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Cogeneration of power and substitute of natural gas using biomass and electrolytic hydrogen

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ABSTRACT

Storing renewable energy sources is becoming a very important issue to allow a further reduction of greenhouse gas emissions. Most of such energy sources generate electric power which not always can be conveniently transferred to the grid and also its conversion to hydrogen presents some critical aspects connected mainly to hydrogen distribution and storage.

Electrolysis generates not only hydrogen, but also oxygen which could be used to burn biomass or waste products (oxycombustion) in power plants with the result to obtain an exhaust gas containing mainly water and CO_2. This last can be converted into a mixture of methane and hydrogen by reacting with electrolytic hydrogen, so that the power used for electrolysis is stored into a fuel which can be distributed and stored just like natural gas.

In this paper, an innovative biomass fuelled plant has been designed and simulated for different layouts with an internal combustion engine as a main power system. Utilizing hydrogen and oxygen produced through electrolysis and applying a hydrogasification process, the plant produces electricity and a substitute of natural gas. The result of such simulations is that the electricity can be stored in a useful and versatile fuel with a marginal efficiency up to 60%.

Introduction

The world energy system is slowly shifting from fossil fuels towards renewable energy sources (RES). Such a change poses some problems whose solution could accelerate the diffusion of RES. The problem of energy storage first of all, because in most cases the energy is available to be used immediately but there is not fit with the energy demand from the grid. A second issue is the quality of electric power because the irregularity of some RES could create instability to the grid. A third issue is that the current technologies convert most of RES into electric power while most of the final use are fuels for transportation via land, sea and air, for heating, cooking and for industrial processes. Among RES, only lignocellulosic biomass has been usually used directly as a solid fuel or converted into liquid or gaseous fuels [1–5].

Hydrogen has been identified as probably the best solution because it is easily obtainable from any kind of RES, either directly or indirectly through electrolysis. However,

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Symbols

m	mass flow rate
T	temperature
W	power
η	efficiency
ρ	compression ratio

Subscripts

compr	compressor
el	electrolyser
exp	expander
g	generator (electric)
marg	marginal

Acronyms

CHF	Cogeneration of heat and fuel
HHV	Higher heating value
ICE	Internal combustion engine
MET	Methanation
NG	Natural gas
POX	Partial oxidation
RES	Renewable energy sources
SI	Spark ignition
SNG	Substitute of natural gas
WGS	Water gas shift

concerning its use as vehicle fuel, though the fuel cell vehicles already feature a long range, the on board storage has not yet reached the ultimate target energy density, the distribution infrastructure does not exist and is very expensive, and the safety requirements make very difficult to convert existing refuelling stations or to build new ones inside urban areas.

Natural gas (NG) is currently the cleanest fossil fuel widely available and suitable to almost all final uses. Unfortunately, it is not renewable and generates carbon dioxide emissions. But methane can be obtained, as other biofuel, from biomasses in the form of “biomethane”, which is renewable and does not increase the carbon dioxide concentration into the atmosphere (considering only the combustion process). Unfortunately, biomasses are not capable to sustain the worldwide energy consumption.

One solution to the aforementioned problems is represented by the possibility to use hydrogen to extract oxygen from organic substances like biomasses. The process is called hydrogasification [6] and increases the amount of methane generated as shown by the following reactions:

$$\text{gasification: } C_4H_6O_2 + H_2O + ½\, O_2 \rightarrow 2\, CH_4 + 2\, CO_2 \quad (1)$$

$$\text{hydrogasification: } C_4H_6O_2 + 7\, H_2 \rightarrow 4\, CH_4 + 2\, H_2O \quad (2)$$

The second process uses an extra energy input of about 1680 MJ and generates an extra energy output of about 1600 MJ: it means that almost all the energy content of hydrogen has been transferred to methane. In other words, if hydrogen is generated from RES, replacing biomass gasification with biomass hydrogasification is a way to store RES efficiently. Obviously the reactions are not complete but hydrogasification is favoured by supplying over-stoichiometric hydrogen obtaining a gas very rich of methane and containing a residual amount of hydrogen.

Distribution of NG containing up to 20% of hydrogen through existing NG pipelines has been proved feasible and safe [7], and direct use of NG containing up to 30% of hydrogen into existing internal combustion engines has been proved capable to improve engine performance [8]. Therefore, the ideal reaction becomes:

$$C_4H_6O_2 + 8\, H_2 \rightarrow 4\, CH_4 + H_2 + 2\, H_2O \quad (3)$$

After cooling, recovering heat for direct uses or for stable power generation, the dry gas obtained is a good substitute of natural gas (SNG) and does not have the drawbacks of hydrogen although it be completely renewable. Some kinds of waste products could also be used in place of biomass.

The concept of mixing electrolytic hydrogen to NG, or using it to produce SNG, is defined Power to Gas (usually shortened as PtG or, sometimes, P2G) and has been deeply investigated in the last decade, as proved by the wide bibliography reported in some reviews [9–12].

In the present study, an alternative to the simple production of SNG is presented and consists on the cogeneration of power and SNG, aiming to generate both high grade (stable) electric power and fuel.

This alternative concept is based on almost pure carbon dioxide production from biomass, followed by methanation with electrolytic hydrogen (Sabatier process). Rönsch et al. [13] and Ghaib et al. [14] recently carried out reviews about different aspects of such a process. Models to compare different options or to optimise operating parameters has been developed and utilised [15–17], and the increasing interest is proven even for future space applications [18].

Besides the improved quality of the output energy with respect to the input energy, a specific advantage of the proposed concept is the use of electrolytic oxygen to obtain both syngas and almost pure carbon dioxide from the burned syngas. This allows to avoid the capital and operation costs of an air separation unit, usually required for oxy-combustion processes. At the same time, electrolytic oxygen is often considered a by-product without value, and therefore released into the atmosphere, whereas in this case it becomes a very useful by-product.

Fig. 1 shows the path followed: after a partial oxidation of biomass with pure electrolytic oxygen to obtain a syngas, this last is completely oxy-burned into a power unit (turbines, internal combustion engines or fuel cells) generating electric power and discharging only carbon dioxide and steam:

$$C_4H_6O_2 + O_2 \rightarrow 3\, H_2 + 4\, CO \quad (4)$$

$$3\, H_2 + 4\, CO + 7/2\, O_2 \rightarrow 4\, CO_2 + 3\, H_2O \quad (5)$$

After steam condensation and separation, carbon dioxide is fed to a Sabatier reactor together with electrolytic hydrogen to obtain methane (e.g. Ref. [20]):

$$4\, CO_2 + 16\, H_2 \rightarrow 4\, CH_4 + 8\, H_2O \quad (6)$$

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