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Feasibility study of methanol production plant from hydrogen and captured carbon dioxide

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A R T I C L E I N F O

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A B S T R A C T

This paper aims to present a feasibility study of the innovative plant for methanol synthesis from carbon dioxide-sequestered by fossil fuel power plant and hydrogen, which is produced by water electrolyzer employing the over-production on the electrical grid. The thermo-economic analysis is performed in the framework of the $MefCO_2$ H2020 EU project and it is referred to the German economic scenario, properly taking into account the real market costs and cost functions for different components of the plant. Three different plant capacities for methanol production (4000 10,000 and 50,000 ton/year) have been investigated, assuming an average cost for electrical energy to feed electrolysers and analyzing the influence of the most significant parameters (oxygen selling option, methanol selling price and electrolysers' capital cost) on the profitability of the plant.

The analysis has been performed in W-ECoMP, software for the thermo-economic analysis and plant optimization developed by the University of Genoa.

1. Introduction

Greenhouse gas (GHG) emissions are one of the most important environmental issues of the twenty first century. The largest source of GHG is the carbon dioxide and its emission has tremendously increased in the last decades, mainly due to fossil fuels combustion for the power generation and the automotive transportation.

Moreover, the global energy demand is expected to double by the 2050 and the fossil fuels exploitation will be still predominant in comparison with the renewable energy penetration that, anyway, is increasing as well [1]. In consideration of this, the European Commission is adopting more and more stringent environmental regulations that push the researchers to study innovative systems for the CO_2 emissions reduction by developing new fuels, which have low carbon footprint for the energy production.

Another important aspect is related to the increasing renewable installed capacity in the energy supply grid and its integration with traditional power plants: the strongly stochastic and intermittent nature of the renewable energy sources (RES), in particular wind and solar, makes the power output variable and unpredictable. This translates into issues like system balancing and capacity adequacy that, in turn, result in difficult operating management strategy for traditional power plants and economic losses as well. The strong development of unpredictable RES, such as solar and wind, which has the priority of dispatchment to the energy market, has caused significant issues to traditional power plants (i.e. combined cycles): forcing them to operate in strong off-design conditions at lower efficiencies and frequent startup/shutdown that reduce their lifetime as well.

The power-to-liquid systems seem to represent a valiant solution for the future energy scenarios: a PtL technology concerns a process that is able to absorb energy (i.e. the overproduction of RES on the grid), converting and storing that energy in chemical form.

The conversion of renewable energy into the more convenient form of liquid energy carriers can be an effective way to moderate the RES intermittency and stabilize the electrical grid, thus avoiding the continuous shut downs that are affecting a number of traditional power plants. Moreover, in comparison with the gas form, the liquid form presents less problems in transportation from the both safety and infrastructure point of view.

One of the most promising products for the PtL systems is methanol (formula CH_3OH): it presents liquid form at atmospheric condition; the melting and boiling point are −97.6 °C and 64.7 °C, respectively.

Methanol is one of the most important building blocks in chemical industry; it is used as feedstock to synthetize chemicals derivatives such as formaldehyde, MTBE and acetic acid, which, in turn, are used in products like adhesives, subfloors, solvents, washer fluid etc…[2].

Moreover methanol is largely used in energy-related applications (about 40% of world production). Methanol presents excellent combustion properties: despite its energy density is about half of the gasoline energy density (20.1 MJ/kg for methanol, 44.3 MJ/kg for

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Nomenclature

Abbreviations

CCS	Carbon capture sequestration
DPBP	Discounted pay back period
GHG	Greenhouse gas
NPV	Net present value
PEC	Purchased equipment cost
PEM	Polymer electrolyte membrane
PtL	Power to liquid
RES	Renewable energy sources
TCI	Total capital investment
TPG	Thermochemical power group
W-ECoMP	Web-based economic cogeneration modular program

gasoline) it has a higher octane number in comparison of gasoline (108 for methanol, 95 for gasoline), that allows higher compression ratio and an increase in combustion efficiency [3,4].

Methanol can be used directly as a vehicle fuel or blended with gasoline to produce a high-octane efficient fuel with lower emissions than conventional gasoline [4]; it is also emerging as a clean-burning marine fuel pushed by the increasingly stringent emissions regulations. Methanol is also a key component in biodiesel, a renewable fuel that can be used in place of conventional diesel fuel, or in blended form [5].

Currently, on the industrial scale, methanol is predominantly produced from natural gas by steam reforming or coal gasification: the resulting syngas is mostly composed by CO, CO_2 and H_2, in correct proportion for the methanol synthesis. The syngas-based methanol production consumed a large amount of fossil resources and inevitably it generates large amounts of carbon dioxide: for each ton of methanol produced in conventional process, about 0.6-1.5 tons of CO_2 are emitted in atmosphere [6,7,8].

As alternative to the traditional approach, an innovative sustainable method for methanol production from RES is investigated in this research paper: methanol is synthesized from a mixture of hydrogen and carbon dioxide. The hydrogen is produced by water electrolysis employing renewable electrical energy or absorbing the overproduction of the grid and CO_2 needed in the reaction can be sequestrated from the flue gas of traditional power plant [9,10]. This process represents an eco-friendly solution for the methanol production by allowing reducing the intensity of fossil fuel consumption and mitigating the CO_2 emission as well. The reaction is reported below:

$$3H_2 + CO_2 \rightarrow CH_3OH + H_2O \quad (1)$$

The catalytic reaction takes place in ranges of temperature and pressure of 250–300 °C and 50–100 bar, respectively on CuO/ZnO/Al_2O_3 as catalyzer [11,12].

This paper work has been carried out within the contest of the E.U. MefCO2 (methanol fuel from CO_2) project (accepted in SPIRE framework of the Horizon 2020 EU Research and Innovation program) [14]. The MefCO2 aims to develop and design an innovative methanol production technology with a low carbon footprint: the overall project concept is based on the sequestration of carbon dioxide emitted by traditional plant and its use in reaction with hydrogen, which is produced from surplus electrical energy. Together with the University of Genoa, important academic and industrial partners are involved in the project. The main activities of the research project are (i) development of innovative catalyst for the methanol reaction from H_2 and CO_2; (ii) development of innovative PEM electrolyser for hydrogen production; (iii) design and installation of demonstrative pilot plant and grid integration; (iv) process optimization and thermo-economic analysis of the plant considering different economic scenarios. Unige is involved in the fourth activity [14].

The German economic scenario is chosen as a reference case, since Germany presents the largest installed capacity of unpredictable RES among the European Countries: in 2014 Germany had the record in terms of both wind capacity (40.4 GW, 31% of all the EU28 Countries) and solar capacity (38.4 GW, 43% of all the EU28 Countries) [15]. The impact of RES has become more and more relevant in the last years in particular the production from solar, which was negligible in 2007, increased up to 35 TWh in 2014 and the production from wind has increased from 39.5 to 56 TWh (Fig. 1). On the other hand, the production from thermal and nuclear plants has decreased because of the economic crisis, the electricity demand has slightly decreased (from 636.4 to 612.6 TWh), although the process is less evident compared to other European Countries. It is worth noting that, starting from 2012, the difference between production and demand corresponds to the production of uncontrollable RES (wind and solar).

In this paper, a feasibility study of a power-to-fuel plant for methanol production is performed throughout a thermo-economic analysis. Three different capacity plants for methanol production (4000 10,000 and 50,000 ton/year) are investigated, assuming an average cost for electrical energy to feed electrolysers and analyzing the influence of the most significant parameters (oxygen selling option, methanol selling price and electrolysers capital cost) on the profitability of the plant.

The study is performed using the W-ECoMP software (Web-based Economic Cogeneration Modular Program) for time-dependent thermo-economic optimization, developed by the University of Genoa. W-ECoMP is a tool for economic feasebility evaluation of innovative plant, coupled with the management strategy optimisation. It is based on a genetic algorithm for the minimization of a target fuction, which is rapresentative of the variable cost of the plant. The first step for the

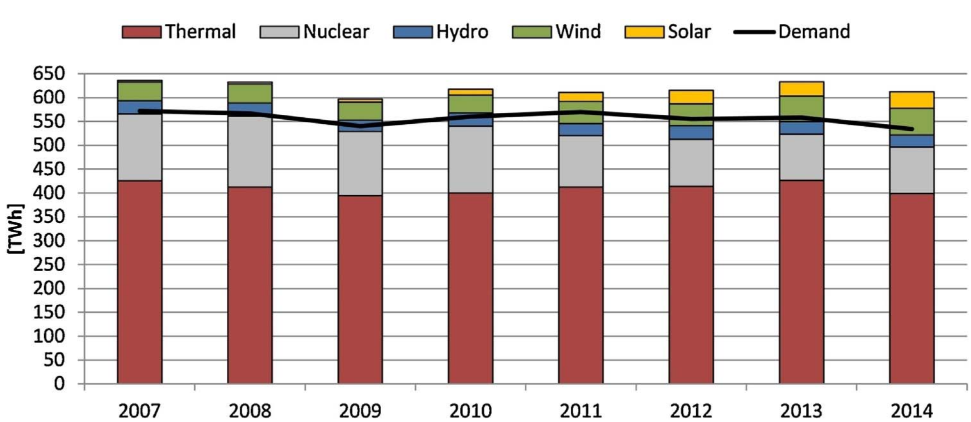

Fig. 1. Energy mix production and electrical demand evolution in Germany (2007–2014) [15].