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Economic analysis of power & CO_2-to-methanol systems for the abatement of CO_2 emissions from an industrial plant

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Abstract

In this work, a Power & CO_2-to-MeOH system is assessed, aimed at cutting CO_2 emissions from a large-scale stationary source such as a cement plant. The assessed system comprises a cement plant with CO_2 capture, a wind park for renewable power generation, a connection with the electric grid for electricity exchange, an electrolysis unit, the methanol plant and the final use of the methanol (which can be used either as a fuel or as a platform chemical). In addition, the system also includes hydrogen and CO_2 storage units, to deal with the time mismatch between the intermittent renewable power generation and the continuous CO_2 production from the cement plant with carbon capture.
For each assessed scenario, the economic optimal size of wind park, electrolysis system and H_2 storage with the constrain of converting the entire amount of captured CO_2 is calculated. With the adopted assumptions that exclude CO_2 capture from conventional methanol production, the results show that CCU allows achieving the highest CO_2 emission reduction, while the CCS scenarios achieve the lowest costs. The breakeven carbon tax for the CCS scenario is about 49 €/t_{CO2}. For the CCU scenarios to match the Reference Scenario without capture, the carbon tax should increase up to around 150-160 €/t_{CO2} in the chemical industry case and 320-330 €/t_{CO2} in the mobility case.

Keywords: CCUS; CCU; CO_2 utilization; Methanol.

1. Introduction

Although CO_2 capture and storage (CCS) is a technically and economically viable option for the reduction of CO_2 emissions from industrial sources, the deployment of CCS projects may be blocked in some world regions by the lack of infrastructures for CO_2 transport and storage and by the poor social acceptance. In this context, carbon capture and utilization (CCU) represents an alternative to CCS, since the captured CO_2 is used as raw material for other processes, avoiding the need of CO_2 geologic storage. Also, in many cases, CCU would allow decarbonizing both the industry where CO_2 is captured from and the industry where CO_2 is used, with an estimated overall decarbonization potential of 3.5 Gt/y [1].

Different CCU applications can convert CO_2 into a variety of products, including chemicals (ethanol, methane, formic acid, methanol, etc.), materials, or fuels. Methanol (MeOH) is one of the main target products thanks to the multiplicity of uses: energy storage, fuel, or base product for the synthesis of chemicals or materials [2].

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Nomenclature

BEV	battery electric vehicle
CCS	carbon capture and storage
CCU	carbon capture and utilization
GHG	greenhouse gas
ICEV	internal combustion engine vehicle
LCA	life-cycle assessment
LHV	lower heating value
MeOH	methanol

Subscripts

cem	cement
el	electric

Previous studies have assessed the techno-economic performance of Power&CO_2-to-MeOH plants [2–4] and have highlighted the importance of a systemic approach based on life cycle assessment (LCA), to compare CCU systems with alternative CO_2 mitigation options [5–7]. All studies agree that the high energy demand is the main drawback of the CO_2-to-methanol process, so there is the need of further investigation: deeper analyses on the electrical energy source should be performed and solutions should be introduced that allow to reduce the size of the capital-intensive components.

In this work, a Power&CO_2-to-MeOH system is assessed, which aims at cutting CO_2 emissions from a large-scale stationary source such as a cement plant. In addition to the cement plant equipped with CO_2 capture, the investigated system comprises a wind park for renewable power generation, a connection with the electric grid, an electrolysis unit and the methanol plant fed with CO_2 and H_2. The final use of methanol can be either as a fuel in mobility or as a platform chemical. The analysis studies also the effects of including hydrogen and CO_2 storage units, to deal with the time mismatch between the intermittent renewable power generation and the continuous CO_2 availability from carbon capture in the cement plant.

The scope is to study the economic and environmental feasibility of the overall CCU process, evaluating the annual operation, with a hourly resolution. Its validity is compared to a baseline alternative that does not include any mitigation action and to a system that simply introduces CCS on the cement plant. The innovative contributions are the adoption of a life-cycle analysis (LCA) approach, the introduction of H_2 and CO_2 storage systems to manage the intermittent energy source, and the comparison of two options for MeOH use: as a fuel and as a chemical feedstock.

2. Methods

The considered system is composed of multiple plants, whose capacities and operations are evaluated in the study in order to assess the CO_2 mitigation potential and the economic feasibility of different configurations. The system is modelled in terms of mass and energy flows and its operation is simulated on an annual basis, with an hour-by-hour calculation approach that considers the variability of the wind speed in a selected location in northern Europe and of the grid electricity price and carbon intensity in the same area. A scheme of the overall assessed system is depicted in Fig. 1.

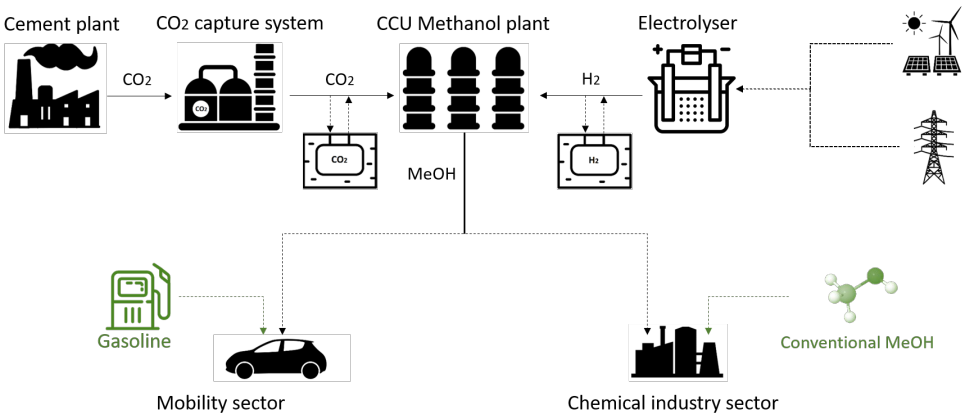

Fig. 1. Scheme of the overall system, comprising all plants and the two options of final use.

The analysis focuses on 4 scenarios: Reference, CCS, CCU-wind and CCU-storage. Each scenario is assessed considering two different uses of the produced methanol: feedstock for the chemical industry or mobility fuel.

The Reference scenario does not introduce any solution for the reduction of CO_2 emissions and therefore the system is composed exclusively of the cement plant without CO_2 capture and the conventional pathways of methanol production from natural gas in the chemical industry case or oil-refined gasoline for internal combustion engine vehicles (ICEVs) in the mobility case.

The CCS scenario adds an oxyfuel CO_2 capture system to the overall scheme. In the mobility case, the CCS scenario considers both gasoline-fueled ICEVs and battery electric vehicles (BEVs).

In the CCU scenarios, a CCU methanol production plant converts the entire amount of captured CO_2 into MeOH, through reaction with H_2 from the electrolysis system. These scenarios feature alternative ways to power the electrolyzer, using grid electricity with the time-specific source mix and/or dedicated power generation from a renewable plant, which is assumed to be a wind park, with or without a hydrogen storage system to balance the intermittent generation. The produced methanol is assumed to replace conventional NG-based methanol in the chemical industry cases or to power passenger cars in the mobility cases.

The introduction of an intermittent energy source makes the electrolyzer produce a variable quantity of hydrogen, according to the hourly available electricity from the wind park. As a consequence, the calculations of the CCU and CCUS scenarios require the implementation of hourly simulations that track electricity availability and energy flow balances. These simulations employ an optimization algorithm, in which the electrolyzer nominal capacity, the wind park rated power, and the hydrogen storage capacity are the three optimization variables.

2.1. Data and assumptions

The main technical assumptions regarding mass and energy balances of the plants that compose the assessed system are summarized in Table 1. For the conventional cement plant, the state-of-the-art baseline case of the Horizon2020 CEMCAP project is considered, which produces 1.36 million tons of cement per year, while consuming 97 kWh_{el}/t_{cem} and emitting nearly 626 kg_{CO2}/t_{cem} [8]. The retrofit oxyfuel CCS system has 90% capture efficiency and adds a consumption of 100.9 kWh_{el}/t_{cem} [8]. In the CCS scenario, the mobility case featuring BEVs assumes that the on-board battery has a capacity of 35.8 kWh. In the CCU scenarios, the calculations assume the conversion of the entire amount of CO_2 captured by the oxyfuel cement plant in one year (765 kt/y), corresponding to a methanol production of 546 kt/y, which is subsequently used in either the chemical industry or the mobility sector. The CCU methanol plant data are derived from literature studies [4,9]. Electrolysis system efficiency reflects current values of proton exchange membrane (PEM) devices, which are the most suitable to frequent load variations, and the value is assumed to include also compression for subsequent storage or delivery [10].

Table 1. Main technical data of the system components.

Component	Parameter	Value	Unit	Reference
Conventional methanol production	Natural gas feed	33.40	2 GJ/t_{MeOH}	[4]
	Direct CO_2 emissions	0.47	kg_{CO2}/kg_{MeOH}	[9]
	Electricity consumption	64	kWh_{el}/t_{MeOH}	[9]
CCU methanol plant	H_2/CO_2 ratio	3	mol_{H2}/mol_{CO2}	[4]
	CO_2/MeOH ratio	1.40	t_{CO2}/t_{MeOH}	[4]
	Direct CO_2 emissions	0.03	t_{CO2}/t_{MeOH}	[4]
	CO_2 conversion efficiency	98	%	[4]
	Electricity consumption	0.15	kWh_{el}/kg_{MeOH}	[4]
Electrolysis system	Electricity consumption	52.4	MWh_{el}/t_{H2}	[10]

To attain consistent comparisons, the analyses assume that the methanol from the Power&CO_2-to-MeOH is used to replace the same or a different fuel, with the guarantee to satisfy the same final service or effect. In the chemical industry cases, a fixed amount of MeOH is to be provided. Therefore, if the CCU methanol plant production is absent or insufficient, any residual amount is provided by a conventional NG-based process (see Table 1). The mobility cases maintain the annual mileage when varying the vehicle type and fueling mode, considering 2930 million km per year, which is the distance that passenger cars would cover if powered by the MeOH produced from the entire captured CO_2 via the CCU methanol plant (MeOH use in ICEVs assumes the same energy efficiency on LHV basis of a gasoline-fed ICEV). The conventional methanol feed to the chemical industry and the conventional energy vectors to the cars (gasoline for ICEVs or electricity for BEVs) are accounted for with the corresponding costs and LCA-based CO_2 emissions.

The model accounts for both capital and operational costs. Capital costs are computed with an exponential law, considering reference costs, capacity and scale factors reported in Table 2.

In order to obtain reliable results of global CO_2 emissions reduction, LCA data are used, while hourly and site-specific data allow to implement an effective model for the economic analysis. Grid emission factors are evaluated considering the actual time series of electricity generation shares in Germany in the selected year, whereas hourly wind speed data are used to calculate the renewable electricity generation, considering available time series for Bremen, Germany [11]. The reference year for the time series is 2018.

Table 2. Investment cost data.

Component	Ref. cost	Ref. capacity	Scale factor	Reference
Conventional methanol plant	7410 k€/(t_{MeOH}/h)	50 t_{MeOH}/h	0.65	[4]
CO_2 capture retrofit on cement plant	128 €/(t_{clk}/y)	1 Mt_{clk}/y	-	[12]
CCU methanol plant	3609 k€/(t_{MeOH}/h)	55 t_{MeOH}/h	0.65	[4]
Electrolysis system	1200 €/kW_{el}	1 MW_{el}	0.85	[13]
Wind turbine	1100 kW_{nom}	10 MW_{nom}	-	[14]
Hydrogen storage (underground, salt cavern)	60 €/m^3	1 million m^3	-	[15]

3. Results

3.1. System operation: CCU-wind scenario

In the CCU-wind Scenario, methanol is produced from CO_2 captured in the cement plant and H_2 supplied by a PEM electrolyzer that is powered exclusively by a dedicated wind park. The hourly generation of the wind park depends on wind speed and, according to the combination of nominal capacities, can be entirely or partially exploited.

Hydrogen production follows the same trend of the electricity absorbed by the electrolyzer. Given that the annual amount of captured CO_2 corresponds to the quantity needed for methanol production (CO_2 losses are assumed negligible), the hourly use in the methanol plant depends on the hydrogen availability and, to manage the imbalances, a temporary CO_2 storage is introduced, which operates following these criteria:

- at any given hour, if the amount of CO_2 requested for a complete reaction with the available hydrogen is lower than the captured CO_2 quantity, the exceeding amount is sent to the storage;
- at any given hour, if the amount of CO_2 requested for a complete reaction with the available hydrogen is higher than the captured CO_2, the additional amount is taken from storage;
- the storage content at the beginning of the year must be equal to that at the end of the year.

The left chart in Fig. 2 illustrates a one week-long example of the CO_2 storage operation. In the first period, the CO_2 storage is filled due to the low electricity generation by the wind park (see Fig. 2-right) and the subsequent limit on hydrogen production, whereas it is emptied in the second period, when wind generation is high. Indeed, the power output of the wind park is even in excess of the electrolyzer capacity, as shown by the plateau of CO_2 flow from the CO_2 storage in the left chart of Fig. 2 and by the red areas of lost electricity in the right chart of Fig. 2.

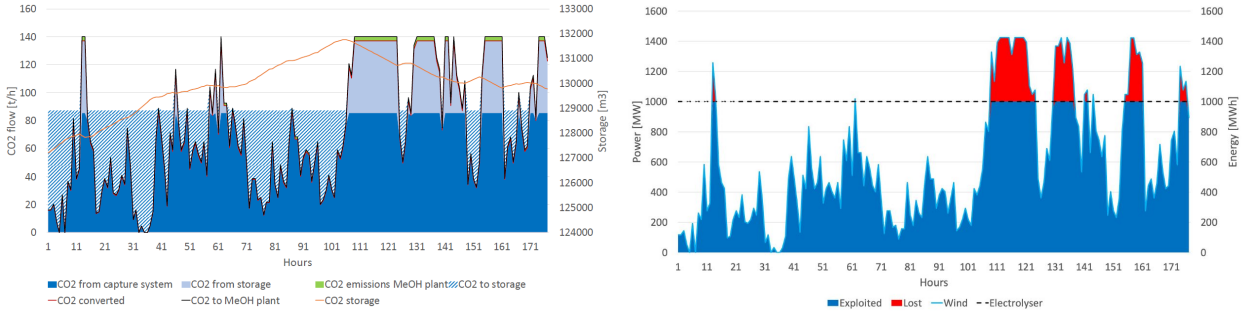

Fig. 2. One week-long example of CO_2 storage operation (left) and of electricity flows (right) in the CCU-wind scenario (electrolyzer 1.0 GW_{el}, wind 1.5 GW_{nom}).

3.2. System operation: CCU-storage scenario

In the CCU-storage scenario, a hydrogen storage is introduced and the electrolyzer is powered by a combination of wind park power generation and grid electricity, the latter constrained by price and associated CO_2 emissions. A CO_2 storage system is also present.

The hydrogen storage allows to accumulate the portion of hydrogen that can be produced but cannot instantaneously react in the CCU methanol plant due to CO_2 limitations. Respecting the constraints on available capacity (stored hydrogen content) and maximum withdrawal rate (10% of capacity per day), at any given hour, the storage operates with the following approach:

- if the hourly H_2 production exceeds the request by the methanol plant, the cavern is filled by the minimum between the surplus production and the maximum flow rate, up to the storage capacity;
- if the hourly H_2 production is lower than the request by the methanol plant, an amount of hydrogen is extracted from the cavern, equal to the minimum between the available stored content, the missing portion of CCU plant demand, and the maximum flow rate.

Moreover, the withdrawal of hydrogen encounters losses for the transfer of the fluid, which are evaluated by means of a storage efficiency (98%).

A one week-long example of the operation principle of the system is shown in Fig. 3, for a given sizes of the wind park, of the electrolysis unit, of the hydrogen storage system, and of the MeOH production plant. MeOH is produced with the variable hydrogen from the electrolysis unit that absorbs wind power (blue area) or grid power when the electricity price is sufficiently low (yellow area) or from the H_2 storage unit (green area). When hydrogen production exceeds the hydrogen demand of the MeOH plant, the surplus hydrogen is stored (light blue area) for later use, up to the storage capacity. Wind power and the corresponding potential hydrogen production may also be lost due to hydrogen storage system limitation (red area) or due to the electrolysis system capacity (light blue dashed area). The interaction between all these will drive the identification of the optimal sizing of the different plants.

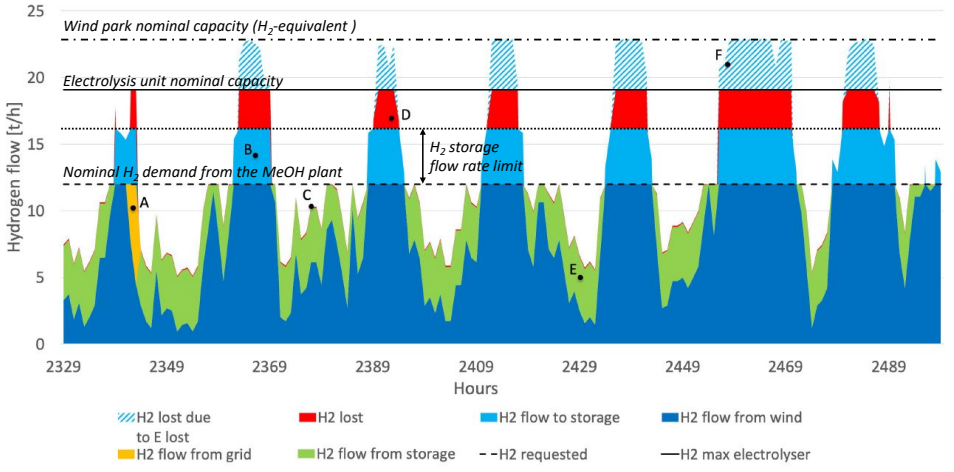

Fig. 3. One week-long example of system operation in the CCU-storage scenario (electrolyzer 1.0 GW_{el}, H2 storage 1000 t_{H2}, wind 1.26 GW_{nom}).

3.3. System optimization

The scenarios in which the electrolysis unit is powered both by the grid and by the wind park require the development of an optimization procedure to properly size the plants in order to maximize the economic advantage. In particular, the optimization variables are: (i) the installed wind park nominal power output, (ii) the electrolysis unit rated capacity, and (iii) the hydrogen storage capacity. Here, the purpose of the model is to utilize in the CCU methanol plant the entire amount of captured CO_2. Based on the conversion efficiency, the maximum converted amount is 749.7 kt/y. The CO_2 storage capacity is assumed unlimited for the calculations and the required size is evaluated afterwards.

First, the model behavior is assessed with a parametric analysis on the optimization variables. The effect of different sizing of the system units is represented in Fig. 4, which shows the amount of converted CO_2 as a function of the wind park installed capacity (x-axis), of the electrolyzer rater power (three options, identified by different colors), and of the hydrogen storage capacity (two options, identified by different line patterns). In all cases, the amount of converted CO_2 increases with the wind capacity, due to the growth in hydrogen production from the renewable electricity, up to the plateau given by the CO_2 availability from the cement plant. At a given P_{wind} value, the amount of CO_2 converted always increases when either the electrolyzer or the hydrogen storage capacity grows.

At low wind park capacity (P_{wind} on the x-axis), the curves show a linear trend with an identical slope; the distance between them is related to the slight increased hydrogen production when accommodating more electricity (larger electrolyzer) or improving hydrogen management (larger H_2 storage). With small electrolyzers, the linear trend ends near the point where the wind park rated output overcomes the electrolyzer capacity and the subsequent gain is possible thank to increased wind generation, at the expense of wind electricity surplus. With large electrolyzers and small

hydrogen storage, the stop occurs earlier due to storage limitation; indeed, the linear trend extends with larger storage capacity (dashed lines).

In presence of the smallest electrolyzer size, it is never possible to convert the entire quantity of CO_2; indeed, even assuming to operate the electrolyzer for 8760 operating hours, the produced amount of hydrogen would be 83.6 kt_{H2}/y, which could only react with 445.8 kt/y of CO_2 (about 60% of the reference quantity). On the opposite, with the larger electrolyzer sizes (1000 MW_{el} or 1400 MW_{el}), the reference converted CO_2 could be reached. Moreover, the larger the electrolyzer nominal power, the lower the wind park rated capacity at which such reference is met, thanks to an improved exploitation of the intermittent electricity.

With a small hydrogen storage (1000 t_{H2}), the increase in electrolyzer size has no effect, as shown by the red solid line overlapping the yellow solid one. With a large hydrogen storage capacity (6000 t_{H2}), instead, a little influence of the electrolysis capacity exists (red dotted line vs. yellow dotted one).

In conclusion, the increase of each of the three optimization variables leads to an increase in the amount of CO_2 converted, with different impacts on costs.

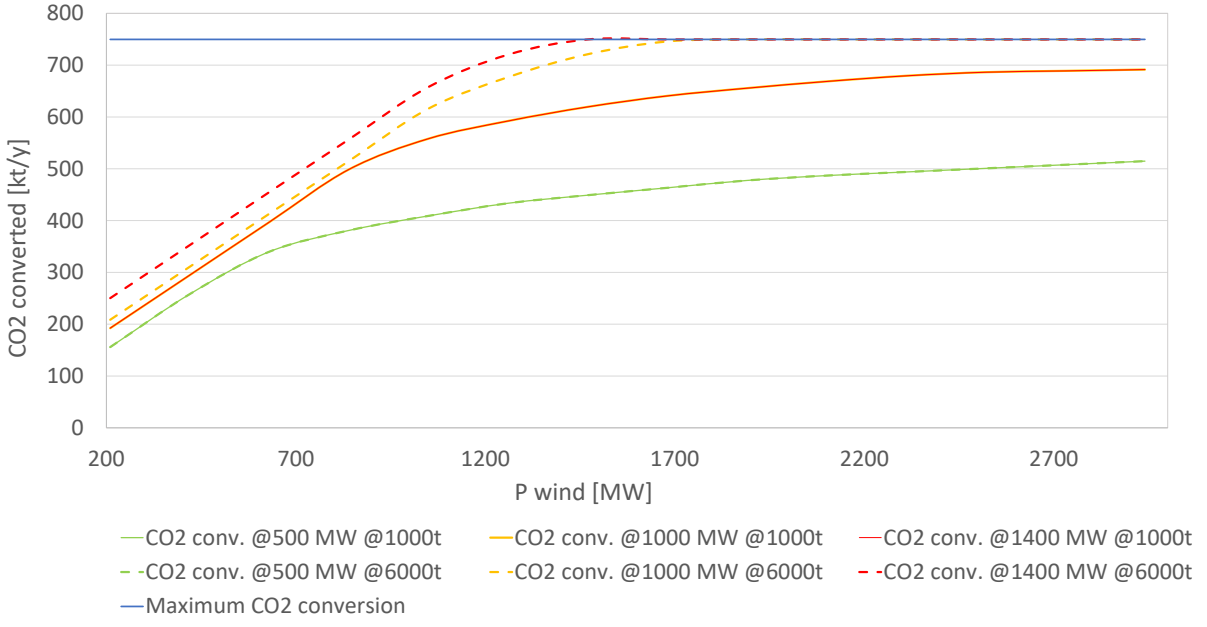

Fig 4. Converted CO_2 as a function of wind installed power, at varying electrolyzer capacity and hydrogen storage capacity.

3.4. Comparison of optimized scenarios

For each proposed scenario, the economic optimal size of wind park, electrolysis system and H_2 storage, with the constraint of converting the entire amount of captured CO_2 is calculated, in both the chemical industry case and the mobility case. From an environmental point of view, it emerges that all solutions reduce CO_2 emissions with respect to the Reference Scenario and that in most cases CO_2 utilization contribute to reduce emissions into the atmosphere, as long as renewable electricity is used to power the electrolyzer. The results can be observed in Fig. 5.

CCU scenarios using part or all renewable energy to feed the electrolyzer give an advantage in terms of emissions in the chemical industry cases. This is due to the fact that the introduction of a CO_2-to-methanol process allows a drop in direct MeOH plant emissions, thanks to the absence of steam reforming. It must be highlighted that this results from the assumption of not considering CO_2 capture from the conventional methanol plant in the CCS scenario. Among the mobility cases, the Reference scenario is the most emitting configuration, since no mitigation actions are adopted. CCU alternatives are not always the best choice from an environmental perspective: comparing CCU-based methanol with gasoline ICEVs, direct CO_2 emissions always reduce in CCU options thanks to a cleaner combustion, whereas

total emissions slightly decrease or increase depending on the scenario. In conclusion, CCU-wind scenarios are always the best solution for CO_2 emissions mitigation both in the chemical industry, showing a 45% reduction from CCS scenario, and in the mobility case, with an 11% reduction if compared to CCS scenarios with gasoline alternatives. On the other hand, the CCS scenario with BEVs achieves lower emissions than the CCU-wind scenario (-20.5%). It must be noted that this result is impacted by the on-board battery energy capacity assumption, which significantly affects the life-cycle emissions of a BEV.

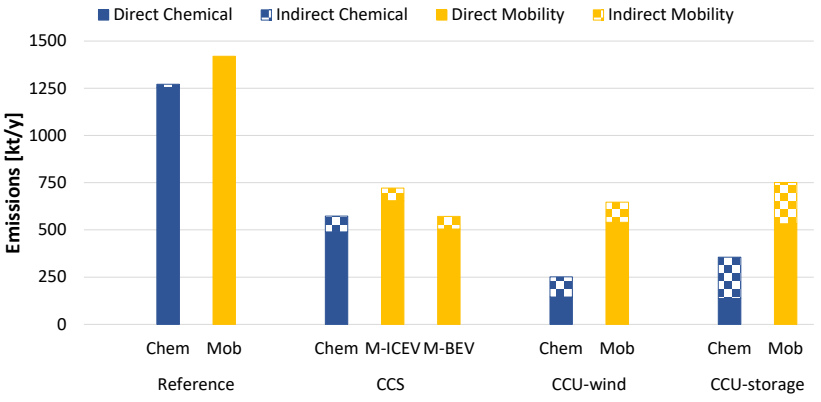

Fig. 5. CO_2 emissions from the Power&CO2-to-MeOH system in the various scenarios.

The economic evaluations consider a carbon tax of 50 €/t_{CO2} on both direct and indirect CO_2 emissions. Results are shown in Fig. 6. CCU scenarios are the most costly, while CCS scenarios feature costs close to or lower than the Reference Scenario. The higher costs of CCU scenarios are mostly due to the relevance of CAPEX for additional system components (roughly 50% wind park, 35-40% electrolysis 10-15% MeOH plant and H_2 storage). The CCU-storage scenarios are less expensive than the CCU-wind ones (-9%), thanks to: (i) a reduction of all the unit capacities that have a higher cost than the additional expenditure for the hydrogen storage and (ii) the possibility of exploiting a larger amount of grid electricity in periods of the year with low price.

In conclusion, the best option with the adopted assumptions is represented by the CCU-wind scenarios from a CO_2 emission reduction perspective, while the CCS scenarios are favored from an economic point of view.

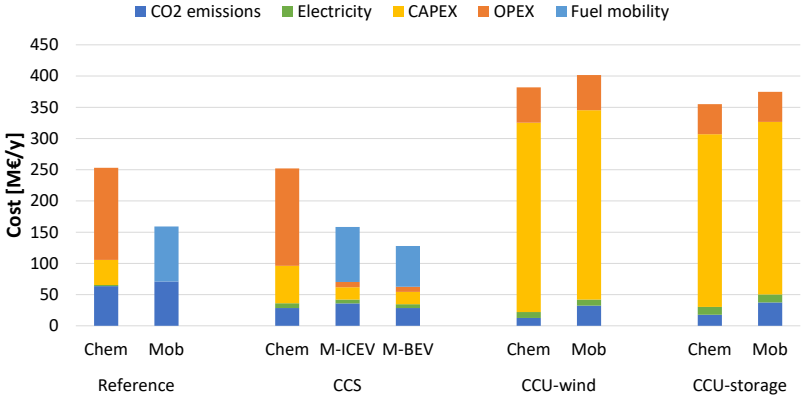

Fig. 6. Cost breakdown of the Power&CO2-to-MeOH system in the various scenarios.

3.5. Sensitivity analysis on carbon tax

As typical in CCS and CCU analyses, the results are sensitive to the assumed value of the avoided CO_2. Hence, a sensitivity analysis is performed on the carbon tax, that is varied from a low value of 20 €/t_{CO2} to very high values above 600 €/t_{CO2}. The calculations assume that the grid electricity is fully decarbonized when the carbon tax overcomes 80 €/t_{CO2}, considering that such value corresponds to the breakeven cost of carbon capture from residual fossil fuel power plants. This assumption implies that, above 80 €/t_{CO2}, indirect emissions from power consumption are zero, but the electricity price increases according to this carbon tax value multiplied by the expected grid emissions before CCS. In this analysis, the costs of CO_2 avoided corresponds to the x-axis value where the Reference Scenario curve intersects the CCS or CCU scenario curves. This is represented in Fig. 7 for the chemical industry and the mobility cases separately. The breakeven carbon tax for the CCS scenario is about 49 €/t_{CO2} for both final uses (just below the assumed carbon tax in the study, consistently with the results in Fig. 6). For the CCU scenarios to match the Reference Scenario the carbon tax should increase up to around 150-160 €/t_{CO2} in the chemical industry case and 320-330 €/t_{CO2} in the mobility case).

When using MeOH as platform chemical, if the carbon tax is between 50 and 400 €/t_{CO2}, CCS is economically preferable over CO_2 mitigation options based on CCU, whereas in case of very high carbon tax (>400 €/t_{CO2}), if electricity for H_2 production is generated by wind power, CCU systems have a lower overall cost, thanks to the CO_2 emissions saved from the conventional MeOH production plant. Again, it must be recalled that the CCS case assumed no CO_2 capture from the conventional methanol plant.

In the comparison of MeOH use for mobility against conventional fuels, CCS is always economically preferred to CCU systems in the considered range of carbon tax variation.

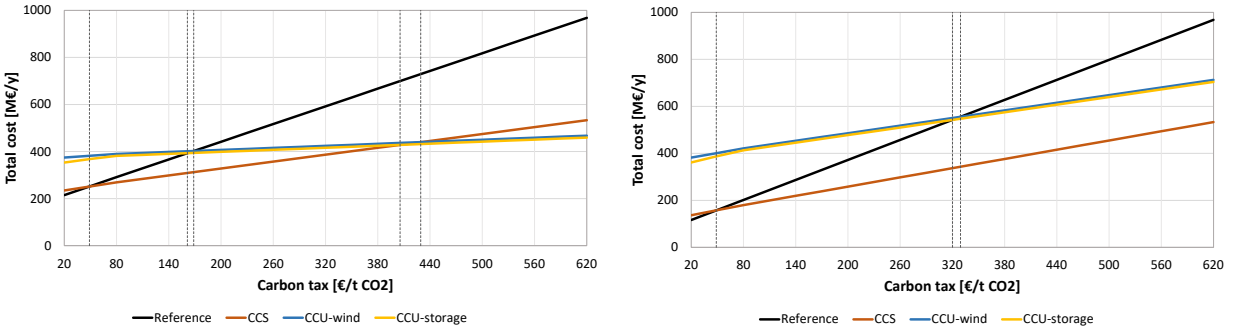

Fig. 7. Sensitivity analysis on the carbon tax: (left) chemical industry case; (right) mobility case.

4. Conclusions

In this work, a Power&CO_2-to-MeOH system has been assessed. An economic optimization has been carried out, aiming to find the economic optimal sizes of the wind park, of the electrolysis unit, and of the H_2 storage unit that minimize the overall system costs. The results for the optimized CCU systems in different scenarios are compared with the total system costs of a reference case (i.e., without CO_2 capture) and of a CCS case, also assessing the impact of different carbon tax values.

The main findings are summarized in the following list:

- In the chemical industry case, the CCU scenarios have lower emissions than the CCS scenario, thanks to the removal of a NG-based process without CO_2 capture.
- In the mobility case, total CO_2 emissions are lower in the CCU scenario than in the CCS configuration, due to avoided emissions in the fuel supply chain as well as lower carbon intensity of the fuel itself (MeOH: 69.0 kg_{CO2}/GJ vs. gasoline: 71.5 kg_{CO2}/GJ).
- Hydrogen storage has little impact on the system: slightly beneficial in terms of emissions thanks to an improved management of energy flows, but slightly detrimental on costs due to the additional element.

- In the chemical industry case, the CCS scenario is the most competitive for a wide range of carbon tax (50-400 €/t_{CO2}), without considering any CO_2 mitigation on the conventional MeOH plant, whereas CCU scenarios become advantageous over the reference scenario for carbon tax close to 150-160 €/t_{CO2} and over the CCS scenario for a very high carbon tax (above 400 €/t_{CO2}).
- In the mobility case, the use of CCU-derived MeOH to replace conventional gasoline shows very little competitiveness over both the reference scenario (carbo tax >300 €/t_{CO2}) and the CCS scenario (breakeven not reached with 600 €/t_{CO2}).

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