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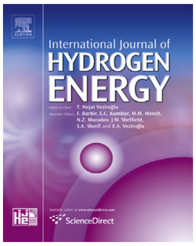

Power to gas-oxyfuel boiler hybrid systems

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ABSTRACT

One of the main future energy challenges is the management of electrical supply and demand, mainly motivated by the increase of share renewable energy in electricity mix. Thus, energy storage represents a crucial line of research and innovative solutions are currently being proposed. Power to Gas is a technology which stores excess of electrical energy in form of synthetic natural gas through the methanation of hydrogen produced by electrolysis. Methanation requires a source of CO_2 which could be provided from the flue gas of an oxyfuel boiler. A further advantage of this hybridization comes from the supply of the oxygen generated by electrolysis to the oxyfuel combustion. In this study the concept is simulated using Aspen Plus® software and the performance of the combined system is analysed through the definition of a size ratio, ξ_{oxy}, that relates the flow of renewable hydrogen produced in electrolyser and the thermal output of the boiler. This variable has allowed defining different ranges of operation for a PtG-oxycombustion hybridized plant. Thus, for ξ_{oxy} of 1.33, the air separation unit required as an auxiliary element for the oxyfuel boiler becomes unnecessary while if this ratio is increased up to 2.29, flue gas is completely consumed in the methanation plant and converted to synthetic natural gas.

Introduction

The constant increase of the renewable energy share in energy markets brings about the appearance of mismatches between supply and electrical demand which affect to security and stability of the grid [1]. The accommodation of energy production with consumption has become a critical challenge for future society that is being tackled by developing innovative energy storage solutions [2].

The low energy density and limited storage potential of pumped hydroelectric storage, compressed air energy storage, flywheels and batteries, make Power to Gas technology one promising option to overcome these limitations [3]. PtG converts electricity in synthetic natural gas that may substitute fossil fuels or be injected into the natural gas network which would be used as storage infrastructure [4]. In this way, electric and gas networks would be connected as a unique energy system increasing the flexibility of the energy supply [5].

In a generic PtG system, the conversion of electricity is strictly carried out by an electrolyser which produces hydrogen. The consumption of this gas through Sabatier chemical reaction (Eq. (1)) produces methane and the synthetic natural gas is obtained. The global process is carried out

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Abbreviations: ASU, air separation unit; FG, flue gas; LHV, lower heating value; M1, methanator 1; M2, methanator 2; M3, methanator 3; PtG, power to gas; SNG, synthetic natural gas.

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through two consecutive reactions: inverse water-gas shift reaction (Eq. (2)) and CO methanation (Eq. (3)) [6].

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad \Delta H_{298K} = -164.9\ kJ/mol \qquad (1)$$

$$CO_2 + H_2 \leftrightarrow CO + H_2O \quad \Delta H_{298K} = +41.5\ kJ/mol \qquad (2)$$

$$CO + 3H_2 \leftrightarrow CH_4 + H_2O \quad \Delta H_{298K} = -206.4\ kJ/mol \qquad (3)$$

Eq. (2) is an endothermic reaction which requires the presence of a catalyst to take place at low temperatures. It promotes conversion to methane in Eq. (3).

Additionally, when the power input to the electrolyser is supplied by renewable energy sources, the obtained SNG will be neutral in CO_2 emissions. The same amount of CO_2 that will be emitted through SNG combustion is required and consumed during its synthesis process.

Different PtG concepts such as hybridization with air separation plants, biogas plants, biomass gasification, sewage plants, fossil power plants or industrial processes have been proposed to obtain the source of carbon dioxide [5]. Two main issues in the PtG systems are the utilization of the residual oxygen produced by electrolysis and the consumption of energy to attain a concentrated stream of CO_2.

Some of the major projects in the world related to methanation (MeGa-stoRE 4.7 MW [7], Erdgas Schwaben 1.0 MW [8], and P2G-BioCat 1.0 MW [9]) upgrade biogas to obtain SNG without previous CO_2 separation, but oxygen from electrolyser do not have a final use. Biomass gasification and sewage plants would solve both issues since oxygen may be used as gasification agent or for the activation of sludge [5]. However, syngas from gasification achieves hydrogen content above 60% and further hydrogen addition is barely needed limiting energy storage potential [7]. Additionally, sewage plants produce poor syngas whose conversion to SNG is relatively expensive. Thus, it is currently preferred to burn this gas in engines for self-consumption [10].

Hence, a suitable option for taking advantage of produced oxygen would be the hybridization of PtG with oxyfuel combustion. In an oxyfuel combustion, a mixture of oxygen and recycled flue gas acts as comburent [11]. Thus, oxygen from electrolyser would reduce the electrical consumption of the required air separation unit, and CO_2 would be taken from the boiler flue gas without extra energy penalty in its separation.

The objective of the study is to determine the global efficiency that would have this hybrid system, the flows of generated SNG and stored CO_2 and other potential variations in the efficiencies of specific elements of the installation as a function of electric power consumption in electrolyser. In addition, the operating ranges for an oxyfuel combustion plant hybridized with Power to Gas technology will be determined highlighting the most convenient size ratios between oxyfuel and PtG plants.

The model and simulation of the proposed concept has been performed under steady state of operation, considering that it will work at full load most part of the year. In Spain, France and Germany, energy loss due to curtailment of wind-generated energy remained under 1% of total wind production during 2010, 2011 and 2012 [11]. Thus, operation of PtG must not be limited to operate with the surplus of electricity from renewable sources. It should be understood as a method for continuous production of SNG and a sink of CO_2 emissions although the proposed concept may also be applied for energy storage.

Hybrid system description and calculation methods

In this section, a thorough description of the hybrid PtG-Oxyfuel boiler system is presented together with the most important interactions between technologies. The input data to the Aspen Plus® simulation engine as well as the chosen calculation methods are also described. Buchholz et al. investigated the combination of a PtG plant and conventional lignite fired power plant [12]. However, no previous analyses of the combined system PtG and oxyfuel boiler with thermal purposes are found in literature. Thus, the efficiencies of the single elements and the hybrid concept are still to be defined.

Description of the hybrid concept

Fig. 1 illustrates the schematic diagram of the hybrid concept. In order to allow for continuous operation, the system is designed to be fed with a constant power input. A source of renewable energy supplies power to electrolysers which store this renewable energy as hydrogen also producing oxygen as a by-product. This amount of oxygen may partially or completely cover the comburent demand in the oxyfuel boiler, increasing the efficiency of this process since the ASU power consumption is reduced. Additionally, methanation takes place between the flue gas from the oxyfuel thermal plant (basically CO_2 and O_2) and the hydrogen from electrolysis to produce synthetic natural gas.

Besides the heat recovered from the oxyfuel boiler, a significant amount of thermal energy is released from the exothermic reaction in methanators and the intercooling stages in compression trains. This extra available heat could be integrated in external thermal processes or in the hybrid concept itself.

Hybrid system modelling with Aspen Plus®

The proposed scheme for the hybridization between oxy-combustion and PtG technologies has been modelled with Aspen Plus® under industrial conditions for steady state operation and chemical equilibrium. In the following, information on the model of each significant element in the system is presented.

Coal is selected as input material for the oxyfuel combustion process since it represents the most extended fossil fuel for thermal energy supply in industry [13]. The ultimate analysis of coal is presented in Table 1.

Oxyfuel combustion plant

Fig. 2 illustrates a scheme of the model developed in Aspen Plus® for the oxyfuel plant. Fuel and comburent are introduced into the boiler to reach chemical equilibrium by minimizing Gibbs free energy.

Flue gas passes through the heat exchangers where steam is produced reducing its temperature down to 270 °C. This