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Hydrogen from intermittent renewable energy sources as gasification medium in integrated waste gasification combined cycle power plants: A performance comparison

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ABSTRACT

In this paper the integration of the energy production from programmable (biomass, waste) and not programmable (solar, wind) renewable sources is examined as an opportunity for increasing the share of electricity from renewable power plants, in order to overcome the major obstacles to their extensive penetration into the grid. The integration is performed by using hydrogen from intermittent renewable energy powered-electrolysis as gasification medium in conventional or advanced gasification systems for the waste treatment. The proposed integrated energy system consists of three main sections: i) the hydrogen production island; ii) the gasification island; iii) the power island. The assessment of the system performance has been conducted by considering two gasification technologies: hydro-gasification and hydro-plasma gasification. The performances comparison has been carried out in terms of syngas composition, energy consumptions and electric efficiency. Results have pointed out that the electric efficiencies of the integrated energy systems are in the range of 40% and 43%.

Furthermore, it is found that by combining the storage of intermittent renewable energy sources with a waste gasification combined cycle power plant it is possible to achieve better performance with respect to the performance that can be obtained by storage and waste to energy systems operating separately.

1. Introduction

The major obstacles for increasing the share of renewable electricity and its penetration into the grid are linked to the intermittency of solar and wind sources, or to the low conversion efficiency of renewable fuels based power plants (biomass, waste).

Thus, different strategies can be proposed according to the type of the renewable sources. This means that a wide utilization of not programmable renewable energy sources for power generation requires the development and the integration with energy storage systems, while the promotion of programmable renewable sources such as the biomass needs efficient energy conversion systems and sophisticated emissions control technologies [1,2].

The main energy storage technologies include electrochemical batteries, supercapacitors, thermal-storage materials, flywheels, pumped hydro, superconducting magnetic energy storage, chemical storage (hydrogen and synthetic natural gas) and compressed air energy storage. Each system is characterized by different storage capacity, storage efficiency and discharge time and thus, the choice of the best technology depends on its application [3,4]. For example, batteries have high storage efficiencies but they have a limited life cycle and problems with depth of discharge; on the contrary, the chemical storage performed by hydrogen-based systems (i.e. water electrolysis), even if it is characterized by a lower efficiency, has a high storage energy density per mass, without problems concerning the durability or the life cycle [5,6].

The use of biomass is a promising solution for increasing the share of electricity production from renewable sources thanks to the wide availability of agricultural residues, forest slash, municipal solid wastes and other organic residues.

The key for accessing to the energy content of the biomass depends on its conversion into a usable form, through two main routes: a) thermo-chemical (combustion and gasification); b) biochemical (via anaerobic digestion and fermentation).

Gasification has several potential benefits over traditional combustion of biomass or solid wastes (incineration), mainly

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related to the possibility of combining the operating conditions to obtain a syngas suited for use in different applications. Thus, whereas incineration converts the input waste into energy onsite, gasification is a very promising option for implementation of clean poly-generation (electricity, heat, hydrogen and chemicals) technologies [6–9]. However, the syngas from the biomass gasification process has to be cleaned and, once used as fuel in conventional energy systems, the electric power is generated with low efficiencies because of its low quality [7–12].

The study proposed in this paper aims to assess a novel strategy to enhance the reliability, dispatchability and efficiency of renewable energy systems through the integration between programmable (biomass, waste) and not programmable (solar, wind) renewable sources [13].

The integration is realized by using hydrogen from intermittent renewable energy powered-electrolysis as gasification medium in conventional or advanced gasification systems fed by biomass or waste.

Thus, the proposed integrated energy system consists of three main sections: i) the hydrogen production island; ii) the gasification island; iii) the power island. The assessment of the system performance has been conducted by considering two different gasification technologies: the hydro-gasification and the hydro-plasma gasification. In the first case the gasification process works at high pressure (30 bar) in an enriched hydrogen environment, while in the second one the hydrogen is used as plasma gas in a reactor that operates at atmospheric pressure. Thus, in both cases, the gasification under hydrogen atmosphere is the process proposed for biomass conversion into suitable fuel.

The overall systems performances (syngas composition, gasification efficiency, electric efficiency, etc.) have been calculated by numerical simulations based on thermochemical and thermodynamic models able to evaluate the properties of the reactants streams, the thermal recovery and the energy and mass fluxes of each plant section.

2. Gasification process under hydrogen atmosphere

Gasification under hydrogen atmosphere involves lower gasification severity conditions (i.e. the temperature is lower) and greater methane yield with respect to the conventional steam/oxygen gasification processes [14]. Other advantages include: a) the elimination of slagging problems in the gasifier since the oxygen injection (for heat input) is not required (the main reactions are exothermic); b) the absence of tars and oils which allows the recovery of high-level heat from the syngas [14,15].

The hydrogasification process proceeds in two stages: the first very rapid stage of pyrolysis under hydrogen environment (hydropyrolysis) and the second relatively slow stage of gasification (hydrogasification) [16,17].

The devolatilization reactions take place from 350 °C to 500 °C (or greater) when the solid fuel is decomposed into gas, char and tar. Furthermore, under hydrogen atmosphere and at elevated pressures, in addition to thermal pyrolysis reactions, coals or coal chars containing volatile matter also exhibit a high reactivity to the formation of methane [18].

The gasification process includes the reactions of char (heterogeneous reactions), tar and light gas (homogeneous reactions). Cracking and reforming of volatile matter and tar occur in the range of 600 °C and 650 °C, while char gasification becomes active from 600 °C.

In the hydrogasification stage, the predominant reaction is the heterogeneous, exothermic methanation–hydrogasification (R1), while the heterogeneous, endothermic water–gas reaction (R2) and the homogeneous CO-shift exothermic reaction (R3) are proceeding to a lesser extent.

$$C + 2H_2 \rightarrow CH_4 \quad \Delta H = -88\ \mathrm{kJ\ mol^{-1}} \qquad [R1]$$

$$C + H_2O \rightarrow CO + H_2 \quad \Delta H = 131\ \mathrm{kJ\ mol^{-1}} \qquad [R2]$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \Delta H = -41\ \mathrm{kJ\ mol^{-1}} \qquad [R3]$$

The domination of the R1 reaction can avoid the need for any heat addition (the hydrogasification process can be considered as thermally self-sustained) [19].

In the hydro-plasma gasification process, hydrogen is used as plasma gas in a plasma reactor that operates at atmospheric pressure. In this case the gasification process takes place at very high temperature that allows to decompose completely the input waste material into very simple molecules. In particular, the organic compounds are converted into a synthesis gas, while the inorganic materials are melted and converted into a dense, inert, non-leachable vitrified slag. The temperature in the core of the plasma plume can be greater than 3×10^4 °C, whereas in the marginal zones, it decreases rapidly and the average operating temperature can be as high as 5000 °C. Due to the high temperatures involved, all the tars, char and dioxins are broken down, thus the syngas generated by the plasma gasification is cleaner than that produced by conventional gasification processes. Thermal plasma gasification uses an external heat source to gasify the waste by means of one or more plasma arc torches which produce a very high temperature plasma gas [20–26].

3. Integrated gasification power plants

The power plant consists of three main sections: i) the hydrogen production island; ii) the gasification island; iii) the power island. Moreover, two different gasification technologies under hydrogen atmosphere have been studied: the hydro-gasification and the hydro-plasma gasification. In the first case the integrated power plant has been called IHGCC (Integrated Hydro Gasification Combined Cycle) whereas in the second one it has been called IHPGCC (Integrated Hydro Plasma Gasification Combined Cycle). Fig. 1 shows the plant layout for both configurations.

The hydrogen production island is characterized by the electrolysis unit and by the hydrogen and oxygen storage systems that permit to decouple the hydrogen production from its utilization. The electric energy for electrolysis is provided by a power plant using intermittent renewable source.

In the IHGCC plant, the hydro-gasification island is formed by i) the CO_2-Slurry system where the waste is pressurized by using a CO_2 stream [27,28], ii) the hydro-gasification reactor operating at high pressure (30 bar) where the waste is gasified in an enriched hydrogen environment, iii) the syngas cooler in which steam is generated by the heat recovery of syngas cooling, iv) the Clean-Up unit for the syngas purification before its utilization in the combustor of the gas turbine.

In the IHPGCC plant, the hydro plasma-gasification island is formed by i) the hydro-plasma gasification reactor operating at atmospheric pressure, in which hydrogen is used as plasma gas, ii) the syngas cooler for heat recovery, iii) the Clean-Up unit for the syngas purification, iv) the syngas compression system.

The power island consists of a CCGT (combined cycle gas turbine) power plant that is a double pressure combined cycle based on a commercial gas turbine.