on the effect of biomass and waste blending ratios, as well as elucidating some of the mechanisms involved in their interaction. These are majorly explained by the response of molecules during pyrolysis and by hydrogen transfer from waste polymers to biomass derivatives. Experimental conditions were also assessed, fluidized beds being reported as the most suitable reactors for biomass and wastes, under several different possible combinations of operational parameters. A critical discussion is presented, aiming to contribute to a more profound understanding of this matter, its key points and noteworthy potential.

1. Introduction

The society as we know it nowadays depends almost exclusively on a primordial foundation, taken for granted by many: energy. On one hand, this simple word may be seen as synonym of industrialization, technology, welfare and wealth, as it provides most of the nation's needs in terms of economy, development and citizen's wellbeing. On the other hand, the means used so far to produce this commodity and some of its appliances are not the most sustainable and by that reason, it can also be seen as synonym of pollution, toxicity and wastes. The energy production from non-renewable sources such as fossil fuels (coal, oil, natural gas) is running out these natural resources besides causing other environmental and public health problems related to harmful gaseous emissions like heavy metals, sulfur and nitrogen compounds. Thereby, alternative cleaner solutions are urgent and obtaining a fuel in gaseous or liquid forms would be desirable, so that it could be suitable for direct use.

Biomass consists in any organic matter derived from plants, and it comprises forestry and agricultural residues, organic waste, energy crops, sewage sludge and woody plants, constituting a promising renewable energy source that can be utilized in the production of fuels and electric energy [1–3]. Once it results from the reaction between carbon dioxide in the air, water and sunlight through photosynthesis, if processed efficiently biomass will recycle the original compounds, leaving carbon dioxide available again to produce new plants [4], therefore contributing to the reduction of greenhouse gas emissions [5–8]. This way, biomass can be seen as a carbon-neutral fuel, reducing carbon dioxide emissions and landfill methane emissions as well, since

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http://dx.doi.org/10.1016/j.rser.2017.07.025
Received 6 June 2016; Received in revised form 6 March 2017; Accepted 6 July 2017
1364-0321/

landfilling and dumping will be gradually replaced [9]. Information on the global distribution of biomass energy use in 2008 by the Organisation for Economic Co-operation and Development (OECD), pointed out 62 countries in the world producing electricity from biomass, being USA the leading producer with 26% share, followed by Germany with 15% and by Brazil in *ex aequo* with Japan, both with 7% production [7]. One of the major issues regarding biomass utilization is its unpredictable availability throughout the year and the diverse regions due to seasonal, geographical and climate restrictions [10–13], which dictate its price and source of income [14]. Scarce gasification reports on biomass species substituting others (pine, eucalyptus and oak wood waste) with no significant influence on the gas composition have been published [15], as commonly this is not the rule as biomass characteristics have different impacts on the final product. Also, in some countries and rural communities, biomass is currently the major source of energy for daily needs as cooking, lightening and some manufactures, as there are few other forms of available energy [12,16]. A possible solution to the biomass availability problem is based on the utilization of energy crops, specifically grown and harvested for energy production. The feasibility of this alternative is greatly dependent on the cost of the whole process from planting to conversion, which so far is challenging when compared to the use of naturally occurring biomass, in most of the cases [13]. Besides the aforementioned concerns, drawbacks like high moisture content, low calorific value, type limitations, heterogeneity, alkali and ash content found in raw biomass [11,13,17–21] as well as the production of poor quality syngas due to low hydrogen and high oxygen contents [22] limit its application because the conversion efficiency is low [11].

The population exponential growth on the last decades and the improvement of their living conditions and daily needs are causing considerable problems regarding emergent waste production, treatment and processing. Municipal solid wastes (MSW) are constituted by a heterogeneous variety of organic and inorganic components generated from various sources due to human activities and although in Europe it corresponds only to about 10% of the total waste generated [23], huge ecological distress is posed regarding its handling. The process of recovering energy (electricity or heat) from waste is called Waste-to-Energy (WtE) and can be seen as a hopeful option to overcome the aforementioned issues [9,24,25]. Regardless of all the attention given to new environmental practices that account for prevention and sustainability measures, MSW production in the European Union has increased from 150 million tons in 1980 to more than 250 million tons in 2005 [25]. By 2008, about 130 million tons of MSW were combusted annually in WtE facilities, producing electricity and steam [26]. The European Environment Agency states that succumbing MSW to WtE treatments will lead to a reduction of 24–41% of the CO_2 emissions by 2020, in Europe. The European Landfill Directive 1999/31/EC enforces EU-member states to reduce the amount of biodegradable waste landfill by 65% (in comparison to 1995 values). Countries like The Netherlands, Sweden, Austria, Denmark and Belgium have already met this target by 2010, through the combination of material recycling, biological treatments and WtE technology [17]. Portugal is still behind the landfill disposal objectives and will need to put much effort to reach the Waste Framework Directive 2008/98/EC recycling target [27,28].

Approximately 80% of world's total primary energy supply comes from fossil fuels with inevitable high values of CO_2 emissions (almost 75% of the total greenhouse gas emissions), renewable sources sharing a very small stake in energy production, although its environmental impact is incomparably lower as depicted in Fig. 1.

Although biomass and wastes minor usage in energy production, they have been gradually stating their power generating capacity, which has been constantly raising in the last decades as shown in Fig. 2. Furthermore, the International Energy Agency designates that electricity generation from these resources in EU has been growing at an average rate of 2.5%/year in the last decade.

From the exposed, biomass and wastes can be thought as advantageous fuels towards their energy generating capacity allied to the almost negligible ecological footprint, which makes their combination an environmental portent.

As a matter of fact, co-gasification of biomass and wastes has been drawing attention of several authors confirming its interest, once a synthetic gas (syngas, also called producer gas) with interesting features like potential as supplementary or successor of fossil-based ones [31,32] is produced. Moreover, co-gasification of mixtures of biomass and plastic wastes, for instance, has been suggested as a useful strategy to prevent problems normally occurring during the gasification of plastics alone such as feeding difficulties and the formation of contaminants [33,34]. The aforementioned disadvantages of either biomass or wastes can be attenuated, and the weaknesses of the gasification of each type of residue alone overcome [35–37]. Likewise, this kind of mixed-fuels can help to solve problems related to the unsteady accessibility of biomass and its unfixed composition, enhancing its utilization and rationalization.

Ahmed et al. [36] investigated the evolution on syngas characteristics produced from feedstock samples composed of different ratios of polyethylene and woodchips, varied from 0% to 100% on 20% intervals of each component. The experiment was conducted at 900ºC under steam gasification and at atmospheric pressure, in a semi-batch reactor. They observed that increasing polyethylene ratio in the mixtures would enhance hydrogen, ethylene and hydrocarbon yields leading to a superior quality syngas. In terms of gaseous content, thermal efficiency, power and energy features the obtained syngas properties were higher than the sum of individual contributions of each of the fuel components, which suggested a strengthening effect from the combined feedstock. Peng et al. [38] studied the co-gasification of forestry waste and wet sewage sludge on a lab-scale fixed bed gasifier experiment in a range of temperatures between 700 °C and 900 °C for several blends of both residues. They were able to find different behaviors once before 370 °C the degradation was similar to that of forestry wastes and after that point a contribution of both components could be seen. Also, two phases could be seen for the blending ratios: for sludge contents between 0% and 50% higher H_2 and CO concentrations were afforded due to the steam in situ generated from the moisture content, while CO_2 content decreased; for sludge contents between 50% and 100% opposite trends were revealed due to the accentuated decrease in organic matter and carbon content feeding. This suggested that the decomposition of the blends would be improved when adding biomass. In what concerns the temperature effect, higher temperatures led to higher dry gas yields, H_2 yield and carbon conversion efficiency being the optimal results achieved at 900 °C for the 30:70 (wet sewage sludge: forestry wastes) blend. Moghadam et al. [39] found the same tendency regarding the influence of temperature in the co-gasification of palm kernel shell and polyethylene in catalytic steam gasification experiments: syngas production was enhanced by higher temperatures, favoring H_2 yield and reducing hydrocarbons and CO_2 contents. They also observed improved syngas production and conversion rates for increased polyethylene fraction in mixtures with palm kernel shell. The optimal syngas produced within the tested conditions was attained at 800 °C for the 30:70 (polyethylene: biomass) blend, under a 1:1 steam/feedstock ratio (kg/kg).

Recently, Đurišić-Mladenović et al. [40] compared co-gasification and co-pyrolysis of olive kernel and crude glycerol through principal component analysis (PCA) of the obtained syngases, aiming to characterize them under different sets of experimental conditions. Parameters such as temperature, air ratio and feedstock composition were explored in order to determine how each of them impacted on the final composition and quality of the producer gas. Some specific conclusions for the used datasets have shown that increasing temperature in co-gasification (within the tested range) directly affected the increase of CO and syngas yields, whereas increasing glycerol fraction in the blends promoted higher H_2 concentrations and higher quantities