The economics of possible CO_2 utilization pathways in a highly decarbonized European energy system

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***Abstract*—To meet ambitious climate protection targets, European greenhouse gas emissions need to be reduced to net zero by 2050. Even under these circumstances, there remain processes in industry, transport, or power and heat supply that require CO_2 as a feedstock or emit CO_2 as flue gas. In this paper, we characterize the physical and economic interrelations of the emerging CO_2 economy. We find that direct air capture processes for CO_2 become essential. We furthermore show that the use of natural gas remains economically more feasible than the use of synthetic fuels if long-term carbon storages are available.**

***Index Terms*--Carbon capture and storage, Carbon economics, Direct air capture, Power-to-gas, CO_2 economy**

I. Introduction

To limit the global temperature increase to preferably below 1.5 °C as stated in the Paris Agreement, anthropogenic CO_2 emissions need to be reduced substantially [1]. In many cases, energy efficiency measures and substituting fossil fuels with renewable energy sources are technically and economically feasible decarbonization strategies. Nonetheless, there remain processes for which carbon neutral alternatives are scarce, little researched or costly: For the provision of heat, for certain industrial processes such as cement production and for transport applications in sea, air and heavy freight road transport, there is currently no dominant strategy for complete CO_2 abatement [2].

Since article 4 of the Paris agreement calls for *net zero emissions* by 2050, alternative CO_2 reduction or compensation strategies for these processes need to be evaluated. Although biofuels can be a carbon neutral alternative in many cases, competition for available land with food production limits their potential. Therefore, the options of Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) are gaining increased attention in the scientific and political debate.

The basic concept of CCS is to capture CO_2 from flue gas streams or ambient air and to subsequently store it underground [3]. Depleted oil and natural gas fields or saline aquifers are suitable storage reservoirs to separate CO_2 from the atmosphere permanently. In case the captured and stored CO_2 originates from a biogenic source (BECCS) or the ambient air (DACCS), this technology can even generate 'negative emissions' [4].

CCU refers to the utilization of CO_2 as a feedstock. The rational is to use captured CO_2 to cover carbon demands currently met by fossil sources. However, this procedure is only climate-neutral if the captured and utilized CO_2 originates from a non-fossil source. The utilization of synthetic fuels dominates the current public discussion on CCU. Here, electrolytic hydrogen is synthesized with captured CO_2 to methane (power-to-gas (PtG)) or liquid hydrocarbons (power-to-liquid (PtL)). These synthetic energy carriers are able to substitute their fossil equivalents in industry, transport and power and heat supply. In some industrial synthesis processes, captured CO_2 can directly serve as a carbon source, too [5]-[7].

If either CCU or CCS is used, physical CO_2 flows persist even in a highly decarbonized economic system. Under the general objective of CO_2 avoidance, CO_2 plays an ambiguous role: While it is regarded as waste in the case of CCS, CO_2 is used as a feedstock in CCU. In consequence, a new economic sector emerges: A CO_2 economy [8]. This paper focuses on a systematization of possible CO_2 flows and their economic evaluation in a highly decarbonized economy in the European Union (EU) in 2050.

II. Characteriazation of a CO_2 Economy

Even assuming that the 1.5 °C target is reached, carbon-based fuels might remain used in industry, transport and power and heat supply [2]. This section outlines a simplified system for meeting the carbon demands in these sectors, presuming that net zero emissions will be achieved. The full system is shown in Fig. 1. In order to systematize the possible physical carbon flows, we first categorize the occurring carbon demands into three groups. Subsequently, four principal routes are developed to cover these demands. The identification of these routes is the basis for a cost-based assessment of this CO_2 economy.

A. Carbon-based energy and feedstock demands

In principle, there are two types of carbon utilization. Firstly, in industry, transport and power and heat supply, carbon-containing fuels are used as energy sources due to their high volumetric energy density. Secondly, in industry, the carbon content of these substances itself is required as a feedstock.

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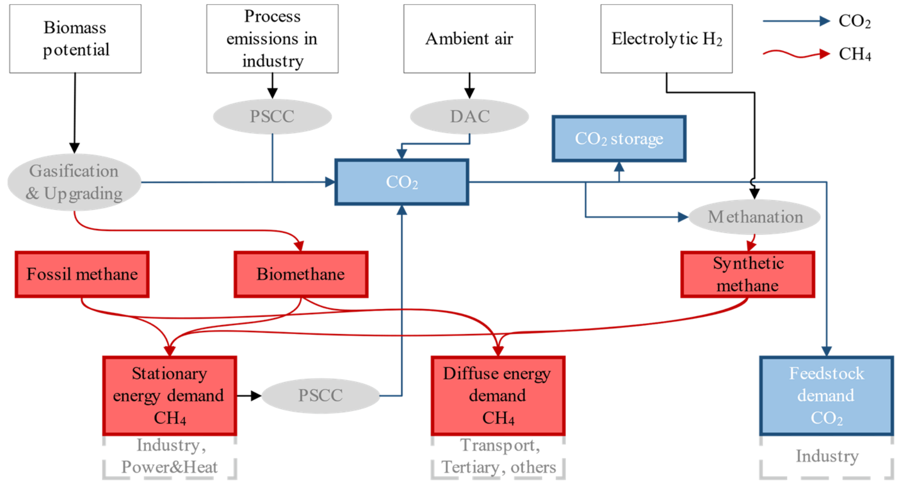

Figure 1. Visualization of a simplified CO_2 economy.

Since CO_2 may have to be captured from flue gas streams to achieve the climate protection targets, it is expedient to subdivide the energetic utilization of carbon-based fuels based on the local concentration of CO_2 emissions: While industry causes strongly localized CO_2 emissions, emissions from transport are diffuse. Although carbon-based fuels are used in different forms - gaseous, liquid, solid - in the different applications of these sectors, we assume in the following analysis that energy demanding processes can be equipped with the gaseous energy carrier methane. Non-energetic carbon demands are assumed to be met with gaseous CO_2 as a feedstock instead. For our analysis, we distinguish between three types of carbon-related demands that are representative of the overall system:

- Stationary demand for methane as an energy carrier in industry and power and heat supply.
- Diffuse demand for methane as an energy carrier in the transport and tertiary sector.
- Direct CO_2 demand as a carbon feedstock in the industry sector.

B. *Possible methane and CO_2 supply routes*

These three carbon-based demands can be met by four principal supply routes: The stationary and diffuse demands for methane as an energy carrier can be met by fossil methane (route 1), biomethane (route 2), or synthetic methane (route 3). Depending on which of these three routes is utilized, carbon capture techniques or storages must be employed to achieve net zero emissions. Industrial feedstock demands are met by a pooled CO_2 stream (route 4), which is fed by direct air capture (DAC), point source carbon capture (PSCC) in bio-methane production, PSCC from stationary flue gases when using methane as an energy carrier, and PSCC from process emissions in industry.

Under the premise that net zero emissions must be achieved, the different routes entail different costs to cover the demands. In order to be able to compare the different routes and to determine economically dominant supply strategies, a cost equation is developed for each of the routes below.

1) *Fossil methane route*

The fossil methane route comprises the following stages:

- Fossil methane needs to be purchased at cost c_{FM} on the market.
- The use of fossil methane causes emissions that must be offset. There are three possible offset methods: Firstly, CO_2 can be captured from the flue gas stream at costs c_{PSCC} in stationary applications. Secondly, CO_2 can be captured from ambient air at costs c_{DAC}. Thirdly, if the fossil methane route and the biomethane route are applied at the same time, the CO_2 resulting from biogas upgrading can be captured at costs c_{UP}. The cheapest available offset method is applied.
- The captured CO_2 is stored in an underground storage at costs c_S.

The marginal cost of methane MC_{fossil} (EUR/MWh) in the fossil methane route result to

$$MC_{fossil} = c_{FM} + \min\{c_{DAC}, c_{UP}, c_{PSCC}\} + c_S. \tag{1}$$

2) *Biomethane route*

The biomethane route comprises the following stage:

- Biomass needs to be purchased at cost c_{BM} on the market, gasified and upgraded at costs c_{GASI}.

The marginal cost of methane $MC_{biogenic}$ (EUR/MWh) in the biomethane route result to

$$MC_{biogenic} = c_{BM} + c_{GASI} \tag{2}$$

3) *Synthetic methane route*

The synthetic methane route comprises the following stages:

- Hydrogen and balance-neutral CO_2 are required to produce synthetic methane. Hydrogen is provided at costs c_{ELEC} by electrolysis. The CO_2 feedstock must be provided by the same sources as on the fossil methane route.

- The synthesis of hydrogen and CO_2 to synthetic methane causes costs of c_{METH}.

The marginal cost of methane $MC_{synthetic}$ (EUR/MWh) in the synthetic methane route result to

$$MC_{synthetic} = c_{ELEC} + c_{METH} + \min\{c_{DAC}, c_{UP}, c_{PSCC}\}. \quad (3)$$

4) CO_2 feedstock route

The CO_2 feedstock route comprises the following stage:

- The CO_2 feedstock must be provided by the same sources discussed in the offsetting of the fossil methane route.

The marginal cost of CO_2 MC_{CO2} (EUR/t) in the CO_2 feedstock route result with the specific emissions of methane $specEm_{CH4}$ to

$$MC_{CO2} = \frac{1}{specEm_{CH4}} \times \min\{c_{DAC}, c_{UP}, c_{PSCC}\}. \quad (4)$$

III. Demands, potentials and technologies

In this section, the underlying data for the economic analysis is summarized. We describe the derivation of the methane demand and the CO_2 feedstock based on third party studies, present the available renewable and storage potentials, and characterize the relevant technologies.

A. Demands

1) Energetic methane and carbon demands

For 2050 we assume a total carbon-based energy consumption of about 4,160 TWh in the European Union. The number is derived from the analysis "A Clean Planet for all" published by the European Commission using the 1.5TECH scenario [9]. This total energy demand is composed of 3,190 TWh of diffuse demand and 973 TWh of stationary demand (see Table I).

Based on the aforementioned assumption that the entire energy demand must be covered by methane, the specific emissions $specEm_{CH4}$ = 0.2 t_{CO2}/MWh translate the energy demand into a CO_2 demand. This results in a total CO_2 demand of about 866 Mt.

2) Carbon feedstock

Today, some industrial processes rely on fossil energy carriers to provide carbon feedstocks. One of these processes is the polymer synthesis in plastic production. CO_2 is expected to evolve as a resource for such processes [10]. The CO_2 is only bound for the lifetime of the manufactured product and released again later. Therefore the ecological advantage of CO_2 as a feedstock lies in the substitution of fossil-based raw materials rather than separating CO_2 from the atmosphere [11]. Fossil carbon feedstock must therefore be replaced by balance-neutral CO_2. The fossil carbon feedstock in 2050 is interpreted as the non-energetic demand for oil and methane in the 1.5TECH scenario of the EU analysis. This amounts to 1,240 TWh [9]. Using the specific emission factors of oil (0.85 t_C/t_{oil}) and methane (0.2 t_{CO2}/MWh) this figure translates into a total feedstock demand of 320 Mt_{CO2} [12].

TABLE I. Derived Energy and CO_2 Demands in Europe 2050 [9]

	Sectors		
	Feedstock demand	***Stationary energy demand***	***Diffuse energy demand***
(non-)energetic demand (TWh)	(1,240.46)	973.43	3,190.11
Maximum CO_2 demand (Mt_{CO2})	**319.32**	**194.69**	**638.02**

B. Potentials

1) Biomass potential

Biomethane can be produced by processing biomass, like energy crops, wood or waste. To do so, two conversion processes will be available in 2050: Gasification and digestion. Since gasification is expected to have a higher conversion rate (70 %) than digestion (60 %), we only focus on gasification [13]. Agricultural and forestry residuals are potential inputs for gasification (see Table II).

TABLE II. Biomass Potentials for Gasification [16], [17]

	Biomass types	
	Agriculture	***Forestry***
Potential (TWh)	1,353.06	777.50
Cost (EUR/MWh)	35	
Methane Potential (TWh)	**946.19**	**543.71**
CO_2 Upgrading Potential (Mt_{CO2})	**80.43**	**46.22**

The production of biomethane is associated with the release of large quantities of CO_2. Biogas consists of 50-75 % biomethane, 25-50 % CO_2, and minor amounts of other elements (<1 %) [14]. Assuming a biogas composition of 70 % biomethane and 30 % CO_2, it contains about 0.085 t_{CO2}/MWh ($BiogasUp$). Biogas upgrading, in which the CO_2 is separated, is necessary to use the biomethane like natural gas. Nowadays the separated CO_2 is released into the atmosphere. In 2050 it could serve as input for CCU and CCS [15]. The maximum amount of CO_2 in the EU from biogas upgrading as determined in [16] is shown in Table II.

TABLE III. CO_2 Storage Potentials [18], [19]

	CO_2 storage types			
	Saline Aquifers *Onshore*	***Saline Aquifers*** *Offshore*	***Depleted fields*** *Onshore*	***Depleted fields*** *offshore*
Potential (Mt_{CO2})	52,623	143,179	15,158	9,579
Cost (EUR/t_{CO2})	5	12	4	11

2) CO_2 storage potential

Adequate CO_2 storage capacity is required if CCS shall be available in the future. Studies are suggesting that Enhanced Oil and Gas Recovery (EOR/EGR), saline aquifers and depleted oil and gas fields could serve as storage solutions [3].

As the potential of EOR and EGR in Europe is rather small compared to others, only saline aquifers and depleted reservoirs are considered for this work [20], [18]. The potential capacities and associated costs for onshore and offshore storages are presented in Table III.

3) Renewable electricity potential

For carbon neutrality, capturing CO_2 and generating synthetic methane require renewable electric energy. In order to estimate the costs for this electrical energy, we use the renewable potential calculation of the energy system model ENERTILE [21]. Assuming that the 'regular' electricity demand of the industry, households, and others must be covered first with the available potentials, the marginal generation costs of renewable electricity available for CO_2 capture and electrolysis start at 70 EUR/MWh. Like the derived demand for methane, the 'regular' electricity demand originates from the 1.5TECH scenario in the EU analysis [9]. Therefore, we assume electricity costs of 70 €/MWh for electrolysis and CO_2 capture.

C. Technologies

1) Direct air capture (DAC)

Starting with the basic idea of capturing CO_2 from ambient air in 1999, several different technological approaches and companies evolved until today [22], [23]. Pursued approaches are adsorption, absorption, membranes or cryogenic methods [24]. Since the concentration of CO_2 in the atmosphere is very low with around 400 ppm, the separation process is very energy intensive [24], [25]. The assumed techno-economic parameters of DAC used for our analysis are summarized in Table IV.

2) Point source carbon capture (PSCC)

According to Fig. 1, we distinguish two types of point sources in a CO_2 economy. The first one occurs when methane is used stationary as an energy source. The flue gas of a gas turbine contains around 4 % CO_2 [26], [27]. Table I shows that the maximum amount of CO_2 from stationary energetic methane utilization is 202 Mt_{CO2}. With a capture efficiency of 90 %, 182 Mt_{CO2} can be harvested. The second CO_2 point source consists of inevitable process emissions from industry. E.g. only around 50 % of emissions in the cement industry can be avoided by the use of renewable energies and efficiency measures [28]. The remaining emissions must be captured from the flue gas, which contains around 25 % CO_2, and stored later [29]. Results from the EU analysis respecting the 1.5 °C target estimate maximum emissions of 75.6 Mt_{CO2} from industrial processes for 2050. Depending on the process post-, pre- and oxyfuel combustion capture are possible [30].

3) Biomass gasification and upgrading

Another localized and stationary CO_2 source occurs when upgrading biogas. During gasification, biomass is converted into methane and CO_2 by pyrolysis and partial oxidation. A conversion rate of 70 % is assumed for 2050 [13]. To obtain pure methane an upgrading process is necessary. Technical approaches to extract the CO_2 from the CH_4-CO_2 mixture are e.g. amine scrubbing, pressure swing adsorption or membrane separation [31]. Since pure methane is required a capture efficiency of 100 % is assumed.

Although there are several technical approaches for PSCC and biogas upgrading, we assume a one-fits-all capture appliance. Variable costs of these appliances depend on the CO_2 content of the flue gas. The techno-economic data can be found in Table IV and Table V.

TABLE IV. TECHNO-ECONOMIC PARAMETERS CO_2 CAPTURE [15], [32]

	CO_2 Capture			
	Capital, O&M costs *(EUR/t_{CO2})*	***Electricity demand*** *(MWh/t_{CO2})*	***Capture rate***	***Lifetime*** *(years)*
Energy PSCC	27.76[a]	0.44[b]	90 %	20
Industry PSCC		0.35[b]	90 %	20
Biogas upgrading		0.32[b]	100 %	20
DAC	28.89[a]	1.32	-	30

a. Derived from total cost per ton CO_2 deducting the energy cost from [15] or [32]
b. 8 percent points of efficiency loss for gas turbine and adjusted [33]

4) Electrolysis and methanation

Synthetic methane is synthesized with hydrogen and CO_2. Hydrogen must be produced by electrolysis using renewable electricity. The energy efficiency for electrolysis is assumed to be 82 % [15]. Methanation as an exothermal process, is assumed not to consume additional electrical energy. Based on the stoichiometric Sabatier reaction, the energetic conversion efficiency of the methanization amounts to ~83%. Further techno-economic assumptions for electrolysis and methanation are presented in Table V.

TABLE V. TECHNO-ECONOMIC PARAMETERS METHANE PRODUCTION [15], [13]

	Generation of synthetic and biogenic methane			
	Capital, O&M costs *(EUR/MWh_{CH4})*	***Full load hours***	***Energy efficiency / Conversion rate***	***Lifetime*** *(years)*
Electrolyser	50.84[a]	3,000	82 %	20
Methanation	1.33[b]	8,000	83 %	20
Gasification	18.22	8,000	70 %	30

a. Derived from total cost per MWh_{H2} deducting the energy cost
b. Derived by linear depreciation of invest and 3 %/a O&M costs as in [34]

IV. RESULTS

1) The utilization of direct air capture is inevitable

In section II we identified three different types of carbon-related demands. One of them, the direct CO_2 demand as a carbon feedstock for industrial products, requires balance neutral CO_2 inputs. The reason is that the carbon content of these products is released at the end of their life cycle. These products cannot be considered as permanent carbon storage [11]. Therefore, the only possible CO_2 sources to cover this demand are atmospheric and biogenic CO_2. While the atmospheric CO_2 potential is not restrained, there is an upper limit for biogenic CO_2. Biogenic CO_2 is obtained from biogas upgrading as well as from PSCC when using biomethane stationary. With the full utilization of the biomass potential, the upper limit consists of the maximum CO_2 amount from upgrading and the maximum amount of PSCC from stationary biomethane use. Comparing this upper limit with the feedstock demand in Fig. 2, it is evident that the potential of biogenic CO_2 is not sufficient to cover the demand. This implies that DAC is inevitably when reaching for net zero emissions.

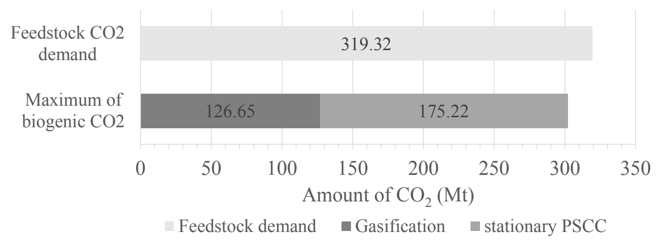

Figure 2. Comparison of biogenic CO_2 potential and feedstock demand.

2) The utilization of fossil methane and CO_2 storages dominates the utilization of synthetic methane

The insight that DAC is necessary to meet the CO_2 feedstock demand has direct implications for the methane routes (1-3) identified to meet the energetic methane demand. Result 1) implies that in a marginal cost analysis the CO_2 sources biogas upgrading (c_{UP}) and PSCC (c_{PSCC}) are unavailable for CCU and CCS applications beyond the utilization as industrial feedstock. The marginal cost formulas presented in section II can therefore be reduced as follows:

1) *Fossil methane route:*

$$MC_{fossil} = c_{FM} + c_{DAC} + c_S \quad (5)$$

2) *Synthetic methane route:*

$$MC_{synthetic} = c_{ELEC} + c_{METH} + c_{DAC} \quad (6)$$

3) *Biogenic methane route:*

$$MC_{biogenic} = c_{BM} + c_{GASI} - c_{DACsaving} \quad (7)$$

While in routes 1 and 2 only the costs c_{DAC} for capturing CO_2 remain, in route 3 the CO_2 obtained by biogas upgrading must be taken into account as a cost-reducing factor: Since CO_2 from biogas upgrading is available balance-neutral and thus reduces the use of DAC, there is a refund of the avoided DAC costs ($c_{DACsaving}$) when using the biomethane route.

In order to identify which of the three methane supply routes is economically dominant under certain conditions, we compare the revised marginal costs in Fig. 3 for different costs of fossil methane c_{FM}. Three intervals with respective dominant strategies to meet the total methane demand of 4,160 TWh (see Table II) can be derived. At fossil methane costs of up to 37 EUR/MWh, the exclusive use of fossil methane dominates. With higher fossil methane costs, the marginal costs of the fossil methane route exceed the marginal costs of the biomethane route. Therefore, from 38 EUR/MWh the biomass potential is fully utilized to cover the energetic methane demand. The remaining demand is met by fossil methane. For synthetic methane to substitute fossil methane as the dominant strategy, the c_{FM} must exceed 154 EUR/MWh (third interval).

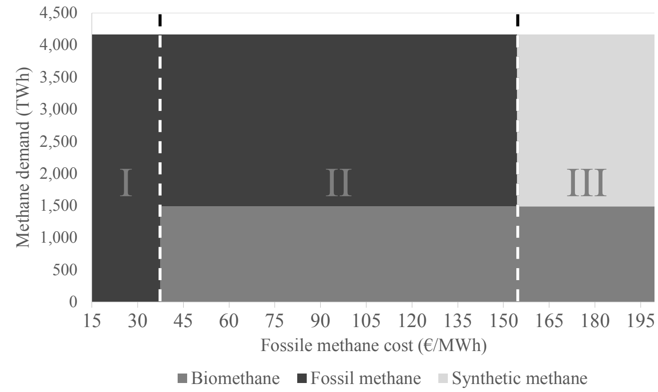

Figure 3. Visualization of optimal methane routes per cost of fossil methane.

3) Statistical range of storage use

For the statistical range of potential CO_2 storages we compare two extreme cases: The maximum amount of storage required for CO_2 in 2050 occurs if the methane demands derived in section III are met solely by fossil methane. According to Table I around 833 Mt of CO_2 need to be stored in this case. Adding industrial emissions, this results in a yearly storage amount of 909 Mt_{CO2}. Taking into account the storage parameters in Table III, this leads to a statistical storage range of more than 240 years. The minimum amount of storage required for CO_2 occurs if no fossil methane is used to cover the energetic demand (i.e. only biomethane and synthetic methane are applied). Only industrial emissions need to be stored, which results in a statistical storage range of almost 3,000 years.

V. CONCLUSIONS

In this paper, we have investigated the ambiguity of CO_2 between disposal and feedstock in a European economy with net zero emissions in 2050. Relevant CO_2 demands were classified, and possible supply routes identified. The analysis of the resulting CO_2 economy leads to three basic findings:

Firstly, in a European economy that strives for CO_2 neutrality in 2050, there needs to be a technology that separates CO_2 from ambient air. This technology should therefore be further researched and developed with great intensity.

Secondly, to meet demands for carbon-containing energy carriers, the use of fossil methane in combination with CCS is predictably considerably cheaper than the use of synthetic energy carriers. Since both approaches require the availability of direct air capture, the decision between natural gas and synthetic methane ultimately results in a cost competition between natural gas and renewable electricity.

Thirdly, since the use of fossil methane is economically beneficial, CO_2 storage facilities must be explored. The literature indicates that the possible CO_2 storage potential in Europe could last at least for a century.

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