

Trade-offs between CO2 utilization and CO2 transport and storage in the global energy transition

Lucas Desport, Carlos Andrade, Sandrine Selosse

▶ **To cite this version:**

Lucas Desport, Carlos Andrade, Sandrine Selosse. Trade-offs between CO2 utilization and CO2 transport and storage in the global energy transition. 16th International Conference on Greenhouse Gas Control Technologies (GHGT-16), Oct 2022, Lyon, France. 10.2139/ssrn.4279696 . hal-03934651

HAL Id: hal-03934651
https://hal.science/hal-03934651

Submitted on 11 Jan 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

16th International Conference on Greenhouse Gas Control Technologies, GHGT-16

23rd -27th October 2022, Lyon, France

Trade-off between CO_2 utilization and CO_2 transport and storage in the global energy transition

Lucas Desport[a,b,*], Carlos Andrade[c], Sandrine Selosse[a]

[a]*Mines paris, PSL University, CMA - Centre for Applied Mathematics, Rue C. Daunesse, 06904 Sophia Antipolis, France*
[b]*TotalEnergies, OneTech, R&D, 2 place Jean Millier, 92078 Paris la Défense, France*
[c]*IFP Energies Nouvelles, 1-4 Avenue de Bois-Préau, 92852 Rueil-Malmaison Cedex, France*

Abstract

We use TIAM-FR, an Integrated Assessment Model representing the world energy system and its impact on climate change to assess the contributions of CO_2 utilization and CO_2 storage. While we assume that no costs for CO_2 transport must be supported in the case of CO_2 utilization, we vary the cost for CO_2 transport and observe the impact of the deployment rate of CCU and CCS in scenarios compliant with the Paris Agreement. In this integrated assessment exercise, we show that the impact of the cost of CO_2 transport and storage on the deployment rate of CCU is not straightforward. Increasing the cost of transport and storage affects the yield of global electricity, resulting in higher prices that in turn make electrolysis more expensive. As CO_2 utilization is very dependent on energy and hydrogen, we find that CCU becomes less competitive as the cost of CO_2 transport and storage rises. Besides, while CO_2 storage is proved very efficient in tackling climate change in the early 2030s, CO_2 utilization is only deployed significantly by 2050, and the increased cost of CO_2 transport and storage delays its roll-out.

Keywords: TIMES modeling, Bottom-up energy model, CO_2 capture, CO_2 utilization, CO_2 transport and storage

1. Introduction

In recent decades, Integrated Assessment Models (IAM) have gained interest in the guidance of decision-makers for their environmental policies. Prospective energy models exploring the future of the world energy system driven by cost-optimal investment choices in energy carriers and technologies help draw pathways in compliance with the climate goals. These energy models have proven and emphasized the need for Carbon Capture and Storage (CCS) technologies to decarbonize our societies [1–5]. In the meantime, poor insights have been delivered concerning the utilization of CO_2. Indeed, Carbon Capture and Utilization (CCU) faces many hurdles: low TRL [6,7], high costs CO_2 [8,9], small market sizes [7,10], and limited environmental benefits [6,11,12]. This might explain why CCU is either poorly represented in energy models [13,14], and rarely a significant contributor to climate mitigation, although it has been found crucial to decarbonate hard-to-abate sectors such as aviation [15–17] or the chemical industry [18,19]. This imbalance leads us to ask the following question: what drives the roll-out of CCU in the results of energy models? We focus on a potential driver: the cost of transport and storage of CO_2. Because CCU does not require specific investments for the transport – and storage – of CO_2, it may become more competitive than CCS for high costs of transport and storage. Generally, in energy models, the cost of CO_2 transport and storage is merely represented through a standard cost of 10 \$/tCO_2 [20], while studies show it can exceed 60 \$/tCO_2 [21,22]. Thus, we explore the sensitivity of CCU roll-out to the costs of CO_2 transport and storage.

Electronic copy available at: https://ssrn.com/abstract=4279696

Nomenclature

IAM	Integrated Assessment Model
CCU	Carbon Capture and Utilization
CCS	Carbon Capture and Storage
IAM	Integrated Assessment Model
SNG	Synthetic Natural Gas
TnS	Transport and Storage

2. Methodology

2.1. The TIAM-FR model

This analysis is carried out with TIAM-FR, the French version of the TIMES Integrated Assessment Model (TIAM) [23,24]. TIAM is a global model and a member of the TIMES family models developed under the Energy Technology System Analysis Program (ETSAP). TIMES is a generator of partial equilibrium techno-economic models representing the energy system of geographical areas – or regions, on a long-term horizon (often 2100). It performs a cost optimization of the energy supply: the present and future energy demands are satisfied by the energy produced within a region and the trades with other regions, depending on the activity level chosen by the solver. TIAM-FR represents the world energy system disaggregated in 15 regions and assesses the impact on climate change. Its technology-rich representation depicts the energy system decade by decade tracking the evolution of different energy forms, technologies, and end-uses (industry, commercial, residential, agriculture, transport), constituting the Reference Energy System (RES).

The technologies are characterized by the energy carriers and materials they consume, the energy services they provide, their techno-economic properties, and the GHG they emit. The structure of the model enables us to consider variations across the 15 regions regarding their socio-economic properties (cost of capital, labor, and energy), energy demand projections, and commercial routes. Driven by end-use demands, TIAM-FR aims to supply energy services at a minimum discounted cost ($d_{r,y}$) by choosing the most strategic investments to operate the energy system. It computes the total net present value (*NPV*) of the total annual cost of the system (*Cost*) in each region *r*. So, the model computes the following objective function, and it solves the problem by minimizing the objective function in a linear program encoded in the GAMS optimization language.

$$NPV = \sum_{r} \sum_{y} \left(1 + d_{r,y}\right)^{y} \times Cost_{r,y}$$

Investment decisions are made on the operation of the energy system over the 21st century and for each region of the model. Specifically, the model produces two types of results when computing optimization. First, the primal solution of the linear program provides, for each period y and region r: technology investments, operation rates, the energy and material flows, the imports and exports of each tradeable commodity, the extraction levels of each primary resource, emissions by technology, by sector and total. Secondly, the program provides a dual solution, which provides the "shadow price" of each commodity of the RES (fuels, materials, energy services, emissions). Thus, information on the marginal costs of environmental measures such as GHG reduction targets is available. The interest of this type of modeling is to offer the opportunity to explore the possible energy futures in the long term based on scenarios i.e., consistent assumptions on the trajectories of the determinants of the system.

In addition, the model is equipped with a climate module allowing accounting for every GHG emitted by the energy system and calculates the impact on temperature elevation in the atmosphere. This type of modeling offers the opportunity for each region to explore the possible energy pathways in the long term through different scenarios.

Electronic copy available at: https://ssrn.com/abstract=4279696

As mentioned, TIAM-FR is geographically integrated and represents the world energy system. It offers this representation in 15 regions, as follows: Africa (AFR), Australia-New Zealand (AUS), Canada (CAN), China (includes Hong Kong, excludes Chinese Taipei; CHI), Central and South America (CSA), Eastern Europe (EEU), Former Soviet Union (includes the Baltic states, FSU), India (IND), Japan (JPN), Mexico (MEX), Middle-East (includes Turkey; MEA), Other Developing Asia (includes Chinese Taipei and Pacific Islands; ODA), South Korea (SKO), United States of America (USA) and Western Europe (EU-15, Iceland, Malta, Norway, and Switzerland; WEU). These different regions of the world are linked together in terms of energy exchanges.

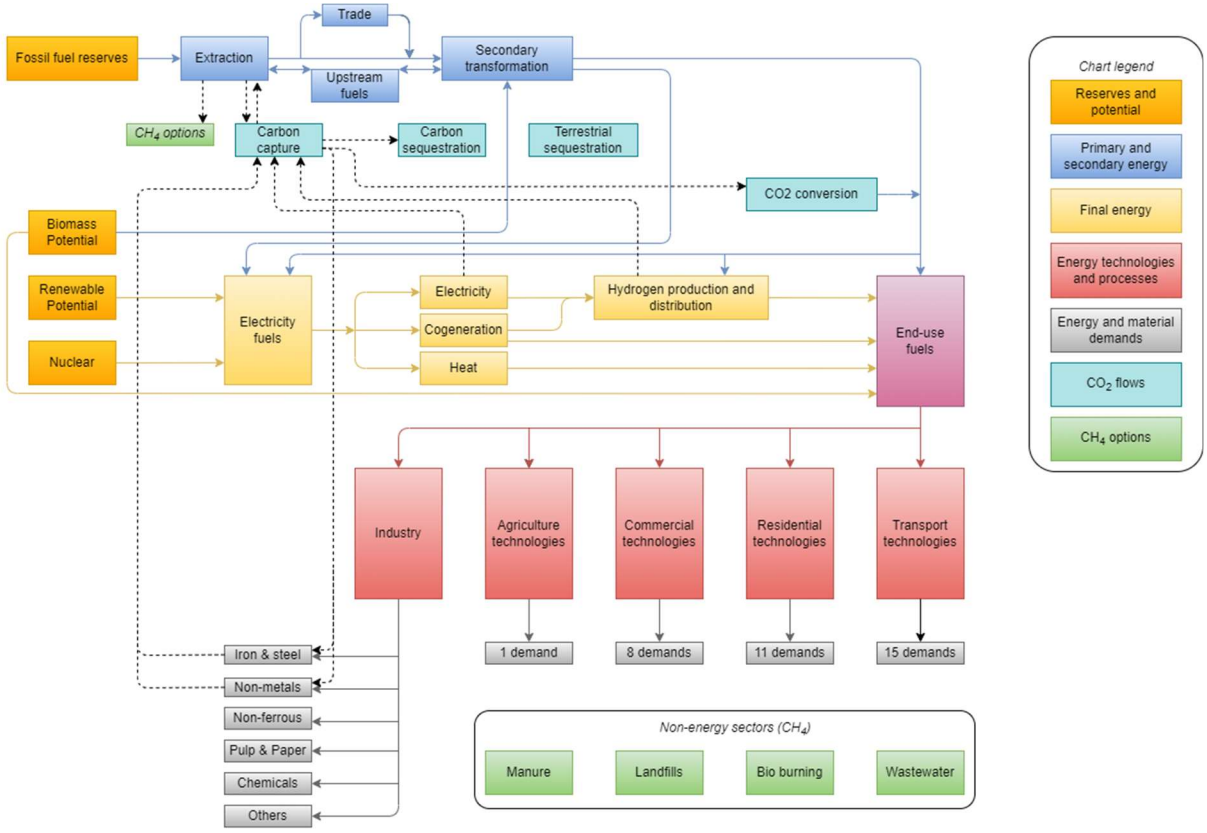


Figure 1. Reference Energy System (RES) of the TIAM-FR model with the carbon loops

Because TIAM-FR is assessing both changes in the energy system and climate, the model is considered an Integrated Assessment Model (IAM). Its technology-rich representation enables to include more than 1000 processes including CCU and CCS technologies, which are described in the next section.
TIAM-FR has been used to assess technology contribution to the decarbonization of the global energy system [2,25], policy assessments [26], and water management constraints [27].

2.2. The modeling of CCS and CCU

In the RES above are described the CO_2 flows available for the model to invest in. TIMES models are driven by techno-economic data (CAPEX, OPEX, efficiencies, discount rate, lifespan, emissions, etc.) extracted from the literature to describe the numerous processes of the RES. The TIAM-FR model features a wide array of opportunities to decarbonize the energy system with CCS and CCU options. It includes three capture techniques (pre-combustion capture, oxy-combustion capture, and post-combustion capture) and different capture technologies with partial (65% to 90%) or nearly full capture (98,5%). The model can invest in CO_2 capture assets in the steelmaking sector [28–33], the cement sector (non-metals) [34–36], the power sector including bioenergy with CCS (BECCS) [37–40], the

Electronic copy available at: https://ssrn.com/abstract=4279696

hydrogen sector [41–43], and in Direct Air Capture (DAC) units [44,45]. Consequently, negative emissions are an option of the model, achievable either from BECCS or DACCS, but also with biochar in the iron and steel industry.

To capture the competition of CCS and CCU with other technical options, the model features other opportunities to decarbonize the aforementioned sectors, i.e., renewables, bioenergy, hydrogen from electrolyzers, electrification, or energy efficiency and material efficiency improvements.

As for the transport and storage of CO_2, we have chosen to represent onshore and offshore options solely, with no disaggregation regarding the transport technology (pipeline or shipping), or storage type (saline aquifers or depleted oil and gas fields). The potentials for CO_2 storage onshore and offshore are extracted from the lower estimate of Kearns et al. [46], which assumes a cumulative storage capacity of 7,900 $GtCO_2$ split unequally in different regions of the world. Enhanced oil recovery (EOR) and Enhanced coal bed methane (ECBM) are not considered.

Unlike CO_2 capture, the costs of CO_2 transport and storage are not well-known, as there are no significant experiences in CO_2 in this link of the chain, but mostly because the costs are very case-dependent. The main parameters are the type of transport (pipeline onshore/offshore and shipping), the distance between the capture site and the storage site, and the depth and capacity of the well. This information is difficult to collect globally and implement in an energy model. In TIAM-FR, the costs of CO_2 transport and storage are taken from Smith et al. [21] in the base case, although those will be modified later in the study.

Our modeling of CO_2 utilization includes the chemical conversion of CO_2 into

- Methanol through hydrogenation [47–49], and possible further enhancement into gasoline through the methanol-to-gasoline (MtG) process [50]. Methanol can be used subsequently in the transport sector.
- Synthetic natural gas (SNG) through methanation [51–55].
- Petroleum liquids (gasoline, diesel, and jet fuels) through the Fischer-Tropsch process [16,56–60].

In addition, CO_2 can be mineralized with steel slags and coal fly ashes and mixed with clinker to produce low-carbon cement [44]. We assume that CO_2 utilization does not have to pay for transporting CO_2, i.e., the CO_2 is captured and used in the same place.

As the environmental impact of CCS and CCU is very dependent on the nature of the carbon used or stored, i.e. fossil or climate-neutral carbon, our modeling ensures a transparent and fair accounting of CO_2 emissions in which any sector is responsible only for its direct emissions, illustrated in Figure 2. Let a process be fuelled by whatever fossil resources, 100% of the carbon it contains will be emitted into the atmosphere in the form of CO_2. Let a process be fuelled by whatever fossil resources and equipped with a carbon capture unit, 10% of the carbon will be released into the atmosphere because of the imperfect capture efficiency (90%), but 90% of the CO_2 captured (CPTCO2) will be sent to dummy processes (represented in yellow in Figure 2) so the solver chooses whether this CO_2 will be used or stored. These sector-specific dummy processes are practical as they enable to aggregate the bulk of captured CO_2 into two entities – also called commodities – for storage (SNKCO2) or utilization (CO2FOS), which prevents duplicating processes in the model, and consequently the resolution time. On one hand, the CCUFOS commodity is converted by the CCU plant into a fuel (SYNFUEL) containing fossil carbon and consumed by the end-use process. This way, the 90% CO_2 that has been avoided by the capture unit is finally released into the atmosphere. On the other hand, the CO_2 to be stored (SNKCO2), can be sent to a storage process either onshore (SINKON), offshore (SINKOFF), or mineralized (CCUS), depending on their storage capacity and costs regionally. Thus, the 90% CO_2 that was avoided at the capture unit is sealed.

In the case where the carbon captured is climate neutral, i.e. either atmospheric or biogenic), the accounting for CO_2 emissions slightly differs. Let a process be fuelled by bioenergy, the emissions are accounted for zero – although upstream GHG emissions due to land use change or biomass harvesting are attributed to another sector.

Let a process be fuelled by biomass and equipped with a carbon capture unit, there are still no direct emissions.

Electronic copy available at: https://ssrn.com/abstract=4279696

However, 90% of the CO_2 flue gas is captured (CPTCO2N) and sent to dummy processes likewise. If the CO_2 is used, it is aggregated into a single commodity (CO2NEU) representing a flux of CO_2 that is not harmful – or neutral – to the environment due to its origin. This CO_2 commodity can be used by any CCU plant, but it will generate a fuel (SYNFUELN) that does not generate CO_2 emissions when it is combusted in an end-use process. Thus, the CO_2 that has been captured and utilized has no direct impact on the environment. However, if the climate-neutral CO_2 captured is to be stored, then the negative emissions are accounted for by the dummy processes: for every ton of CO_2 captured from a given sector, the same amount of CO_2 is deducted from the emissions of this sector.

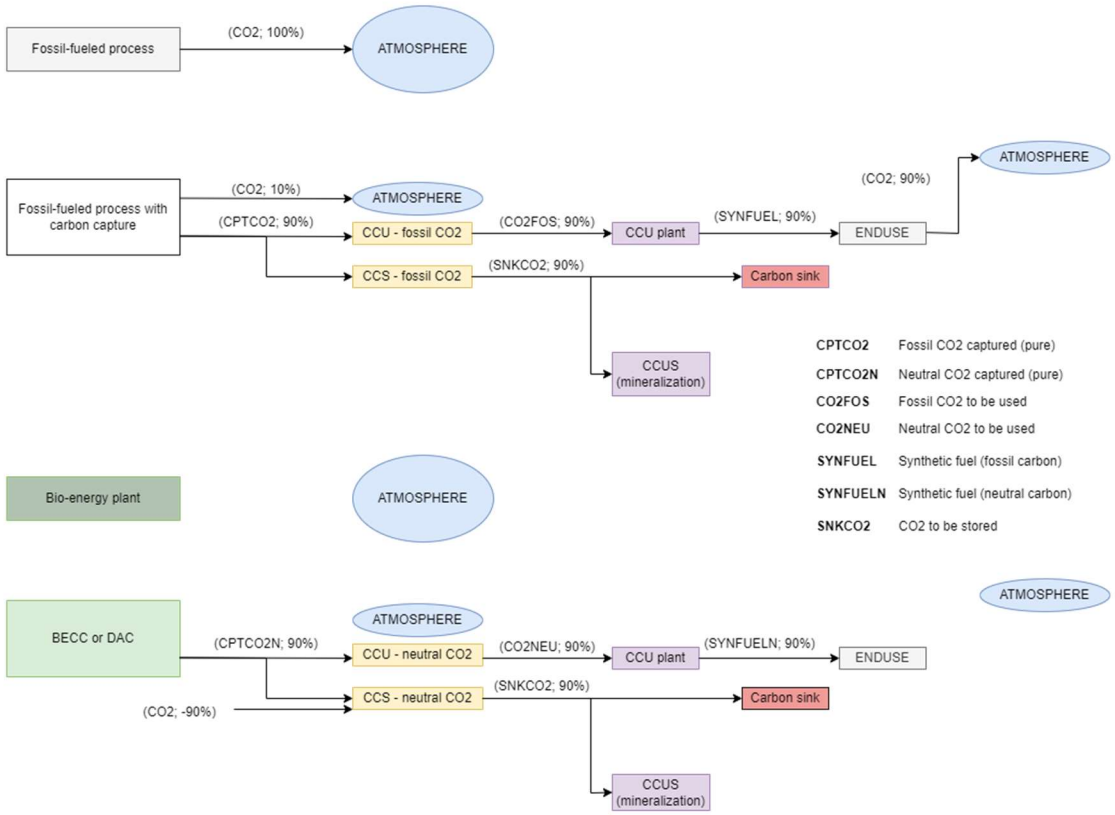


Figure 2. Accounting of CO_2 fluxes. CO_2 emissions are represented with arrows that are directed to the atmosphere. The percentage assigned represented the proportion of CO_2 captured initially from the hydrocarbon.

3. Scenarios

As mentioned above, there is considerable uncertainty about the cost of CO_2 transport and storage, which might influence the deployment rate of CO_2 capture. The costs of CO_2 utilization are also very uncertain due to the lower maturity of the process it involves. Furthermore, the utilization of CO_2 is closely related to the availability and cost of hydrogen to manufacture synthetic fuels, which are uncertain also. With the TIAM-FR model, we explore the penetration potential of CO_2 utilization in Mt of CO_2 utilized by varying the cost of CO_2 storage between 10\$/tCO_2 to 90\$/tCO_2, and the cost of CO_2 utilization processes, including DAC and hydrogen.

Reviewing the techno-economic literature on processes that convert CO_2 into synthetic fuels, one can find very different estimates in their techno-economic properties, reflecting the degree of optimism of the research. For each of the CO_2 utilization pathways, we define three scenarios (low, medium, and high) with different techno-economic properties regarding the CCU chain, i.e., the cost of utilization plants, the cost of hydrogen, and the cost of DAC. The

Electronic copy available at: https://ssrn.com/abstract=4279696

same approach was developed for the production cost of hydrogen. Table 1 describes the main techno-economic properties of CCU processes for each scenario. An exhaustive description of techno-economic assumptions is available in Appendix A.

All scenarios are compliant with the Paris Agreement, i.e. the model minimizes the total annual cost of the energy system so the temperature elevation does not exceed 1.5°C by 2100, without overshooting. For each of the fifteen scenarios, we analyze the deployment rate of CCU and CCS by tracking the CO_2 flows from the capture to utilization or storage.

Table 1. Main techno-economic parameters considered in the three scenarios

Process	Scenario	Reference	CAPEX	OPEX	Efficiency
Fischer-Tropsch	Low	[57]	56 $/GJpa	6,0 $/GJ	77%
	Medium	[60]	90 $/GJpa	6,0 $/GJ	66%
	High	[59]	116 $/GJpa	6,1 $/GJ	58%
Methanation	Low	[52]	27 $/GJpa	0,11 $/GJ	78%
	Medium	[53]	52 $/GJpa	0,10 $/GJ	78%
	High	[7,61]	80 $/GJpa	0,53 $/GJ	73%
Hydrogenation to methanol	Low	[47]	31 $/GJpa	0,10 $/GJ	80%
	Medium	[48]	45 $/GJpa	0,05 $/GJ	70%
	High	[49]	93 $/GJpa	0,16 $/GJ	70%
Electrolysis	Low	Different scenarios taken from [41,43]	730 $/kWel	19 c$/t$H_2$	71%
	Medium		975 $/kWel	34 c$/t$H_2$	66%
	High		1256 $/kWel	52 c$/t$H_2$	61%
DAC	Low	Different scenarios taken from [44]	126 $/t$CO_2$	21 $/t$CO_2$	4,0 GJ/tCO_2
	Medium		196 $/t$CO_2$	33 $/t$CO_2$	5,0 GJ/tCO_2
	High		522 $/t$CO_2$	61 $/t$CO_2$	5,8 GJ/tCO_2

Electronic copy available at: https://ssrn.com/abstract=4279696

4. Results and discussion

Unsurprisingly, the deployment rate of CCS is very impacted by the cost of CO2 TnS. Notably, the increase in CO2 TnS costs impacts both the global yield of electricity and production costs. The higher the cost of CO2 TnS, the fewer CCS is competitive compared to other power units which reduces the amount of electricity generated, requires to operate more expensive plants, and raises the cost of electricity (Figure 3). We observe the same impact on the hydrogen sector which uses much less electricity to operate electrolyzers as the cost of electricity increases with higher CO_2 TnS costs. The electrolyzers are then replaced by more expensive bio-gasification processes to manufacture hydrogen, increasing the cost by more than 15% percent in all scenarios.

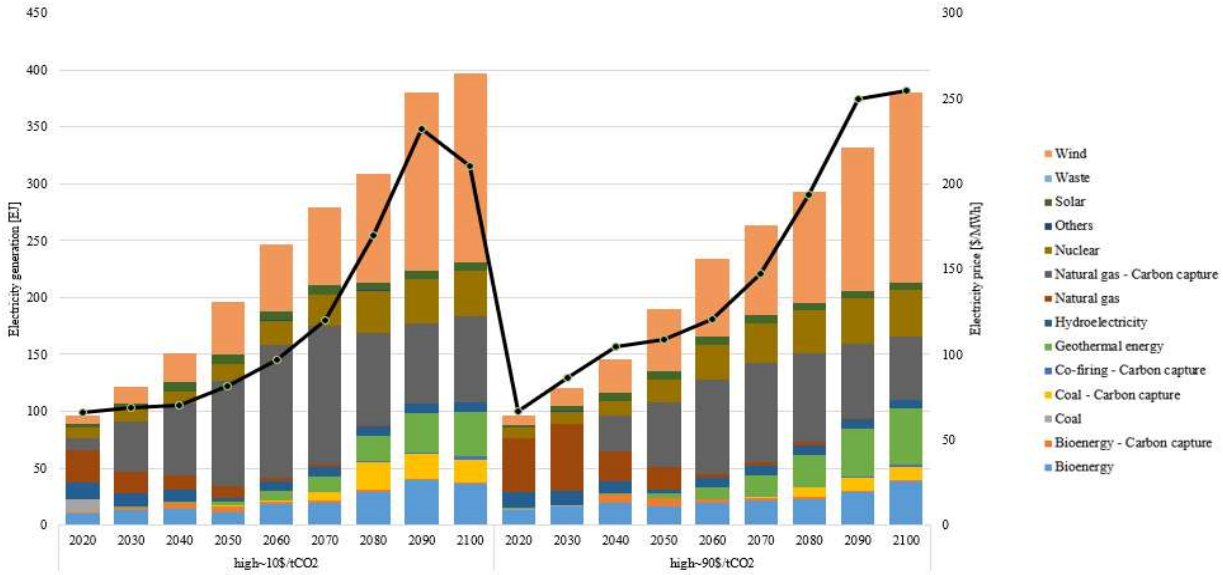


Figure 3: Global electricity production and price in a "High" cost scenario.
On the secondary axis is displayed the cost of electricity plotted with a black line.

The combined effects of less electricity and hydrogen available at higher prices directly impact the deployment of CO_2 utilization. Indeed, in each scenario, the deployment rate of CO_2 utilization decreases as the cost of CO_2 TnS increases (Table 2), although we have assumed that CCU plants are exempt from the costs of CO_2 transport. This counter-intuitive result can be explained by the collateral effects of higher CO_2 TnS cost, particularly on the electricity and hydrogen sectors, on which CCU depends. Thus, CCU processes, which are already known to be expensive, become less and less attractive as the cost of CO_2 TnS rises.

Table 2: Cumulative amount of CO_2 utilized at the horizon 2100 in $GtCO_2$

TnS cost scenario	Low	Medium	High
10$/$tCO_2$	108	63	65
30$/$tCO_2$	118	56	58
50$/$tCO_2$	106	52	55
70$/$tCO_2$	104	51	41
90$/$tCO_2$	104	52	42

Electronic copy available at: https://ssrn.com/abstract=4279696

Regardless of the scenario, the utilization of CO_2 remains much less important than the storage of CO_2 with 7% of the CO_2 captured sent to utilization assets in the Low scenario, and 4% in the Medium and High scenario. In terms of absolute values, this represents the annual conversion of up to 5.0 to 3.3 $GtCO_2/y$ depending on the scenario (Figure 4). While CO_2 starts being stored from 2025 onwards, the penetration of CO_2 utilization is as sharp as it is late, since no CO_2 is converted before 2050 in the Low scenario, or 2070 in the High scenario.

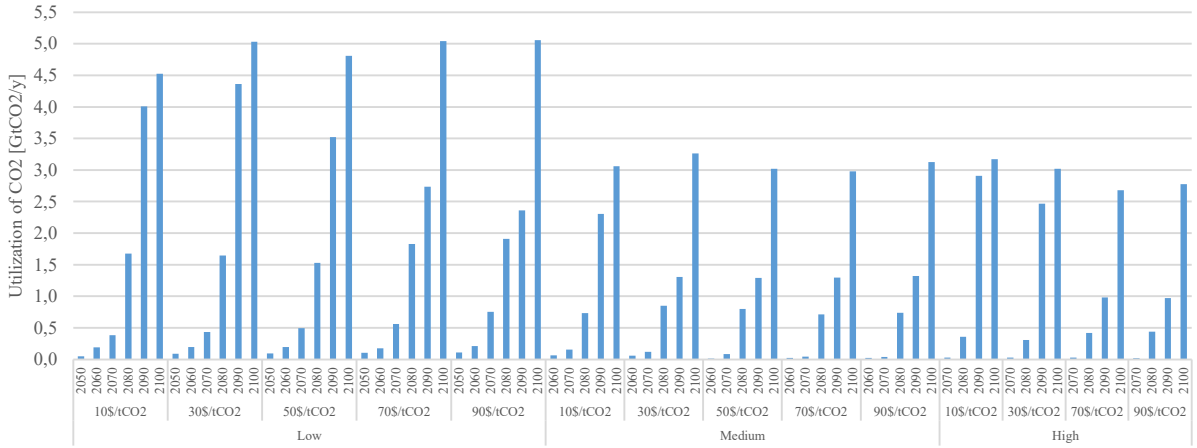


Figure 4: Progressive penetration of CO_2 utilization

The CO_2 used is entirely dedicated to producing fuels, especially methane in the Low and Medium scenarios, that is subsequently used in the industry sector (Figure 5). Only in the High scenario, the model invests in Fischer-Tropsch processes converting CO_2 into gasoline, diesel, and jet fuels to power the transport sector. Because hydrogen manufacture is so expensive in this scenario, CO_2-based fuels become more competitive than the hydrogen route as it requires investing in capital-intensive hydrogen means of transportation in the end. This observation can be made also when comparing the Medium scenario with the High scenario; when the cost of CO_2 TnS is between 10 to 50$/$tCO_2$, higher amounts of CO_2 are used in the High scenario because of the lower competitiveness of hydrogen in these cases. The remaining CO_2 is used to produce carbon-neutral methanol either used raw or enhanced into diesel for the transport sector.

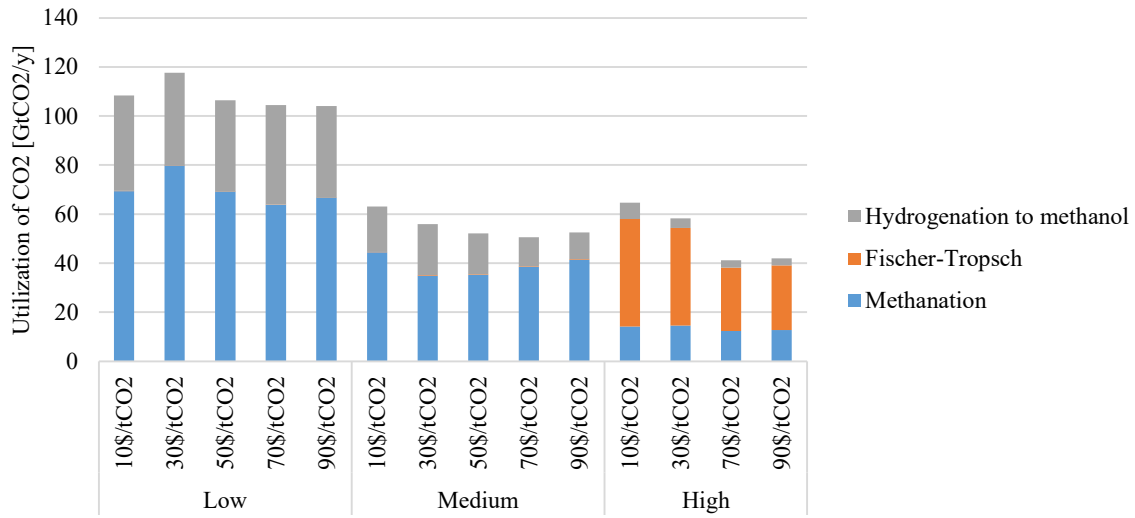


Figure 5: Utilization of CO_2 by process and scenario

Electronic copy available at: https://ssrn.com/abstract=4279696

The large majority of the CO_2 used concerns inevitable process CO_2 coming from the electricity sector and the industry sector, i.e. from cement plants and iron and steel plants. Consequently, CO_2 utilization cannot play a significant role in mitigating GHG emissions as the CO_2 used is then reemitted again when the CO_2-based fuels are combusted. Any additional tons of CO_2 used are biogenic, captured from ethanol fermentation processes. There is no CO_2 captured directly from the atmosphere, even for very low-cost DAC such as in the Low scenario.

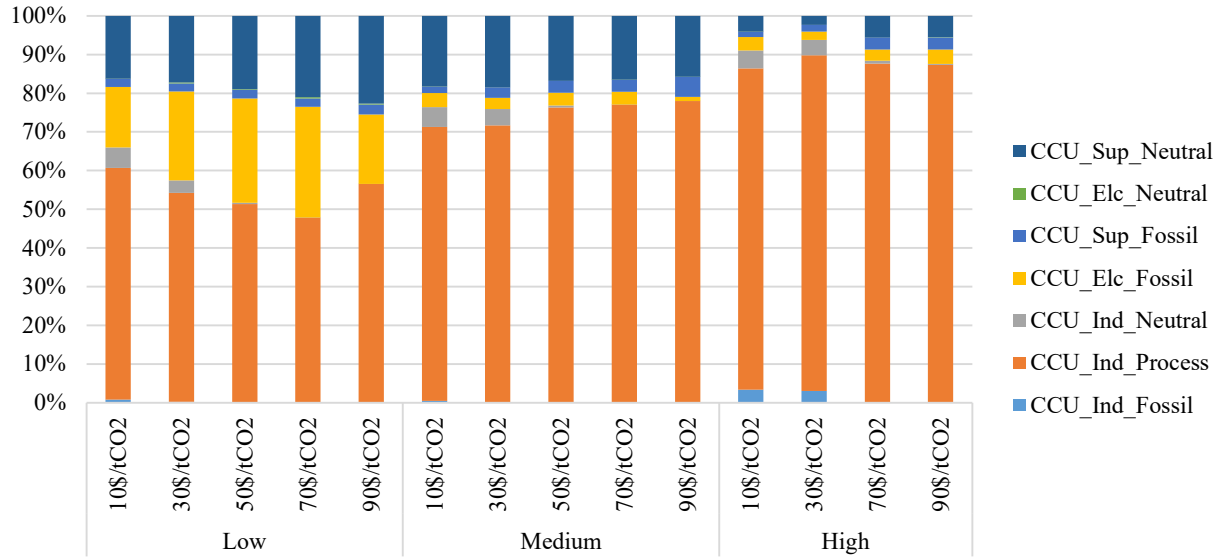


Figure 6: Breakdown of the origin of CO_2 utilized.
Sup refers to the supply sector, Elc refers to the electricity sector, Ind refers to the industry sector, Fossil denotes fossil CO_2 used, Neutral denotes carbon-neutral CO_2 used, and Process denotes industrial process CO_2 used.

5. Conclusion and discussion

The results reflect the complexity of CCU deployment, as it interacts with many other technologies of the energy system. The scenarios obtained with our integrated tool TIAM-FR reveal a counter-intuitive result that the amount of CO_2 used is inversely proportional to the cost of CO_2 transport and storage, whilst CO_2 utilization assets do not incur that cost. Since the increased cost of CO_2 transportation and storage does limit the deployment of CCS in the energy system, it impacts the production and cost of electricity and hydrogen, two essential commodities for operating CO_2 conversion units. Thereby, the competitiveness of CCU is reduced so we observe a decline in the quantity of CO_2 used as the cost of CO_2 TnS increases. Nonetheless, the results prove that the cost of hydrogen has a significant impact on the deployment rate of CCU as the quantity of CO_2 used is roughly doubled from the High scenario to the Low scenario. Finally, DAC plants are never started up to run CO_2 utilization plants or to generate negative emissions.

However, the importance of CCS appears much greater than CCU in the near future and after, as no CCU is deployed before 2050. CCS is massively deployed to eliminate the emissions of the industry and to generate negative emissions. It can be expected that if CO_2 is to be buried offshore with high costs induced, it would increase the cost of hydrogen and electricity, affecting the deployment of CO_2 utilization.

Acknowledgments

This research is funded by TotalEnergies and the Ministry of Higher Education and Research as part of a doctoral program (CIFRE). This work is also supported by the Chair Modeling for sustainable development, driven by Mines Paris - PSL and École des Ponts ParisTech, supported by ADEME, EDF, GRTgaz, RTE, SCHNEIDER ELECTRIC,

Electronic copy available at: https://ssrn.com/abstract=4279696

TotalEnergies, and the French ministry of ecological and solidarity transition. The views expressed in the reports, or any public documents linked to the research program are attributable only to the authors in their personal capacity and not to the funder.

References

[1] A.C. Köberle, The Value of BECCS in IAMs: a Review, Curr. Sustain. Energy Rep. 6 (2019) 107–115. https://doi.org/10.1007/s40518-019-00142-3.
[2] S. Selosse, Bioenergy with carbon capture and storage: how carbon storage and biomass resources potentials can impact the development of the BECCS, in: Bioenergy Carbon Capture Storage, Elsevier, 2019: pp. 237–256. https://doi.org/10.1016/B978-0-12-816229-3.00012-0.
[3] IEA, CCUS in clean energy transitions, Energy Technol. Perspect. (2020) 174.
[4] J. Morris, H. Kheshgi, S. Paltsev, H. Herzog, Scenarios For The Deployment Of Carbon Capture And Storage In The Power Sector In A Portfolio Of Mitigation Options, Clim. Change Econ. CCE. 12 (2021) 1–29.
[5] S. Paltsev, J. Morris, H. Kheshgi, H. Herzog, Hard-to-Abate Sectors: The role of industrial carbon capture and storage (CCS) in emission mitigation, Appl. Energy. 300 (2021) 117322. https://doi.org/10.1016/j.apenergy.2021.117322.
[6] R.M. Cuéllar-Franca, A. Azapagic, Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts, J. CO2 Util. 9 (2015) 82–102. https://doi.org/10.1016/j.jcou.2014.12.001.
[7] R. Chauvy, N. Meunier, D. Thomas, G. De Weireld, Selecting emerging CO2 utilization products for short- to mid-term deployment, Appl. Energy. 236 (2019) 662–680. https://doi.org/10.1016/j.apenergy.2018.11.096.
[8] F. Ueckerdt, C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, G. Luderer, Potential and risks of hydrogen-based e-fuels in climate change mitigation, Nat. Clim. Change. 11 (2021) 384–393. https://doi.org/10.1038/s41558-021-01032-7.
[9] C. Hepburn, E. Adlen, J. Beddington, E.A. Carter, S. Fuss, N.M. Dowell, J.C. Minx, P. Smith, C.K. Williams, The technological and economic prospects for CO2 utilization and removal, Nature. 575 (2019) 87–97. https://doi.org/10.1038/s41586-019-1681-6.
[10] Global CCS Institute, Accelerating the uptake of CCS: industrial use of captured carbon dioxide, 2011. https://www.globalccsinstitute.com/resources/publications-reports-research/accelerating-the-uptake-of-ccs-industrial-use-of-captured-carbon-dioxide/ (accessed July 17, 2020).
[11] K. de Kleijne, S.V. Hanssen, L. van Dinteren, M.A.J. Huijbregts, R. van Zelm, H. de Coninck, Limits to Paris compatibility of CO2 capture and utilization, One Earth. 5 (2022) 168–185. https://doi.org/10.1016/j.oneear.2022.01.006.
[12] D. Ravikumar, G.A. Keoleian, S.A. Miller, V. Sick, Assessing the Relative Climate Impact of Carbon Utilization for Concrete, Chemical, and Mineral Production, Environ. Sci. Technol. (2021) acs.est.1c01109. https://doi.org/10.1021/acs.est.1c01109.
[13] L. Desport, S. Selosse, An overview of CO2 capture and utilization in energy models, Resour. Conserv. Recycl. 180 (2022) 106150. https://doi.org/10.1016/j.resconrec.2021.106150.
[14] I. Butnar, J. Cronin, S. Pye, Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios, Final Rep. (2020) 57.
[15] K. Dahal, S. Brynolf, C. Xisto, J. Hansson, M. Grahn, T. Grönstedt, M. Lehtveer, Techno-economic review of alternative fuels and propulsion systems for the aviation sector, Renew. Sustain. Energy Rev. 151 (2021) 111564. https://doi.org/10.1016/j.rser.2021.111564.
[16] P. Schmidt, V. Batteiger, A. Roth, W. Weindorf, T. Raksha, Power-to-Liquids as Renewable Fuel Option for Aviation: A Review, Chem. Ing. Tech. 90 (2018) 127–140. https://doi.org/10.1002/cite.201700129.
[17] C. Zhang, X. Hui, Y. Lin, C.-J. Sung, Recent development in studies of alternative jet fuel combustion: Progress, challenges, and opportunities, Renew. Sustain. Energy Rev. 54 (2016) 120–138. https://doi.org/10.1016/j.rser.2015.09.056.
[18] A.M. Bazzanella, F. Ausfelder, Low Carbon Energy and Feedstock for the European Chemical Industry, DECHEMA Gesellschaft für Chemische Technik (2017) 168.
[19] A. Kätelhön, R. Meys, S. Deutz, S. Suh, A. Bardow, Climate change mitigation potential of carbon capture and utilization in the chemical industry, Proc. Natl. Acad. Sci. 116 (2019) 11187–11194.

Electronic copy available at: https://ssrn.com/abstract=4279696

https://doi.org/10.1073/pnas.1821029116.
[20] IPCC, Climate change 2014: mitigation of climate change ; Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge Univ. Press, New York, NY, 2014.
[21] E. Smith, J. Morris, H. Kheshgi, G. Teletzke, H. Herzog, S. Paltsev, The cost of CO2 transport and storage in global integrated assessment modeling, Int. J. Greenh. Gas Control. 109 (2021) 103367. https://doi.org/10.1016/j.ijggc.2021.103367.
[22] IEAGHG, The Status and Challenges of CO2 Shipping Infrastructures, 2020.
[23] R. Loulou, M. Labriet, ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure, Comput. Manag. Sci. 5 (2008) 7–40. https://doi.org/10.1007/s10287-007-0046-z.
[24] R. Loulou, ETSAP-TIAM: the TIMES integrated assessment model. part II: mathematical formulation, Comput. Manag. Sci. 5 (2008) 41–66. https://doi.org/10.1007/s10287-007-0045-0.
[25] S. Kang, S. Selosse, N. Maïzi, Contribution of global GHG reduction pledges to bioenergy expansion, Biomass Bioenergy. 111 (2018) 142–153. https://doi.org/10.1016/j.biombioe.2017.05.017.
[26] A. Didelot, N. Maïzi, V. Mazauric, E. Assoumou, S. Selosse, Balancing Energy Efficiency and Fossil Fuel: The Role of Carbon Pricing, Energy Procedia. 105 (2017) 3545–3550. https://doi.org/10.1016/j.egypro.2017.03.814.
[27] S. Bouckaert, E. Assoumou, S. Selosse, N. Maïzi, A prospective analysis of waste heat management at power plants and water conservation issues using a global TIMES model, Energy. 68 (2014) 80–91. https://doi.org/10.1016/j.energy.2014.02.008.
[28] P. Griffin, G. Hammond, J. Norman, Industrial Energy Use from a Bottom-Up Perspective: Developing the Usable Energy Database (Beta version), (2013) 53.
[29] ETSAP, Iron & Steel, 2010. https://www.iea-etsap.org/E-TechDS/HIGHLIGHTS%20PDF/I02-Iron&Steel-GS-AD-gct%201.pdf (accessed July 30, 2022).
[30] A. Keys, M. van Hout, B. Daniëls, Decarbonisation options for the Dutch steel industry, (n.d.) 66.
[31] T. Kuramochi, A. Ramírez, W. Turkenburg, A. Faaij, Techno-economic assessment and comparison of CO2 capture technologies for industrial processes: Preliminary results for the iron and steel sector, Energy Procedia. 4 (2011) 1981–1988. https://doi.org/10.1016/j.egypro.2011.02.079.
[32] T. Kuramochi, A. Ramírez, W. Turkenburg, A. Faaij, Comparative assessment of CO2 capture technologies for carbon-intensive industrial processes, Prog. Energy Combust. Sci. 38 (2012) 87–112. https://doi.org/10.1016/j.pecs.2011.05.001.
[33] V. Vogl, O. Olsson, B. Nykvist, Phasing out the blast furnace to meet global climate targets, Joule. 5 (2021) 2646–2662. https://doi.org/10.1016/j.joule.2021.09.007.
[34] IEAGHG, Deployment of CCS in the cement industry, 2013.
[35] European Cement Research Academy, CSI/ECRATechnology Papers 2017, Duesseldorf, Geneva, 2017. http://www.wbcsdcement.org/technology.
[36] CEMCAP, Design and performance of CEMCAP cement plant with MEA post combustion capture, 2016.
[37] L. Irlam, Global CCS Institute : Global Costs of Carbon Capture and Storage, Global CCS Institute, 2017. https://www.globalccsinstitute.com/archive/hub/publications/201688/global-ccs-cost-updatev4.pdf.
[38] IEAGHG, Update techno-economic benchmarks for fossil fuel-fired power plants with CO_2 capture, IEAGHG, 2020. https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/1041-2020-07-update-techno-economic-benchmarks-for-fossil-fuel-fired-power-plants-with-co2-capture (accessed September 9, 2021).
[39] S. Kang, La place de la bioénergie dans un monde sobre en carbone: Analyse prospective et développement de la filière biomasse dans le modèle TIAM-FR, MINES ParisTech, 2017.
[40] J. Morris, J. Farrell, H. Kheshgi, H. Thomann, H. Chen, S. Paltsev, H. Herzog, Representing the costs of low-carbon power generation in multi-region multi-sector energy-economic models, Int. J. Greenh. Gas Control. 87 (2019) 170–187. https://doi.org/10.1016/j.ijggc.2019.05.016.
[41] B. Parkinson, P. Balcombe, J.F. Speirs, A.D. Hawkes, K. Hellgardt, Levelized cost of CO2 mitigation from hydrogen production routes, Energy Environ. Sci. 12 (2019) 19–40. https://doi.org/10.1039/C8EE02079E.
[42] DNV-GL, Study on the Import of Liquid Renewable Energy: Technology Cost Assessment, (2020) 32.
[43] O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson, S. Few, Future cost and performance of water electrolysis: An expert elicitation study, Int. J. Hydrog. Energy. 42 (2017) 30470–30492.

Electronic copy available at: https://ssrn.com/abstract=4279696

https://doi.org/10.1016/j.ijhydene.2017.10.045.
[44] National Academies of Sciences Engineering and Medicine, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, (2019) 59. https://doi.org/10.17226/25259.
[45] N. McQueen, M.J. Desmond, R.H. Socolow, P. Psarras, J. Wilcox, Natural Gas vs. Electricity for Solvent-Based Direct Air Capture, Front. Clim. 2 (2021). https://doi.org/10.3389/fclim.2020.618644.
[46] J. Kearns, G. Teletzke, J. Palmer, H. Thomann, H. Kheshgi, Y.-H.H. Chen, S. Paltsev, H. Herzog, Developing a Consistent Database for Regional Geologic CO2 Storage Capacity Worldwide, Energy Procedia. 114 (2017) 4697–4709. https://doi.org/10.1016/j.egypro.2017.03.1603.
[47] M. Pérez-Fortes, J.C. Schöneberger, A. Boulamanti, E. Tzimas, Methanol synthesis using captured CO2 as raw material: Techno-economic and environmental assessment, Appl. Energy. 161 (2016) 718–732. https://doi.org/10.1016/j.apenergy.2015.07.067.
[48] H. Zhang, L. Wang, J. Van herle, F. Maréchal, U. Desideri, Techno-Economic Optimization of CO2-to-Methanol with Solid-Oxide Electrolyzer, Energies. 12 (2019) 3742. https://doi.org/10.3390/en12193742.
[49] C. Hank, S. Gelpke, A. Schnabl, R.J. White, J. Full, N. Wiebe, T. Smolinka, A. Schaadt, H.-M. Henning, C. Hebling, Economics & carbon dioxide avoidance cost of methanol production based on renewable hydrogen and recycled carbon dioxide – power-to-methanol, Sustain. Energy Fuels. 2 (2018) 1244–1261. https://doi.org/10.1039/C8SE00032H.
[50] M. Hennig, M. Haase, Techno-economic analysis of hydrogen enhanced methanol to gasoline process from biomass-derived synthesis gas, Fuel Process. Technol. 216 (2021) 106776. https://doi.org/10.1016/j.fuproc.2021.106776.
[51] R. Chauvy, L. Dubois, P. Lybaert, D. Thomas, G. De Weireld, Production of synthetic natural gas from industrial carbon dioxide, Appl. Energy. 260 (2020) 114249. https://doi.org/10.1016/j.apenergy.2019.114249.
[52] M. Fasihi, D. Bogdanov, C. Breyer, Long-Term Hydrocarbon Trade Options for the Maghreb Region and Europe—Renewable Energy Based Synthetic Fuels for a Net Zero Emissions World, Sustainability. 9 (2017) 306. https://doi.org/10.3390/su9020306.
[53] J. Gorre, F. Ortloff, C. van Leeuwen, Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage, Appl. Energy. 253 (2019) 113594. https://doi.org/10.1016/j.apenergy.2019.113594.
[54] S. Park, K. Choi, C. Lee, S. Kim, Y. Yoo, D. Chang, Techno-economic analysis of adiabatic four-stage CO2 methanation process for optimization and evaluation of power-to-gas technology, Int. J. Hydrog. Energy. 46 (2021) 21303–21317. https://doi.org/10.1016/j.ijhydene.2021.04.015.
[55] S. Szima, C.-C. Cormos, CO2 Utilization Technologies: A Techno-Economic Analysis for Synthetic Natural Gas Production, Energies. 14 (2021) 1258. https://doi.org/10.3390/en14051258.
[56] F.G. Albrecht, D.H. König, N. Baucks, R.-U. Dietrich, A standardized methodology for the techno-economic evaluation of alternative fuels – A case study, Fuel. 194 (2017) 511–526. https://doi.org/10.1016/j.fuel.2016.12.003.
[57] S. Schemme, J.L. Breuer, M. Köller, S. Meschede, F. Walman, R.C. Samsun, R. Peters, D. Stolten, H2-based synthetic fuels: A techno-economic comparison of alcohol, ether and hydrocarbon production, Int. J. Hydrog. Energy. 45 (2020) 5395–5414. https://doi.org/10.1016/j.ijhydene.2019.05.028.
[58] C. Falter, V. Batteiger, A. Sizmann, Climate Impact and Economic Feasibility of Solar Thermochemical Jet Fuel Production, Environ. Sci. Technol. 50 (2016) 470–477. https://doi.org/10.1021/acs.est.5b03515.
[59] G. Zang, P. Sun, A.A. Elgowainy, A. Bafana, M. Wang, Performance and cost analysis of liquid fuel production from H2 and CO2 based on the Fischer-Tropsch process, J. CO2 Util. 46 (2021) 101459. https://doi.org/10.1016/j.jcou.2021.101459.
[60] M. Marchese, G. Buffo, M. Santarelli, A. Lanzini, CO2 from direct air capture as carbon feedstock for Fischer-Tropsch chemicals and fuels: Energy and economic analysis, J. CO2 Util. 46 (2021) 101487. https://doi.org/10.1016/j.jcou.2021.101487.
[61] R. Chauvy, D. Verdonck, L. Dubois, D. Thomas, G. De Weireld, Techno-economic feasibility and sustainability of an integrated carbon capture and conversion process to synthetic natural gas, J. CO2 Util. 47 (2021) 101488. https://doi.org/10.1016/j.jcou.2021.101488.

Electronic copy available at: https://ssrn.com/abstract=4279696