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Power to Gas–biomass oxycombustion hybrid system: Energy integration and potential applications

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HIGHLIGHTS

- A novel PtG–biomass oxyfuel boiler hybrid system is studied.
- Most suitable potential applications are district heating and industries.
- Available extra thermal energy is integrated to increase overall efficiency.
- Overall efficiency may be increased in a 29.7%.

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ABSTRACT

A promising hybridization which increases the chances of deployment of Power to Gas technology is found in the synergy with oxycombustion of biomass. This study assesses the efficiency of an energy integrated system under different sizes and potential applications. District heating and industrial processes are revealed as the most suitable potential applications for this hybrid technology. Global efficiency of the combined system may be increased through thermal energy integration. The relative increment of efficiency achieved for those designs which avoid the requirement of an air separation unit and for those which completely consumed the generated CO_2, are 24.5% and 29.7% respectively. A 2 MW_{th} district heating case study is also analysed, revealing that 81.2% of the total available heat from the PtG–oxy system could be integrated raising the global efficiency up to 78.7% at the adequate operational point. Further 'full-fuel-cycle' analysis will be required prior to decide the interest of the concept under a specific scenario in comparison to other available energy storage technologies.

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1. Introduction

In the mid-term, one of the most promising energy storage technologies might be the Power to Gas (PtG) process [1]. Strictly, renewable electricity is converted to fuel gas by means of electrolysis, storing electrical energy in form of hydrogen. Then, the generated H_2 can be combined with carbon dioxide to produce methane through the Sabatier reaction [2].

$$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O \quad \Delta H_{298K} = -165 \text{ kJ/mol} \tag{1}$$

The availability of a suitable source of CO_2 is the main limiting factor when assessing the potential of Power to Gas deployment in a region; reducing considerably the geographic location possibilities for this technology [3]. Therefore, the access to a continued carbon dioxide flow to be fed to the PtG process becomes a crucial issue that must be properly addressed.

Biogas plants, waste managers, industries and power plants are the largest CO_2 sources and the most interesting partners for integration with PtG [4]. Nevertheless, attention must be focused on the last two options since their efficiencies will be strongly penalized when the operation of carbon separation technology is accounted.

Biogas is mainly composed by methane (50–85%) and carbon dioxide (15–50%) [5], so a direct conversion of CO_2 without previous separation is possible, avoiding the energy penalty associated to carbon capture. Due to this advantage, some of the major PtG projects in the world perform directly the methanation of the biogas (MeGa-store 4.7 MW [6], Erdgas Schwaben 1.0 MW [7], and P2G-BioCat 1.0 MW [8]). Similarly, waste management plants

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Abbreviations: 4GDH, 4th Generation District Heating; ASU, air separation unit; DH, district heating; DHW, domestic hot-water; LHV, lower heating value; M, moisture; M1, methanator 1; M2, methanator 2; M3, methanator 3; PtG, Power to Gas; SNG, synthetic natural gas; Z, ash.

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Nomenclature

Variables

cp	specific heat at constant pressure (kJ/kg K)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow (kg/s)
$\dot{n}$	molar flow (kmol/s)
P	pressure (bar)
$\dot{Q}$	thermal power (kWt)
T	temperature (K)
$\dot{W}$	electric power (kWe)
y	molar fraction (–)
η	efficiency (%)
ξ_{ASU}	minimum required ratio between electrolyser power and boiler net output to avoid ASU necessity (kWe/kWt)
ξ_{CO_2}	minimum required ratio between electrolyser power and boiler net output to consume flue gas completely (kWe/kWt)
ξ_{oxy}	ratio between electrolyser power and boiler net output (kWe/kWt)
ϕ_{FGM}	percentage of flue gas directed to methanation (%)

Subscripts

ASU	air separation unit
aux	auxiliary consumption
b	boiler
CO_2	carbon dioxide
comp	CO_2 compression
e	electric
ele	electrolyser
f	fuel
FG	flue gas
H_2	hydrogen
Loss	losses in condensation phase prior M3
M	methanator
meth	methanation
O_2	oxygen
oxy	oxyfuel plant
PtG	Power to Gas
PtG + oxy	Power to Gas–oxyfuel hybrid system
SNG	synthetic natural gas
th	thermal

produce a gas mixture of CH_4 and CO_2, but it is usually burnt for self-consumption given its low quality [9].

Power plants and most industries generate CO_2 during fuel combustion for electric or thermal energy production. However, carbon dioxide concentration in flue gas is low and capture costs up to 75€/t_{CO_2} depending on CO_2 concentration [10]. Therefore, the hybridization of PtG–Oxycombustion is proposed as a method that avoids the capture penalty and allows the direct comparison between biogas upgrading and flue gas methanation.

During oxycombustion, a mixture of recycled flue gas and pure oxygen is used as comburent instead of air [11]. Thus, the large N_2 content is substituted by the combustion products (mainly CO_2 and H_2O), and flue gas can achieve a high carbon dioxide concentration once steam is condensed. Energy penalty associated to this capture process comes from the air separation unit (ASU) that produces pure oxygen from air with a 190 kW h/t_{O2} average consumption [12]. However, with an adequate size design of the PtG–Oxycombustion system, the by-produced oxygen from electrolysis can replace the requirement of the ASU.

Furthermore, biomass has been selected as fuel for oxycombustion boiler to convert the process into an entirely carbon neutral one. As the carbon dioxide used in the methanation process comes from biomass combustion, the generated synthetic natural gas (SNG) will be equally carbon neutral.

The scope of this study is to analyse the possible applications of hybrid PtG–Oxycombustion systems depending of its size and operation conditions. Methanation process and CO_2 compression produce extra thermal energy that can be useful. The maximum potential increment of the efficiency associated to complete integration of these heat streams is also calculated.

Since the target of the work is to clarify what applications are feasible depending on the most suitable operation point for every size scale, the integrated system is characterized without regarding any external loss that will penalize the profit of the concept. Prior to decide the interest of the concept under a specific scenario in comparison to other available energy storage technologies, further 'full-fuel-cycle' analysis should be performed.

2. Hybrid system description

The proposed configuration is a hybrid system which combines an oxyfuel boiler and a Power to Gas plant. A source of renewable energy supplies power to the electrolysers in the system (Fig. 1) to store a constant amount of electricity in the form of hydrogen also co-producing oxygen. The oxygen generated in the electrolysers might be used to partially or completely cover the comburent demand in an oxyfuel boiler. In this way, the efficiency of this process is increased since the power consumption of the ASU would be reduced or even avoided. Additionally, methanation takes place between the CO_2 contained in the flue gas from the oxyfuel thermal plant and the hydrogen from electrolysis to produce synthetic natural gas. If the flue gas is not completely consumed in methanation, the remaining can be directed to the compression train for transportation and storage.

In a prior study, the different operation ranges of the installation were obtained through simulation for a coal-fired oxyfuel boiler [13]. The analysis was performed by means of the definition of ξ_{oxy}, the ratio between the energy contained in hydrogen produced by electrolysis ($LHV_{H_2} \cdot \dot{m}_{H_2}$) and the net thermal power generated by the oxyfuel boiler ($\dot{Q}_b$) (Eq. (2)).

$$\xi_{oxy} = \frac{LHV_{H_2} \cdot \dot{m}_{H_2}}{\dot{Q}_b} \left[\frac{kW_{H_2}}{kW_{th}}\right] \quad (2)$$

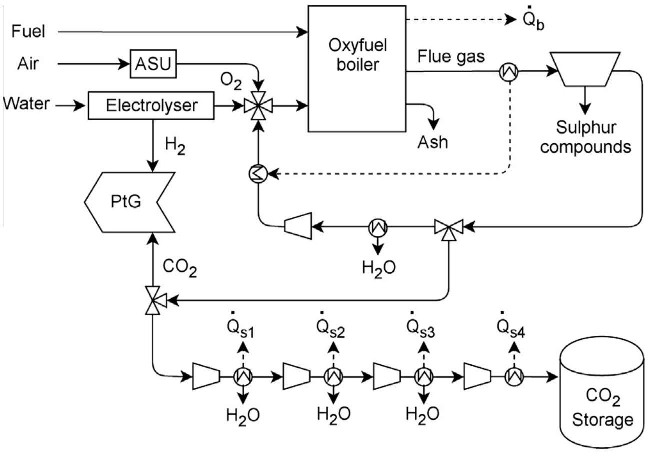

Fig. 1. Block diagram of the hybrid power system.

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