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ScienceDirect

Energy Procedia 158 (2019) 4721–4728

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Economic feasibility of methanol synthesis as a method for CO_2 reduction and energy storage

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Abstract

In this paper, a thermo-economic analysis concerning a methanol production plant is performed. In particular, this study was developed with the aim of evaluating the opportunity and viability of obtaining methanol from the chemical reaction between recycled CO_2, emitted from a fossil-fuel power station, and hydrogen produced by water electrolysis. This solution can represent an interesting carbon dioxide reduction method and methanol as a product can be considered an energy storage means.
As a first step, a thermodynamic analysis is performed in order to determine the mass and energy flows of the plant; then, a feasibility analysis concerning a large size methanol production plant is performed taking into account three different economic scenarios (Germany, Italy, and China). In order to evaluate the economic viability, the total investment cost and payback period are calculated in all the scenarios. Different methanol and electrical energy prices are considered, to take into proper account the influence of these parameters on mid-term future scenarios. Moreover, a sensitivity analysis, considering different oxygen selling prices and PEM electrolyzer capital costs, were performed.

Keywords: thermo-economic analysis; energy scenarios; methanol synthesis; biofuels.

1. Introduction

In the last century, the strong industrial development led to an important increase of global energy demand: since most of the electrical energy was produced by fossil fuels exploitation, Green House Gas (GHG) emissions increased significantly [1][2]; in addition, fossil fuel reserves are not unlimited and their availability is going to reduce, causing higher costs for their supply. In consideration of this, the European Union (EU) adopted important energy policies to promote sustainable strategies aimed to GHG emissions reduction, developing new technologies in order to reduce the dependence by fossil fuels [3]. More in detail, the EU formulated targets for 2020 and 2030, aimed to:

- reduce GHG emissions by 20% (2020) and by 40% (2030), compared to 1990 levels
- increase the share of renewable energy sources (RES) in the EU's energy mix to 20% (2020) and 27% (2030) of final consumption
- improve energy efficiency by 20% (2020) and 27% (2030).

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10.1016/j.egypro.2019.01.730

In answer to the EU 2020 and 2030 energy targets, the impact of RES has become more and more significant. The production from solar energy, which was negligible in 2006, reached in 2015 the value of 108 TWh and the wind energy contribution increased from 82 to 304 TWh [4]. The increase of wind and solar energy exploitation is particularly evident in Italy, and Germany: the contribution of electrical energy production from not programmable RES (i.e. wind and solar) increased respectively from 0.9% to 13.4% (Italy), and from 6.7% to 18.1% (Germany) of the total [4]. It is worth noting that, also on global scale, the most significant increases of electricity production concern solar and wind sources: statistics by International Energy Agency (IEA) confirm that wind technology exploitation has strongly increased in the last years, from 0.3% in 1990 to 22.9% in 2015; similarly, the solar source has increased from 0% in 1990 to 7.7% in 2015 [5].
Despite the environmental advantages, the strong increase of RES, in particular not programmable ones (i.e. wind and solar) presents some critical aspects, related to: (i) the management of the existing traditional power plants, which are forced to operate in strong off-design conditions, at lower efficiencies; (ii) the unpredictability of RES production. The conversion of renewable energy into the more convenient form of energy carriers can be an effective way to moderate the RES intermittency, avoiding also the problems in term of management that are affecting several fossil fuel power plants in these years.

Nomenclature

EU	European Union	GHG	Green House Gas
IEA	International Energy Agency	PBP	Pay Back Period
PEC	Purchased Equipment Cost	PtF	Power-to-Fuel
RES	Renewable Energy Sources	TCI	Total Capital Investment
TPG	Thermochemical Power Group		

1.1. MefCO2 European project

In this paper, the evaluation of the future possibility of employing electrical energy to produce methanol is performed. The work has been carried out in the framework of the European Project MefCO2 (Methanol fuel from CO2) [6], which aims to develop and design an innovative methanol production technology with a low carbon footprint: the project concept is based on CO_2 sequestration and utilization in order to mix it with H_2 produced by water electrolysis to produce methanol (CH_3OH). The project involves partners from different EU member states: the organization is constituted by both industrial partners and academic groups whose aim is the applied research and innovation. The industrial partners' tasks are mainly focused on the whole methanol value chain from power generation and distribution, carbon capture starting from exhaust gases, energy storage and hydrogen generation to methanol synthesis. On the other hand, the research partners deal with other issues: materials choice, catalyst design, chemical and process engineering, energy efficiency and thermo-economic analysis of the process in different scenarios. In particular, the University of Genoa is involved in the process optimization and in the thermo-economic analysis of the plant in different scenarios [6].
In this paper, a feasibility study of a power-to-fuel (PtF) plant for methanol synthesis is carried out, considering a capacity plant of 50,000 ton/year in terms of CH_3OH: the size was determined in a previous study by the authors [7]. The study is performed in three different scenarios (Germany, Italy, China), assuming an average cost for electrical energy to feed the PtF plant and analyzing the influence of several parameters (i.e. methanol selling price, electrical energy cost and oxygen selling) on the plant feasibility.
The study is performed using the W-ECoMP (Web-based Economic Cogenerative Modular Program) tool for thermo-economic plant optimization: the software, developed at University of Genoa by the author's research group [8], is able to analyze the influence of several economic parameters that affect the feasibility of the whole system. More details on the software can be found in several author's recent publications [9-11]. In this particular analysis, the software has been employed in order to evaluate the Total Capital Investment (TCI), the annual cash-flows and the Pay-Back Period (PBP) for the different scenarios, defined as follows:

$$PBP = \frac{Total\ Initial\ Investment}{Annual\ Net\ Income} \quad (1)$$

The Annual Net Income is calculated as the difference between the total annual revenues (coming from the methanol and oxygen sale) and the total annual cost (mostly related to the electrical energy purchase).

2. Plant configuration

A simplified scheme of the PtF plant investigated in the present work is reported in Fig. 1. The process for methanol synthesis can be divided into three main sections:

- Water electrolysis section, where H_2 and O_2 are produced employing electrical energy: hydrogen is used for methanol synthesis, while oxygen is directly sold to external users;
- Carbon Capture Sequestration (CCS) section: the amine-based CCS is connected to a coal-fired power plant and sequestrates the carbon dioxide necessary for methanol synthesis;
- Methanol reactor, where, after the compression of the reactants H_2 and CO_2 produced in the previous sections, the synthesis of CH_3OH occurs.

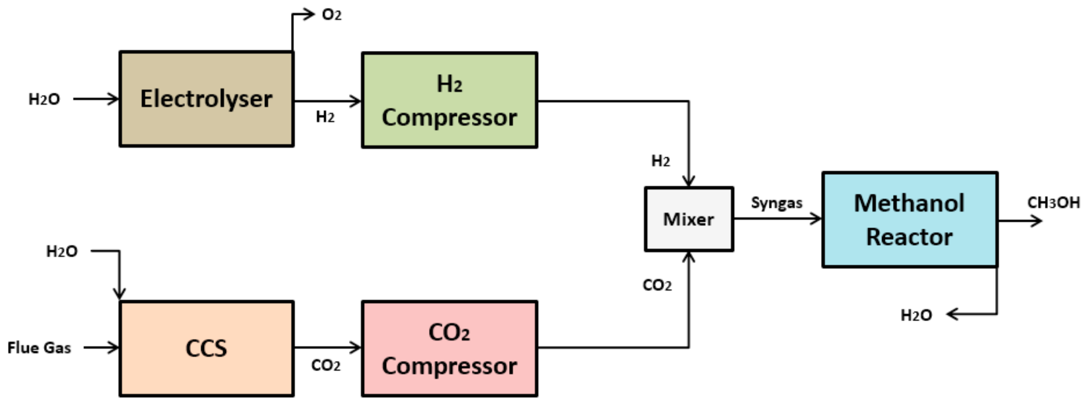

Fig. 1 Plant layout (simplified)

The main thermodynamic assumptions made for the different sections are illustrated in Tab.1: from these assumptions (obtained by literature and by private communications from the other partners of the MefCO_2 project), the first step before performing the thermo-economic feasibility analysis is the calculation of the energy and mass flow rates at the inlet and outlet of each section. Assuming the parameters reported in Tab. 1, considering a system for the production of about 50,000 ton/year of methanol operating continuously throughout the year, and considering the stoichiometric methanol reaction, about 9,835 ton/year of H_2 and 72,125 ton/year of CO_2 are needed. The CCS system is sized in order to be able to capture the required amount of CO_2; as far as the PEM electrolyzers are concerned, about 63 MW are installed and about 78,700 ton/year of O_2 (8 times more compared to hydrogen) are co-produced in this section.

Tab. 1 Main assumptions for thermodynamic analysis [12-16]

Electrolysis section		**Methanol reactor section**	
Electrical consumption	5.2 kWh/ Nm^3 H_2	H_2:CO_2 ratio	3:1
Efficiency	68%	Recirculation factor	85%
Outlet pressure	30 bar	Operative pressure	80 bar
		Conversion efficiency	96%
CCS section		**Compression sections**	
Treatment kind	amines	Isoentropic efficiency	86%
CO_2 capture rate	90%	Mechanical efficiency	99%
CO_2 outlet pressure	2 bar		
Thermal energy consumption	3 GJ_{th}/ton CO_2		

It is worth noting that both hydrogen and carbon dioxide need to be compressed up to the reactor working pressure, equal to 80 bar, with a not negligible energy consumption. The main results of the thermodynamic analysis in terms of mass and energy flowrates are reported in Tab. 2.

Tab. 2 Mass and energy flowrates for the main sections of the PtF plant

	Energy	**Mass**
Electrolysis section (63 MW)		
Electrical consumption	63 MWh	
H_2 production		1.2 ton/h
O_2 production		9.6 ton/h
CCS section		
Exhaust inlet		43.9 ton/h
CO_2 outlet		8.8 ton/h
Thermal energy consumption	7.37 MWh_{th}	
Electrical energy consumption	0.44 MWh_{el}	
Methanol reactor section		
$H_2 : CO_2$ ratio	3:1	
Inlet gas mix		10.0 ton/h
Methanol outlet		6.1 ton/h
Compression sections		
CO_2 compressor (up to 30 bar)	0.62 MWh	8.8 ton/h
H_2 and CO_2 compressors (up to 80 bar)	0.82 MWh	10.0 ton/h

The results reported in Tab. 2 are implemented in the single modules, representative of each section of the PtF plant, employed for the feasibility analysis in the different scenarios under analysis. The aim of the study is to determinate in which kind of scenarios and for what values of the different parameters the plant can represent an economically feasible solution. It is worth noting that the economic assumptions, reported in the next paragraph, are strictly related to the present scenario (electrical energy cost in Germany and Italy) or to close-to-midterm future scenarios.

2.1. Economic assumptions

Before proceeding to the thermo-economic feasibility analysis, it is mandatory to present the most significant assumptions made by the authors. First of all, in order to determine the TCI of the plant, dedicated cost functions have been developed and implemented in W-ECoMP software, basing on literature data [15][17-19], as reported below.

PEM Electrolyser $$C_{PEM} = 1.204 \cdot 10^6 \cdot P^{0.85} \quad (2)$$

CCS section $$C_{CCS} = 2.403 \cdot 10^3 \cdot (M_{in})^{0.65} \quad (3)$$

Methanol Reactor $$C_{MeOH} = 12.783 \cdot 10^3 \cdot (M_{in})^{0.65} \quad (4)$$

H_2 Compressor $$C_{H_2} = 36.858 \cdot 10^3 \cdot (M_{in} \cdot ln\beta)^{0.65} \quad (5)$$

CO_2 Compressor $$C_{CO_2} = 2.651 \cdot 10^3 \cdot (M_{in} \cdot ln\beta)^{0.65} \quad (6)$$

The Total Capital Investment (TCI) cost is calculated starting from the Purchased equipment cost of the plant: it is assumed that the PEC is about the 62% of the TCI. Moreover, it is assumed that the TCI corresponds to the Initial Investment. In addition, to perform the economic analysis the following assumptions have been considered:

- **Plant lifetime:** assumed equal to 20 years, considering the lifetime of electrolyzers [15];
- **Plant reliability**: assumed equal to 95%, which represents a target value for large size plants for methanol synthesis;
- **Oxygen selling price**: assumed equal to 150 €/ton, which represents a typical market value [20];
- **Methanol selling price**: The average methanol market value in Europe is about 400 €/ton [21], but the methanol market is expected to increase [22], thus its market value may become higher in the close-to-midterm future; thus, different market values (from 400 €/ton up to 800 €/ton) are considered in the analysis.

- **Electrical energy cost**: this value is strongly affected by the country; in particular, among the scenarios considered in this analysis, Italy presents the highest average market value (53.95 €/MWh), Germany has an intermediate value (33.31 €/MWh) and China presents the lowest (10 €/MWh) [23 -24-25].

3. Results and discussion

In the present work, the plant feasibility analysis has been performed for different economic scenarios: Italy, Germany (representing the Southern and Central Europe areas) and China (representing the Asian area).
For each scenario, the PBP and the methanol production cost were calculated and compared taking into account the actual electrical energy market price and the actual methanol market price (400 €/ton). The TCI, considered equal for each economic scenario, is around 85.7 M€ and the total PEC resulted equal to about 53.3 M€. In Fig. 3, the percentage distribution of the PEC among the modules is reported.

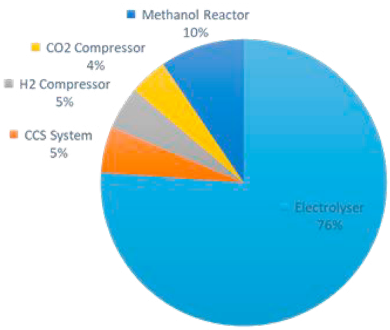

Fig. 2 Purchased Equipment Cost percentage distribution

The electrolyzer is the most expensive component accounting about the 76% of the total PEC. Considering that the PEM technology has not reached a high technology readiness level yet, and it cannot be considered a mature technology, it is possible to assume that the capital cost of the PEM will decrease in the next years. For this reason, the impact on the plant feasibility of a percentage reduction in PEM capital cost of about 30% has been analyzed. Tab. 1 reports, for each scenario analyzed, the annual revenues coming from the sale of methanol and oxygen, the annual cost due to the electrical energy purchasing from the grid at each country market price and from the fixed annual cost (e.g. the TCI annual rate assuming to spread the cost over the plant lifetime). Moreover, the PBP and the methanol production cost are reported.

Tab. 3 Revenues, cost, methanol production cost and PBP calculated for the Italian, German and Chinese scenarios

	Italy @ 53.95€/MWh		**Germany @ 33.31€/MWh**		**China @10€/MWh**	
	Revenues	Cost	Revenues	Cost	Revenues	Cost
Methanol	21,185,200.00 €		21,185,200.00 €		21,185,200.00 €	
Oxygen	12,410,496.00 €		12,410,496.00 €		12,410,496.00 €	
Electrical Energy		30,158,947.73 €		18,620,844.28 €		5,590,166.40 €
Fixed Annual Cost		4,285,859.25 €		4,285,859.25 €		4,285,859.25 €
Methanol Production cost	650 €/ton		433 €/ton		186 €/ton	
PBP @400€/ton	>20 years		6 years		3 years	

In the Italian scenario, the methanol plant results not feasible under the actual market conditions: the production cost is 650 €/ton that is much higher than the actual methanol market price due to the high cost of the electrical energy. The German scenario presents a lower cost of electrical energy that allows for a significant reduction in the production cost up to 430€/ton. Even though the methanol production cost is slightly higher than the selling price, the PBP is lower than 10 years thanks to the revenues coming from the oxygen sale. In the end, China results the most promising scenario for the installation of this kind of plant. The production cost is lower than 200 €/ton. It is worth noting that the oxygen sale accounts for about 37% of the total revenues and it plays a crucial role in the economic feasibility of the plant. For this reason, the impact of an increase in the oxygen selling price up to 200€/ton has been investigated.

In Fig. 3, the PBP is reported as function of the methanol selling price (in the range between 300 and 1000€/ton) and the electrical energy purchasing cost (in the range between 10 and 110 €/MWh), for different value of the oxygen selling price (150 and 200 €/ton) and for different value of the PEM capital cost (100% and 70% of actual value).
The resulting PBP values are divided into ranges and represented as different colored areas. The light-blue area corresponds to a PBP lower than 5years. In the green area the PBP is in between 5 and 10 years (that is considered as the limit value for the plant feasibility). The orange area contains the PBP values in the range between 10 and 20 years (corresponding to the plant lifetime). The red area represents the PBP higher than 20 years: in this case, the total annual revenues result higher than the annual cost, but the net incomes are so low that would not allow the return of the investment within the plant lifetime. Finally, the grey area represents a not viable condition in which the total annual net income results negative, meaning that the annual variable costs are higher than the annual revenues.
It is interesting to note that the correlation between the methanol price and the electrical energy cost is almost linear.
In each plot, the three economic scenarios are reported considering the actual electrical market price and the methanol price. Considering the Italian case, it is possible to note that in the plot A, its PBP falls in the red area (PBP >20yr), but, increasing the oxygen price up to 200 €/ton (plots B), the PBP falls in the orange area meaning that the total investment can be recovered within the plant lifetime in more than 10 years; assuming also to reduce the capital cost of the PEM of about 30% (plot D), the PBP results under 10 year and the investment can be defined as feasible. In the same way, it is possible to define for each case and fixed a value methanol price, the maximum value of the electrical energy price that allows a PBP equal to 10 years and therefore is it possible to identify the appropriate economic scenario. Vice versa, defined a certain value of the electrical energy cost, it is possible to define the minimum price of the methanol that allows for a PBP lower than 10years. For example, assuming that the methanol price increases from 400 €/ton up to 600€/ton, in the case (A) the maximum value of the electrical energy cost increases from about 44€/MWh up to about 65 €/MWh.

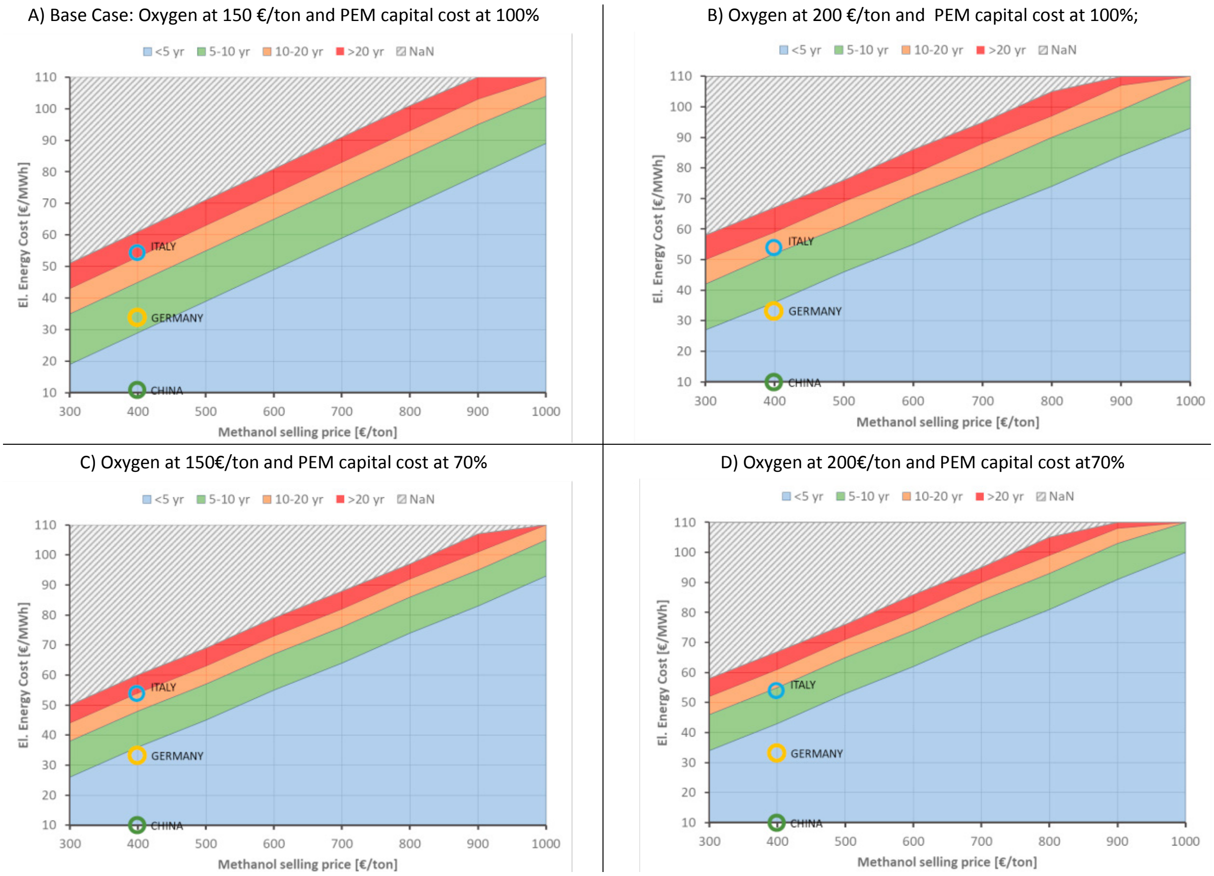

Fig. 3 PBP as function of the methanol selling cost and the electrical energy price for different values of the oxygen price and PEM capital cost: A) Base Case: Oxygen at 150 €/ton and PEM capital cost at 100%; B) Oxygen at 200 €/ton and PEM capital cost at 100%; C) Oxygen at 150€/ton and PEM capital cost at 70%; D) Oxygen at 200€/ton and PEM capital cost at70%;

In Fig. 4, the economic feasibility areas, in which the PBP is lower than 10 years, is reported as function of the methanol selling price and the electrical energy cost for the different case reported above (A, B, C, and D).

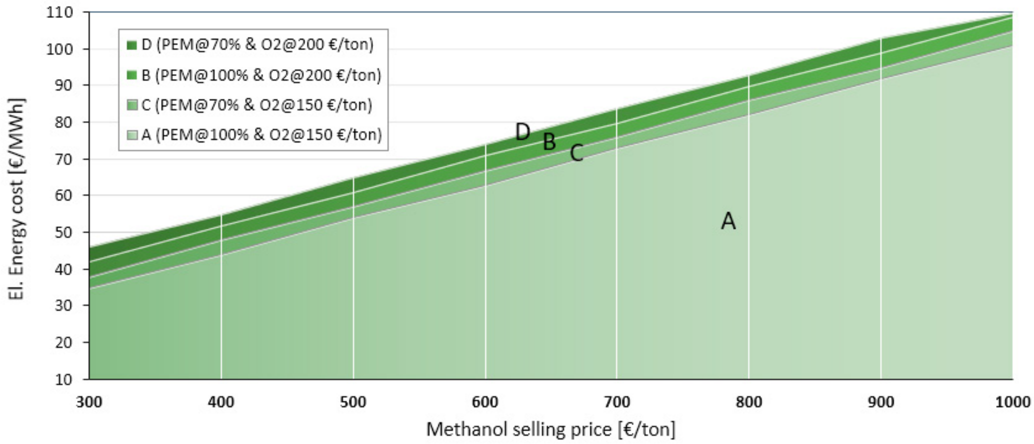

Fig. 4 Impacts of the increase of the oxygen selling price and of the decrease in the capital cost of the PEM in terms of an increase in extension of the PBP<10yr area.

This plot shows the impacts of the increase of the oxygen selling price and of the decrease in the capital cost of the PEM in terms of an increase in extension of the PBP<10 yrs area. It is interesting to note that an increase in the oxygen price of the about 30% (up to 200 €/ton) is more affecting than a decrease in the PEM capital cost of about 30%. In fact, the capital cost reduction allows for an area extension of about 9% respect the *base case* (O_2 at 150€/ton and PEM cost at 100%), whereas the oxygen price increase allows for an area extension of about 20% respect the *base case*: at 400€/ton of methanol cost, the corresponding value of the maximum energy price increase from 44€/MWh of the base case up to 48 €/MWh and 52€/MWh respectively. On the other hand, considering the Italian scenario with an actual electrical energy price equal to about 54€/MWh, the minimum methanol selling price decreases from 500€/ton of the base case (A), up to 470€/ton in case C, 420 €/ton in case B and 390€/ton in case D.

4. Conclusion

In this paper, a feasibility study for methanol synthesis from H_2, produced by water electrolysis, and CO_2, sequestered by a CCS section, has been performed, considering three different economic scenarios. The following conclusions can be drawn:

- The cost of the electrical energy price is the parameter that mainly affects the economic feasibility of the plant.
- The capital cost of the electrolyzer is still high, but it is reasonable to assume that in the next future the increasing development will drive to a lower capital cost. A reduction of the 30% of the actual cost, may reduce the PBP by of about 10%.
- The oxygen sale is a fundamental aspect to reach the plant economic feasibility. With reference to the "base case" (O_2 at 150€/ton and MeOH at 400€/ton), the revenues coming from the oxygen selling represent around the 40% of the total revenues of the plant. An increase of the around 30% in the oxygen selling price allows for a PBP reduction of about 20%.
- It is reasonable to assume that the methanol selling price will increase considering its use as fuel for the automotive transportation market. An increase of the methanol price up to 800€/kg (equivalent to the actual cost of diesel in terms of energy content [26]) would allow for a PBP reduction higher than 50%.
- From the environmental point of view, it is worth underlying that the CO_2 used for the methanol synthesis is captured from the fossil-fueled plant. In particular, a 63MW of methanol plant allows about

76kton of CO_2 per year to be recycled. This can be translated from the economic point of view in a considerable money saving considering the actual CO_2 European market value equal to about 7€/ton [27]. This aspect will become more relevant in the next future because the CO_2 taxation is expected to increase [28].

Acknowledgments

Authors gratefully acknowledge the financial support from the 'EU Framework Program for Research and Innovation Horizon 2020' under the grand agreement No. 637016 (MefCO2).

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