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Power to fuel concept: process analysis and economic evaluation

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Abstract:

The significant increase of greenhouse gas emissions in the last decades has led to the adoption of measures for their drastic mitigation. The CO_2 transformation into valuable fuels through the Carbon Capture and Utilization (CCU) concept attracts the attention of the researchers for further investigation in the last years, since the global community is hesitant to the CO_2 storage. Power to Fuel (PtF) is a CCU scheme that exploits CO_2 from energy intensive industries and low cost electricity. Through this process, CO_2 is catalytically hydrogenated with H_2 derived from water electrolysis unit, yielding fuels such as the methanol, or other chemical products. However, since this concept has not been commercialized yet, there is an expanded research area for further reduction of the methanol production cost and the optimization of the overall concept. Hence, this study focuses on the investigation of the plant performance for various cases and the determination of their competiveness against the conventional routes of methanol production. More specifically, a thorough economic evaluation, including the specific costs estimation, the capital and the operational expenditures is carried out in order to evaluate the influence of each component on the overall concept. The economic evaluation is followed by a sensitivity analysis based on the most crucial parameters.

Keywords:

Power to Fuel, Methanol, Carbon Capture and Utilization, Electrolysis, Economic Evaluation.

1. Introduction

In 2013, global CO_2 emissions reached an new time high of 35.3 billion tons, with fossil fuel combustion being responsible for about 90% of the total emissions (excluding deforestation and other land uses) [1]. With future projections predicting 50% increase on CO_2 emissions until 2050 numerous approaches are being explored for their mitigation [2]. One such concept is Carbon Capture and Utilization (CCU), where CO_2 is captured from conventional thermal power plants, industrial areas or even the atmosphere and transformed into value added chemicals and fuels [3].

Within the CCU scheme, Power to Fuel (PtF) is a concept that attracts significant interest over the last years. Through the PtF pathway a number of alternative fuels and chemical products are produced from the reaction of captured CO_2 with H_2. The H_2 utilized for this process is produced from water electrolysis units, using conventional electricity and/or electricity derived from renewable energy sources such as wind, solar and others [4]. The most important yield from this process is the methanol that is used widely for the production of a number of high added value products in the chemical and energy industry, such as formaldehyde and gasoline/fuel applications. [5]. In 2013, the worldwide methanol demand reached about 60 million tons, with forecasts predicting that by 2017 it will exceed the 80 million tons [6, 7].

Currently, methanol is synthesized mainly from natural gas through the syngas route. However, taking into consideration that the most secure gas deposits are expected to reach their peak by 2016 and start to decline by 2030, an eminent need for an alternative synthesis pathway will be appeared [8]. PtF offers the alternative route needed for the production of methanol and its derivatives and their further utilization in the methanol economy, as Olah et al proposed in their study [9]. Within the PtF scheme, methanol and its primary derivative dimethyl ether (DME) are produced from hydrogen and captured CO_2. The quantity of CO_2 emitted from internal combustion engines using fuels containing the produced methanol and DME is lower compared to conventional fuels, since a part of the CO_2 is recycled [10-12]. In the case that the hydrogen production is based only on renewable energy sources (RES), the total CO_2 emissions are even lower, since RES can be considered carbon free. Thus, this environmental friendly production route can offer significant contribution on reducing the reliance from fossil fuels and also mitigate the CO_2 emissions. Furthermore the employment of methanol as H_2 carrier could also be promoted, since it can be easily reformed back to H_2 (syngas) at modest temperatures, without the need for high pressure storage and the dangers involved in H_2 storage and distribution [3, 13].

The process of methanol synthesis from CO_2 is a new technology, since the first studies were carried out in the late 80s and is still under development [14]. Recently, Van-Dal et al.[10] simulated a methanol plant using CO_2 and H_2 as feedstock, focusing on the process, whereas Mignard et al.[15] apart from the process also conducted a thorough feasibility study. Furthermore Anicic et al. [16] and Clausen et al. [17] compared the different ways of producing methanol. The first commercial plant, following the PtF concept is the George Olah Renewable Methanol Plant, located in Iceland. The plant’s production capacity is about 5 million litres of methanol, by recycling about 4500 tons CO_2 per year [18]. Following Iceland’s example other European countries are planning on implementing the PtF concept, such as the German Lünen Power Plant, offering a further promotion of the concept [18].

In this study, the techno- economic evaluation of the Power to Methanol scheme is performed, examining the main economic parameters related to the process. Unlike other similar assessments, this study focuses on the cost breakdown of the produced methanol, indicating the influence of the capital and operational expenditures on the final methanol cost. Apart from the cost breakdown, this study also aims to investigate under which conditions the methanol cost could be further mitigated, thus optimizing the scheme. For this purpose, a sensitivity analysis on the plant scale, the electricity cost, the electrolyzer efficiency and the CO_2 cost is carried out, indicating the impact of each parameter on the final methanol cost.

2. Methodology

In this section, the Power to Methanol Concept is more thoroughly presented, followed by the description of the developed scenario and assumptions made for the techno-economic assessment.

2.1. Power to Methanol Concept

The Power to Methanol Concept consists of a process chain including the stages of the Electricity Generation, the Methanol Production and its Applications, as depicted in Fig. 1.

The electricity comes from conventional power plants and/or renewable energy sources. Electricity from the grid can be used as feedstock during off peak hours, thereby exploiting low cost electricity but also stabilizing the grid, when the surplus electricity production is utilized in the process.

The derived electricity is utilized in the water electrolysis plant for the production of the required H_2 for methanol production. Currently, two technologies are commercially developed for industrial water electrolysis, Alkaline and PEM electrolysis, with Alkaline chosen as more mature and low cost technology for large scale production [17].

The H_2 produced within the electrolyser, is transported in gas or liquid form to a buffer and finally to the methanol plant. The buffer is employed in the scheme in order to ensure the continuous and stable hydrogen flow for the methanol synthesis, since the electrolyzer may not operate continuously. The oxygen derived through the decomposition of water is a valuable electrolysis by-product that can be sold for industrial or medical applications.

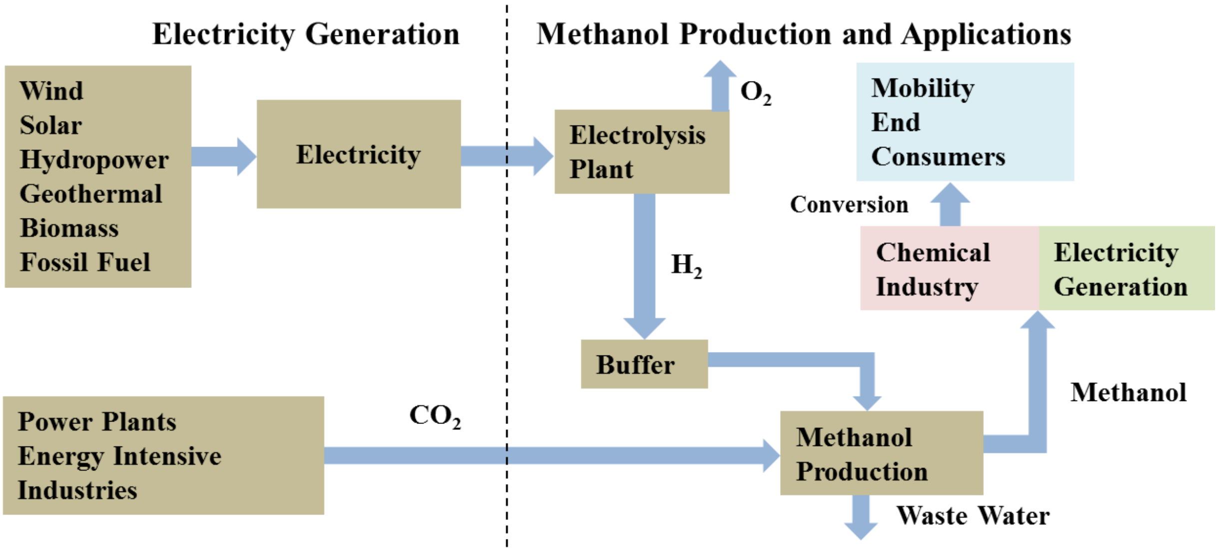

Fig.1. Power to Methanol process chain diagram.

The second feedstock to the methanol plant is CO_2. There are three major methods of capturing CO_2, pre-combustion, where CO_2 is captured from the reformed synthesis gas in a gasification unit, post-combustion, with CO_2 captured from flue gas after combustion and oxyfuel, where pure O_2 is used for combustion increasing the CO_2 concentration [19]. The captured CO_2 is transported via pipelines or ships to the methanol plant, where its catalytic reaction with H_2 takes place.

The main catalytic reaction taking place for the production of methanol within the reactor of the plant is described in (1). The catalysts used for methanol synthesis are Cu/ZnO based, often containing additives such as ZrO_2, GaO_3 and SiO_2 over alumina.

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O\text{ , }\Delta\mathrm{H} = -49.5\text{ kJ/mol } (1)$$

Because of its exothermic nature, the reaction's efficiency increases for lower temperatures (150-250^{o}C, avoiding the Reverse Water Gas Shift Reaction), high pressure (>20bar) and the stoichiometric CO_2/H_2 ratio (3:1).

2.2. Description of the scenario

For the definition of the basic scenario, a number of parameters have to be determined. As far as the H_2 production is concerned, the electrolyser system chosen is based on the Hydro bi-polar Alkaline Electrolyzer System (Atmospheric Type No.5040 - 5150 Amp DC), since a large scale production is assumed. The total electrolyzer system consists of 150 electrolyzer units, with a nominal daily production 1.046 kg of hydrogen per unit (485 Nm^3 H_2 per hour). The electrolyte utilized in the process is KOH and water is used for the electrolysis and for cooling. Based on the Hydrogen Analysis studies from the US Department of Energy [20], the energy consumption of the system is 50kWh/kg H_2 which translates to 67% efficiency and a capacity of 2,179kW per unit. The operation of the H_2 plant is simulated during off peak hours, when the electricity cost is low. Therefore, a 40% plant Capacity Factor (CF) is taken into consideration by assumption within the study.

For the purposes of the study, it is considered that the H_2 and methanol plants are co-located in order to minimize the transport cost of H_2. The produced H_2 is compressed to 30bar and sent to a buffer before the reaction with CO_2. Regarding the scenarios to be examined, the storage of hydrogen in gas form is adopted as the most economic method, compared to the storage in liquefied form [21, 22].

The O_2 produced within the electrolyzer as by-product has a 99.5% purity grade which makes it suitable for several applications, even for the healthcare industry, since the US Food and Drug Administration (FDA) has set the purity standard at 99.2% [23, 24].

The CO_2 needed for the process is chosen to be captured from a coal power plant by the post-combustion method with amines, a well-established and mature technology, favored because the retrofitting of existing plants is possible. The captured CO_2 can reach the methanol plant either by pipeline or by ships. In this study, both ways of transport are taken into consideration in order to get more representative results.

For the direct synthesis of methanol from CO_2 and H_2, the process proposed by B. Anicic et al. is adopted [16]. Within the methanol plant, the H_2 and CO_2 feed is led into the first reactor for methanol synthesis in a stoichiometric ratio. The first reactor's output contains H_2, CO_2, methanol, H_2O and CO. The feed is cooled and driven to a flash-separator in order to separate the liquid and gaseous phase. The gaseous phase is separated in three streams, with the majority of the stream recycled back to the first reactor, whereas the second part is led to the second reactor for methanol synthesis. The third smallest part undergoes combustion. The output stream of the second reactor is cooled and led back to the flash-separator. The final step of the process consists of three distillation columns, where the final product is derived after purification and separation. The first column is used for the separation of dissolved gases obtained as gaseous distillate and undergoes combustion and the second and third column are used for water and methanol separation. By the use of two columns, a better heat integration is achieved. The diagram of the described method is presented in Fig. 2.

The catalyst used for the methanol synthesis is Cu/ZnO based, doped with ZrO_2 for higher conversions, usually used for methanol synthesis. The total conversion to methanol using this type of catalyst is 21%, with a methanol selectivity rate at 68% and the respective rate for CO at 31%.

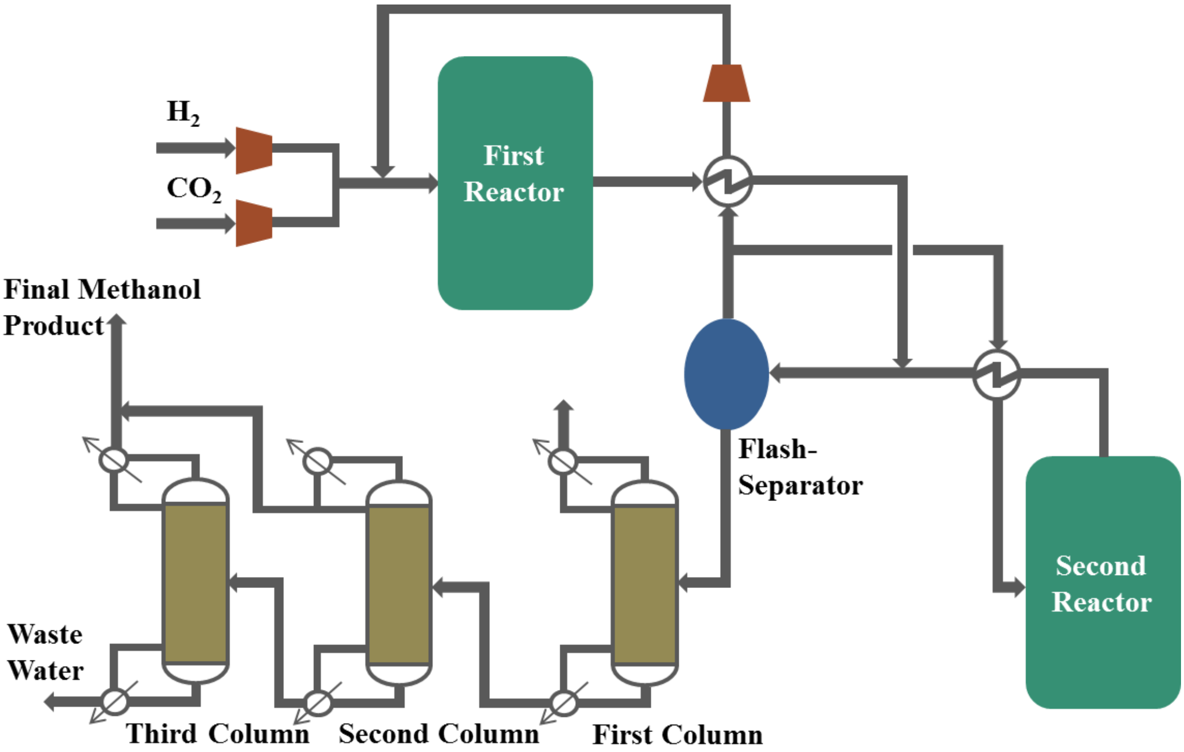

Fig.2. Power to Methanol process.

2.3. Economic indicators

After having determined the Power to Methanol process, the techno-economic assessment of the scheme is performed. Firstly, the cost estimation methodology for H_2 is presented based on the Hydrogen Analysis models proposed by the US Department of Energy [20]. The cost of H_2 utilized as feedstock for methanol synthesis includes the production cost, increased, for the basic scenario, by an extra 10% for storage [20, 22]. Regarding the described scenario a favorable low electricity cost is adopted, assuming that operation during off peak hours is arranged. Table 1 shows the most important economic indicators of the described scenario, for the water electrolysis plant.

Table 1. Electrolysis Plant economic indicators

Parameter	Electrolysis Plant
Life Plant	40 years
Plant Depreciation	20 years MACRS
Internal Rate of Return	10%
Year cost	2009
Startup Year	2014
Construction Period	2 years
Cost of Electricity	10€/MWh
Uninstalled Electrolyzer System Cost (2009)	579,591.35€/unit [20]

The O_2 by-product, derived from the electrolysis plant, will be sold in the healthcare industry at a typical selling price of 0.88€/kg O_2 [23].

The next parameter evaluated is CO_2. Based on studies and future assumptions from the International Energy Agency a CO_2 acquisition cost of 25€/tnCO_2 is assumed, which consists mainly of capture, transportation costs by pipelines and ship as well as the carbon price costs [25].

In what concerns the techno-economic assessment of the methanol plant, the methodology proposed by Peters and Timmerhaus is adopted [26]. The Total Capital Investment (TCI) is estimated through a number of intermediate cost types. Firstly, the Total Purchased Equipment Cost (TPEC) is calculated, including the purchased equipment cost based on similar processes from literature. With the cost of an equipment b at a given capacity known, the cost of a similar unit α with X times the capacity of b is X^f times the cost of the initial unit, as presented in (2).

Cost of equipment α = (cost of equipment b)X^f, (2)

where f is a scaling factor depending on literature data.

In Table 2 the equipment cost of the methanol plant is displayed. It is assumed that the same reactor as in the Syngas synthesis route can be used, since the nature of the reactants is similar. The cost of heat exchangers is not taken into account, since it is negligible compared to the other components [16].

Table 2. Methanol plant equipment cost estimation

Equipment	Base Capacity	Units	New Stream	Base Cost (10^6€)	Year	Scaling Factor	Total Purchased Cost (10^6€)	Reference
Compressors	1.07	MWe	0.47	0.58	2002	0.67	0.49	[26]
Reactor 1	5000	tn/day	189.36	65.57	2005	0.67	9.15	[27]
Reactor 2	5000	tn/day	143.38	65.57	2005	0.67	7.59	[27]
Distillation Column	5292	tn/day	310.51	13.06	2008	0.67	1.99	[28]

After having estimated the TPEC, the Total Capital Investment is calculated based on the methodology presented in Table 3.

Table 3.Methanol Plant Total Capital Investment estimation approach

Direct Costs	
Total Delivered Equipment Cost (TDEC)	110% of TPEC
Purchased equipment installation	39% of TDEC
Instrumentation & Controls (installed)	26%
Piping (installed)	31%
Electrical systems (installed)	10%
Buildings (including services)	29%
Yard improvements	12%
Total Direct Costs (TDC)	247%
Indirect Costs	TDEC percentage
Engineering and supervision	32%
Construction expenses	34%
Legal expenses	4%
Contractor's fee	19%
Contingency	37%
Total Indirect Costs (TIC)	126%
Fixed Capital Investment (FCI)	TDC & TIC
Working capital (WC)	15% of FCI
Total Capital Investment (TCI)	FCI & WC

The next step for the economic calculations is the estimation of the operating costs, which consist of the Fixed and Variable Operating Costs. The Fixed Operating Costs include General Overhead Costs, Insurance and Taxes, whereas Variable Operating Costs consist of Feedstock costs, Catalyst costs, Salaries and Maintenance and Repair costs given in a yearly basis. The Fixed and Variable Costs are summarized in Table 4. Labor Costs are calculated based on the number of process steps in the plant, by estimating the employee hours needed for a given plant capacity and multiplying them with the average employee hour cost found in Eurostat [29].

Table 4. Fixed and Variable Operating Costs

Parameter	Price	Reference
Fixed operating costs		
Insurance and taxes	2% of FCI	[26]
General overhead	60% of labour supervision and maintenance	[26]
Variable operating costs		
Maintenance and repairs	2% of FCI	[26]
H_2 total cost	427.13(€/tn methanol)	For basic scenario
CO_2 total cost	37.10 (€/tn methanol)	For basic scenario
Methanol synthesis catalyst	56.8 (€/m^3 methanol)	[16]
Electricity consumption for compression	10 (€/MWh)	Assumption

With the Capital and Operational Expenditures defined, the Cash Flow Analysis of the investment is performed. The main economic assumptions followed are summarized in Table 5. The Modified Accelerated Cost Recovery System (MACRS) is used as depreciation model and a zero salvage value is assumed at the end of the plant’s lifetime.

Finally, through the analysis the selling price of methanol per ton is estimated, for a zero Net Present Value (NPV) and a 10% Internal Rate of Return (IRR), in order to determine the selling price for a marginally feasible investment.

Table 5. Main Economic Assumptions

Parameter	Methanol plant
Life Plant	25 years
Plant Depreciation	7 years MACRS
Internal Rate of Return	10%
Year Cost	2011
Startup Year	2014
Construction Period	3 years
Land Cost	6% of TPEC

As shown in the Table 4 and 5 the lifetime for hydrogen plant is considered 40 years, while the respective lifetime for methanol plant is considered 25 years. In other words, this means that there will be a selling market for the produced H_2 after the end of the methanol plant's lifetime.

3. Results and Discussion

3.1. Mass balance

The mass balance calculations of the electrolysis and methanol plants, needed for the equipment cost scaling and the economic evaluation, are presented in Table 6.

Taking into consideration the mass flow, the thermal power of the produced methanol is estimated at 71.48MW$_{th}$, considering the Lower Heating Value (LHV) of methanol at 19.92 MJ/kg.

Table 6. Mass Balance

Electrolysis Plant			Methanol Plant		
Component	Reactant mass flow (tn/h)	Product mass flow (tn/h)	Component[1]	Reactant mass flow (tn/h)	Product mass flow (tn/h)
H_2O	29.083	5.687	H_2	2.615	-
H_2	-	2.615	CO_2	19.168	-
O_2	-	20.781	CH_3OH	-	12.918
			H_2O	-	0.012
			CH_3CH_2OH	-	0.006
			$CH_3CH_2CH_2OH$	-	0.001

[1] Due to their negligible amount, the produced ethanol and propanol are not taken into consideration for the calculations.

The CO_2 emissions rate of a typical coal power plant varies within 0.75-0.95tn/MWh$_e$ of the net electricity generated [30]. For the scale of 500MW$_{el}$ the total CO_2 emissions would be 300tn/h, assuming 75% capacity factor. Thus, in what concerns the basic scenario, the proposed system would treat about 7% of the emitted CO_2.

3.2. Cost Breakdown

Based on the methodology followed for the techno- economic evaluation, and with respect to the costs shown in the Tables 1 to 5, the minimum cost of methanol, for a marginally feasible investment, is calculated at 657.31€/tn methanol. However, in the case that the O_2 selling market is considered, the final cost falls to 490.03€/tn.

In this section, the cost breakdown of the basic scenario is presented. As observed in Fig. 3 the main contributor, defining the methanol cost, is the hydrogen utilized in the process. The production and storage of hydrogen reaches 68% of the total cost, whereas the remaining 32% consists of the capital and operational expenditures of the methanol (MEOH) plant, including the CO_2 cost. The parameters with the highest impact on the hydrogen production cost are the electrolyzer system and the electricity cost, with 21% and 18% contribution to the total cost, respectively. Regarding the methanol plant, the capital costs have the most significant influence with 16%, followed by the 6% contribution of the CO_2.

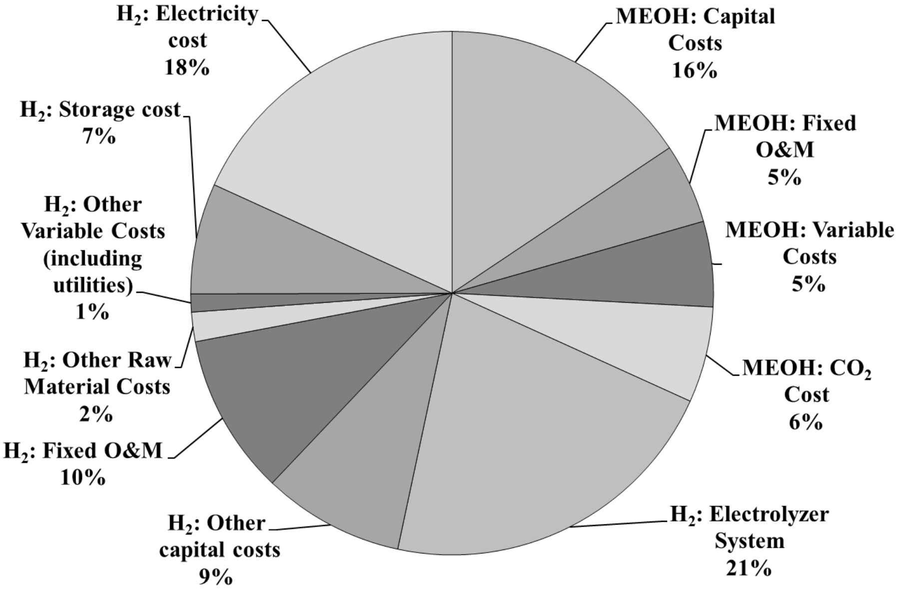

Fig.3. Base Scenario Cost Breakdown.

The price of methanol produced from conventional routes varies in the range of 125-525€/tn for the European market, as indicated on data provided by Methanex for the period 2002-2015 [31]. Since the basic examined scenario of the PtF concept is by 31% more expensive than conventional routes (339€/tn, February 2015), the following sensitivity analysis, aims to present the scenarios where Power to Methanol could compete with the conventional production routes.

3.3. Sensitivity Analysis

3.3.1. Plant Scale

The scale of the H_2 and methanol plant is investigated in this section. The scaling is performed based on the number of electrolyzer units in the H_2 plant. Table 7 shows the relation between the H_2 plant scaling scenarios and the estimated methanol capacity (MW_{th}), for all the examined scenarios.

Table 7. Plant scaling description

Description	Methanol Capacity (MW_{th})
50 electrolyzer units	23.83
100 electrolyzer units	47.65
150 electrolyzer units (basic scenario)	71.48
200 electrolyzer units	95.31
250 electrolyzer units	119.13

After having determined the scale of the plants, the economic evaluation is performed. In Fig. 4 the production cost with or without having considered the O_2 selling market is demonstrated. For the smaller capacity scenarios, significant increase of the cost is observed, whereas for larger capacities the cost decreases with a lower rate. The increase of the cost is explained by the fact that for smaller capacities the capital and operational expenditures for both the H_2 and methanol plants are notably higher. Through the analysis an economy of scales is achieved, with a total 43% cost decrease between the 23.83 and 119.13MW_{th} methanol scenarios.

The total cost mitigation, due to the O_2 varies from the smallest to the largest scale from 19% to 29%, respectively. For the largest scale examined, the final methanol cost is 18% more expensive than the current price of methanol, whereas for the basic scenario the respective rate was 31%. Hence, O_2 in combination with increased production scale can offer considerable economic advantages to the process, making it more competitive against the conventional methanol production routes.

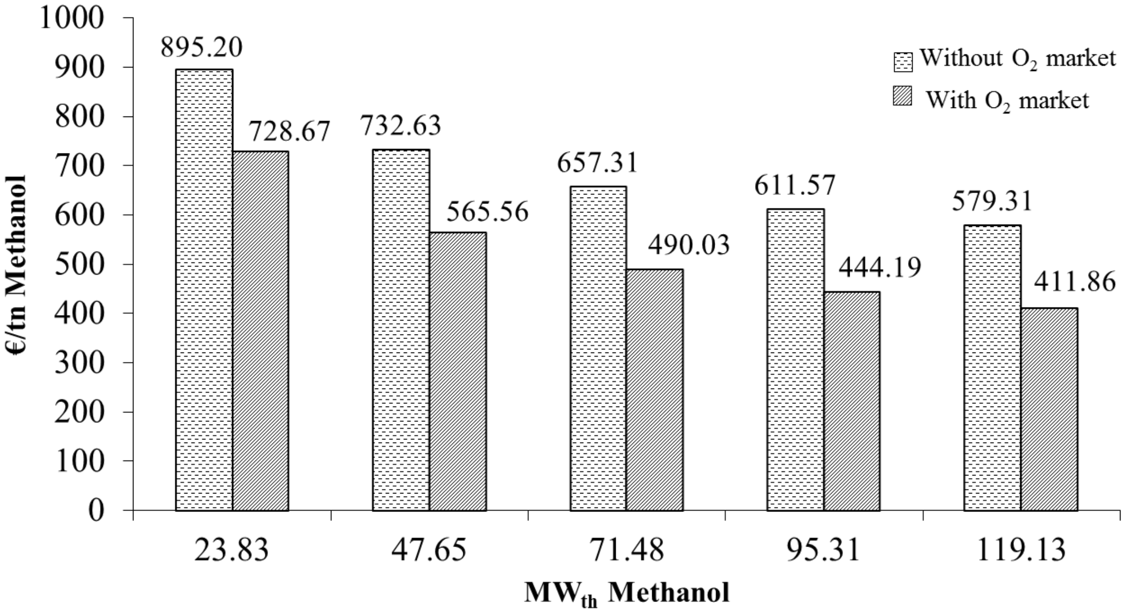

Fig.4. Total methanol cost for different plant scales.

3.3.2. Electricity Cost

Apart from the O_2 market that was considered for all scenarios, another important factor defining the viability of the process is the electricity cost. For the basic scenario a favorable cost of 10€/MWh was assumed, but the electricity cost has significant variations depending on a number of parameters, such as the feed in tariff according to the legislative framework, the electricity demand and supply etc. Thus, a sensitivity analysis on the electricity cost is performed, indicating its impact on the total cost. In Fig. 5, the methanol cost for the different electricity cost scenarios assumed is illustrated.

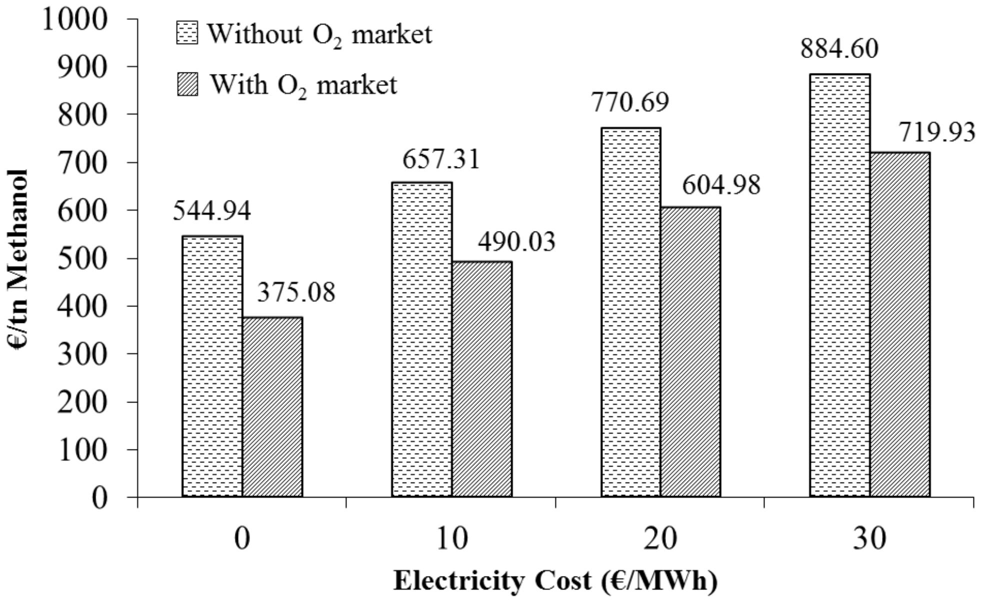

Fig.5.The impact of the electricity cost on the total methanol cost.

The electricity cost scenarios investigated vary from 0 €/MWh to 30€/MWh. The 0 €/MWh is mostly unrealistic, but it was examined for comparative reasons. As presented in Fig. 5, the increase in the electricity cost results in considerable rise of the total cost. In the 30 €/MWh case, the methanol cost rises by 47% (719.93 €/tn) compared to the basic scenario, making the process highly unprofitable, compared to the current price of conventional methanol (339€/tn). So the viability of the PtF process is, strongly related to the electricity cost, as also expected from previously published studies [15-17].

The breakdown cost of methanol is also affected by the electricity cost variation. In the 30€/MWh case, the electricity cost now contributes with 40% to the total methanol cost, compared to 18% and 31% for the 10 and 20€/MWh cases, respectively.

3.3.3. Electrolyzer Efficiency

The efficiency of the electrolyzer system is also a parameter to be investigated. Since electricity is utilized as feedstock for electrolysis, higher efficiency could reduce the amount of electricity utilized and further mitigate the total hydrogen related costs. Based on literature data, in the future it is most likely that the electrolyzer efficiency will rise to about 73%, considering improvements for the electrolyzer stack and the balance of the electrolysis plant [20]. Hence, in the sensitivity analysis below three different efficiencies are examined, the current (67%, 50kWh/kg H_2), the future (72.83%, 46kWh/kg H_2) and the ideal one (100%, 33.5kWh/kg H_2). The ideal efficiency, which is limited by the 2nd law of thermodynamics, is used in order to estimate the maximum cost reduction that could be achieved through the efficiency optimization. Figure 6 illustrates the impact of the electrolyzer efficiency on the total methanol cost, for the scenarios examined.

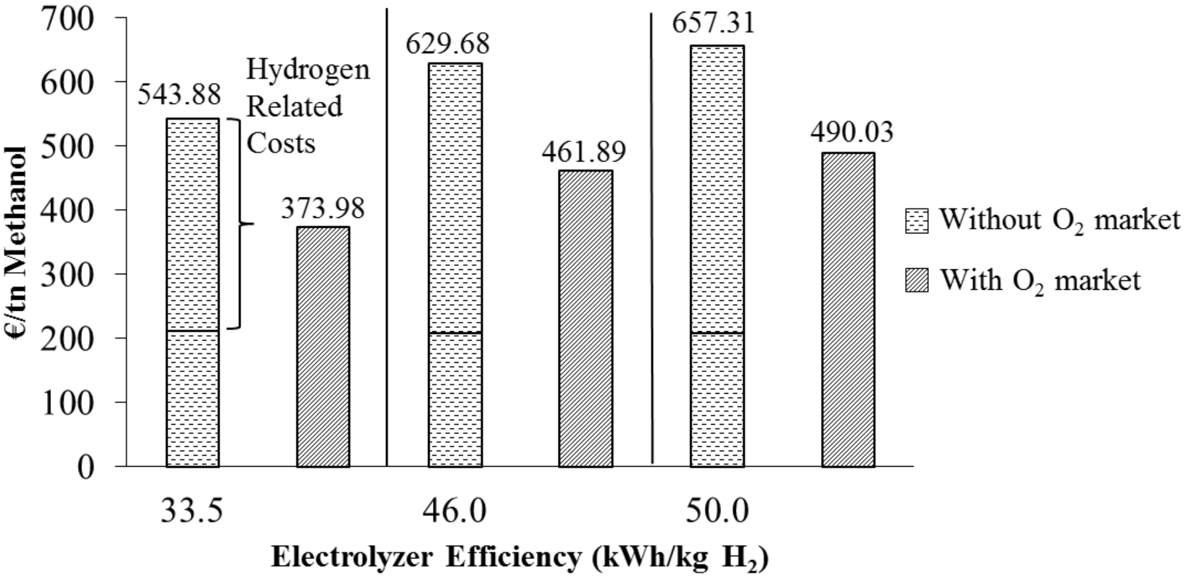

Fig.6.The impact of the electrolyzer efficiency on the total methanol cost.

Between the current and the future scenario 6% cost reduction is calculated, whereas for the current and ideal scenarios the decrease reaches 24%. Hence, the increase of the electrolyzer efficiency offers further mitigation of the total methanol cost, aiding the promotion of the scheme.

In what concerns the breakdown cost, in the basic scenario, 68% of the total cost came from Hydrogen Related Costs, whereas for the future and ideal efficiency the percentage falls slightly to 67% and 61%, respectively.

3.3.4. Cost of CO_2 for capture and transport

Finally, the sensitivity analysis is performed for the CO_2 cost. For the basic scenario, a cost of 25€/tnCO_2 was assumed. However, this cost varies depending on the transportation type and distance, the capture technology chosen and the CO_2 carbon price. Hence the CO_2 cost varies within a range of 0-40 €/tnCO_2, as depicted in Fig.7.

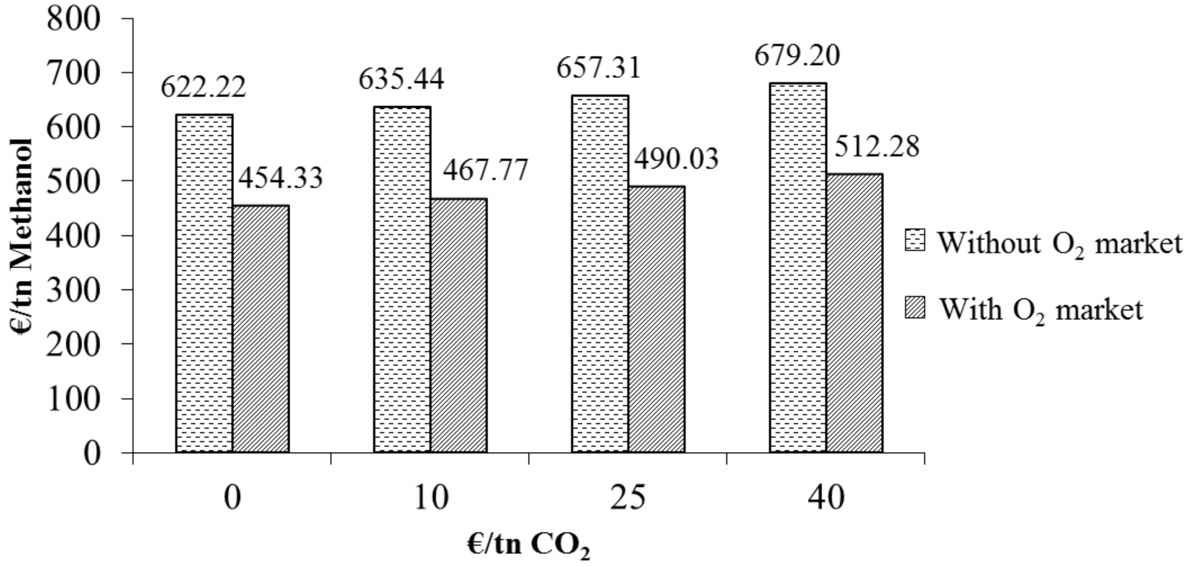

Fig.7.The impact of the CO_2 cost on the total methanol cost.

As illustrated in Fig.7 the total methanol cost for the 40€/tnCO_2 scenario, is only 5% higher than the basic scenario. Hence, notable future increase from the CO_2 cost assumed for this study would not have significant influence on the total cost. This aspect makes CO_2 a less important parameter in terms of economic feasibility of the concept, compared to the other parameters investigated.

4. Conclusions

In this study the economic evaluation and cost breakdown of the Power to Methanol scheme were performed, by indicating the contribution of each component on the final methanol production cost. Regarding the basic scenario of 71.48MW_{th} methanol capacity, the cost breakdown analysis concluded that the hydrogen production cost is the main cost contributor in the process, with 68% contribution. The methanol capital related costs also had notable contribution on the final cost with 16%. The selling of O_2 by-product, produced during water electrolysis offers a cost mitigation of 25%, making the concept more competitive. Without the selling of O_2 the process became highly unprofitable. In the Cash Flow Analysis performed, the minimum production cost of methanol for a marginally feasible investment was estimated. The total methanol cost was calculated at 490.03€/tn, which was 31% more expensive than the current methanol selling price from conventional production routes (339€/tn), indicating the need for further cost reduction.

Different scales were examined, leading to the conclusion that for larger capacities the PtF process becomes more competitive against conventional production routes. For the largest scale examined the total cost was16% lower than the base case. For the highest value of electricity cost investigated (30€/MWh), the total cost reached 719.93€/tn, making the process unable to compete with conventional production routes. The electrolyzer efficiency was also examined, resulting up to 24% cost mitigation, for 100% efficiency. Furthermore, the CO_2 cost proved to be a less important factor for the total cost reduction.

Apart from the parameters examined for the purposes of this study, a more thorough evaluation of the methanol capital costs would be of interest, due to their significant cost contribution. The Capacity Factor (CF) of the electrolysis and methanol plants should also be further investigated, since a change on the CF affects the capital and operational expenditures, as well as the electricity cost.

Finally, this study concludes that with low cost electricity, larger scales and the selling of O_2, the Power to Methanol scheme may be able to compete with conventional methanol production routes while offering reduction of the CO_2 emissions and a more environmentally friendly production route for methanol.

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