Highlights of Sustainability

ISSN 2696-628X, A Peer-Reviewed Open Access Journal by Highlights of Science

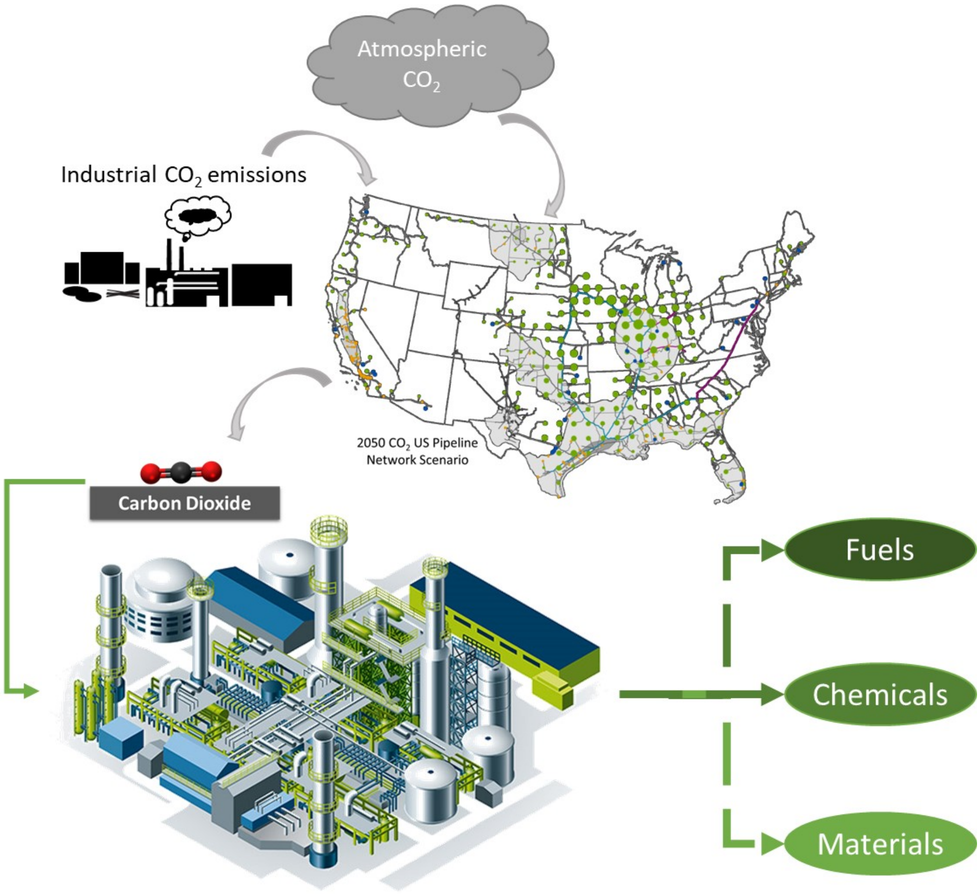
https://www.hos.pub/ho/sustainability

A Carbon Dioxide Refinery: The Core of a Sustainable Carbon-based Circular Economy

by Maria M. Ramirez-Corredores

Cite this Article

Ramirez-Corredores, M. M. (2024). A Carbon Dioxide Refinery: The Core of a Sustainable Carbon-based Circular Economy. *Highlights of Sustainability*, 3(2), 205–239. https://doi.org/10.54175/hsustain3020013



Highlights of Science

Publisher of Peer-Reviewed Open Access Journals

https://www.hos.pub

Barcelona, Spain

Highlights of Sustainability

Review

A Carbon Dioxide Refinery: The Core of a Sustainable Carbon-based Circular Economy

Maria M. Ramirez-Corredores

Idaho National Laboratory, Energy and Environment Science & Technology, Idaho Falls, ID 83415, USA;
E-Mail: mariamagdalena.ramirezcorredores@inl.gov

Abstract The atmospheric carbon dioxide (CO_2) accumulation (2–2.5 ppmv/year) is the result of the enormous gap between its emissions (37 Gton/year) and its capture, storage, and utilization (<500 Mton/year). Climate has been dramatically affected due to the failure of natural sinks, in working effectively. To address this Gton-scale gap, numerous uses and applications are needed particularly, those consuming vast volumes of this compound and/or rendering longevous products or long lifecycle services. Thus, carbon utilization (CU) can be seen as the step to close the carbon cycle. Among CU, R&D on CO_2 chemical conversion has proposed a variety of processes, with different degrees of developmental maturity. These chemical process technologies could be efficiently and effectively integrated into refineries to upgrade emitted CO_2. A technology pipeline consisting of a database of these processes and the technology market status should be defined based on published scientific results and patents. Then, an innovative top-down methodology is proposed to eco-design configurations of that refinery, to warrant a sustainable carbon cycle (in terms of energy, environment, and economy) and to change the ways of producing fuels, chemicals, and materials. Additionally, the proposed methodology could be used to identify research and development gaps and needs, for orienting science and technology investments and measures. Hopefully, sustainable CO_2 refineries will be implemented to close the carbon cycle of a circular C-based economy and underpin a decarbonized chemical industry.

Keywords CO_2; CO_2 utilization; CO_2 conversion; decarbonization; CO_2 upgrading; negative emission technologies

1. Background

Carbon dioxide (CO_2) is one of the carbon-containing compounds within the greenhouse gases (GHGs) whose accumulation in the atmosphere has been held responsible for climate change. This rate of accumulation has been increasing with time, motivating 195 countries belonging to the United Nations (UN), to rule for limiting global warming not to exceed 1.5 °C by 2050, during the 26th UN Climate Conference (COP26), known as the Glasgow Climate Pact [1]. By the end of 2022, CO_2 global emissions were reported to be 37 GtonCO_2/year, reaching an atmospheric concentration of 417 ± 0.1 parts per million (ppm) [2].

The three to four orders of magnitude difference in scale of CO_2 emissions (Gton/year) [2] and its utilization (Mton/year) [3,4] calls for vast increases in the number of uses, applications, and/or conversion processes, for this compound. More particularly, processes employing or consuming massive CO_2 volumes, involving lower intensity in carbon (C) and in energy, and rendering products or services with longer longevity or lifecycle are desirable. In general, the reduction of C-intensity has been focused mainly on the mitigation of CO_2 emissions. Meanwhile, C-valorization has been gaining track as a revenue generation approach. In this case, CO_2 emissions are considered as an unlimited and renewable C-feedstock [5–7]. The R&D on CO_2-based chemistry has attained a well-advanced status to propose numerous routes of conversion pathways [8] that would lead to an improvement in the Earth's C-balance. In return, an improved C-balance will contribute to mitigating climate change effects [9]. Consequently, closing the carbon cycle by combining operations of carbon capture (CC), and storing (CS) with CU provides a platform for a carbon-based circular economy (CCE). However, only under strict conservation practices through careful management of the carbon-bearing species, compounds, and materials, sustainability might be warranted. Additionally, since utilization through C-valorization has been recognized for its significant contribution to the economic feasibility of a CCE [10], the implementation of chemical process technologies will require efficiency and effective measures.

Open Access

Received: 12 December 2023
Accepted: 16 April 2024
Published: 9 May 2024

Academic Editor
Fausto Cavallaro, University of Molise, Italy

CO_2 emissions in the United States (US) are made readily available, by the US Environmental Protection Agency (EPA) together with other GHGs [11]. For this reason, the US data will be used here to exemplify[1] the vast proportion of available CO_2 feedstock. Thus, the map shown in Figure 1 shows the single-point static CO_2 emissions in the US and confirms the magnitude of the feedstock availability.

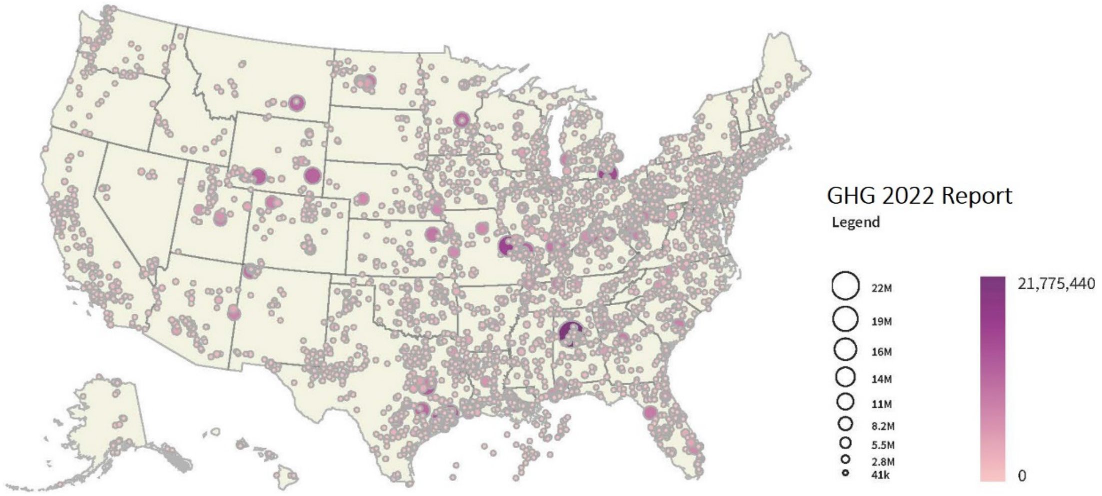


Figure 1. Carbon dioxide emissions from the US operating facilities ($tonCO_2$) [11].

In 2022, the total CO_2 emissions from these facilities (7586 facilities reported GHG emissions to EPA, from which 6842 reported CO_2 emissions) were nearly 2.5 $GtonCO_2$/year [11]. Emissions by state ranging from 13 $ktonCO_2$/year to nearly 350 $MtonCO_2$/year are shown in Figure 2. Emissions from more than 35 states exceed 20 $MtonCO_2$/year, as shown in Figure 2. The current strategy for industrial decarbonization is based on the belief that the composition of the emitted stream differs from one facility to another and requires either a tailor-made design solution or at least, adaptation measures of existing technologies. This atomistic view of one decarbonizing technological solution per emitting source (one-to-one strategy) not only results in high costs but also gives rise to difficulties for the implementation of any holistic criterion for carbon management. Therefore, this one-to-one carbon capture, utilization and storage (CCUS) decarbonization strategy will require nearly 7000 CCUS technologies, for the US facilities. In 2022, Texas reported to EPA GHG emissions from 853 facilities, out of which 770 emitted CO_2 amounting to 366 $MtonCO_2$/year. Thus, the number of technological solutions to mitigate the CO_2 problem, for the largest emitting US state, Texas (see Figures 1 and 2) is 770, if the status quo of the decarbonization one-to-one strategy is applied.

In the case of utilization, the emitted volumes as well as their composition derive from mismatches between the emission source and the use or application. Three mismatches can be identified: logistic, composition, and concentration. The logistic mismatch locates the CO_2 sources at a long (uneconomical) distance from the using location. Meanwhile, the composition and concentration of the source set a mismatch in the presence of undesirable compounds or a too-low C-content in the emitted stream from those suitable for the expected use or application. Additionally, it might also be that the dynamics of the emissions scale differ from that required by the use or by the product market size. The slowness of technology development and implementation could be associated by connecting these mismatches with the atomistic view of the one-to-one decarbonizing strategy. In solving their emission problem, larger facilities with $MtonCO_2$/year-scale of CO_2 emissions could benefit from both the economy of scale and the advantages of CU valorizing technologies. Instead, under these circumstances, smaller facilities with $ktonCO_2$/year-scale of CO_2 emissions will incur costs no longer competitive with those of a larger facility, to address decarbonization.

---

[1] Recurrently along this work, US data and information will be used to exemplify specific cases and situations and to illustrate particularities, facilitate discussion and/or derive potential implications. which may become valid globally. However, regardless of these regional examples, one needs to keep in mind that emissions are a global problem, technologies are globally applied and feedstocks and products are globally commercialized.

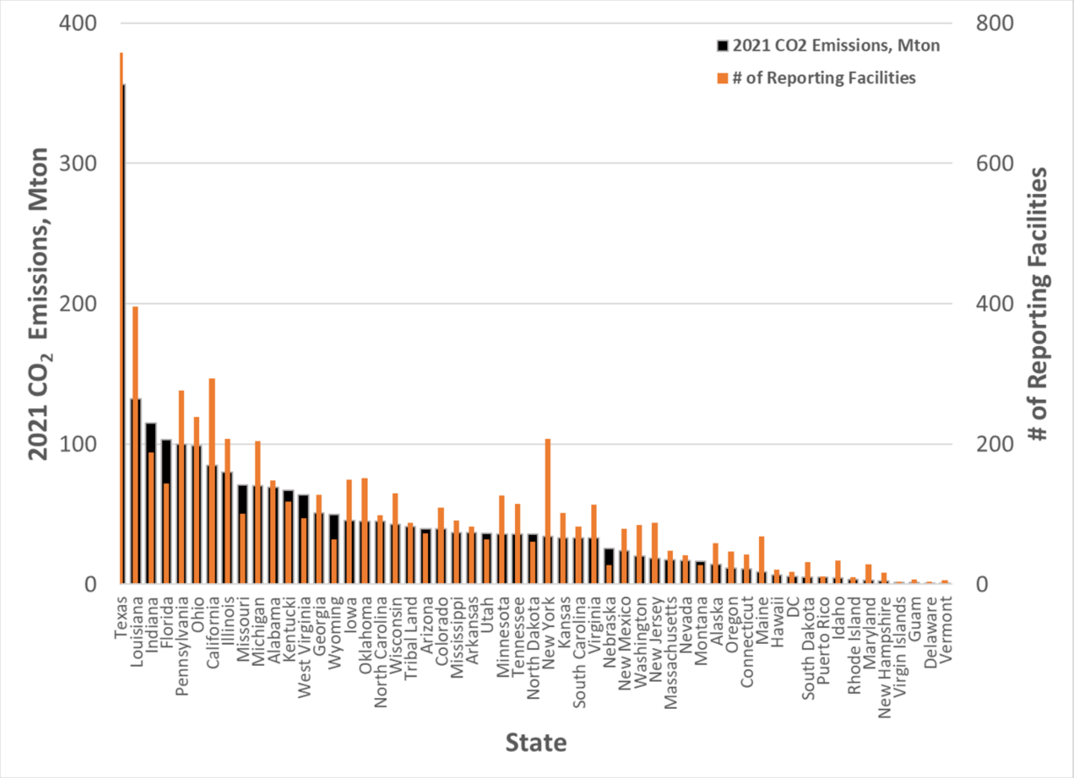


Figure 2. CO_2 emissions by state (from data reported in [11]).

Regarding CC, there are several commercially available technologies while only a few technologies are commercially available, for using and/or utilizing CO_2 (CU). Current industrial use of CO_2 demands about 2000 Mton/year [12], which represents consumption of about 5% of the yearly global emissions [13]. Historically, the most extensive use of CO_2 is in enhanced oil recovery (EOR) [14], in which it would remain geologically stored. Therefore, this is a combined utilization and storing technology, with an upstream capture system (CCUS). Meanwhile, C-valorization remains at the lowest implementation rate, partially because of the high costs associated with transforming CO_2 into economically valuable molecules [15]. The costs involved in the chemical conversion of CO_2 are associated with its high thermodynamic stability ($\Delta G^o_f = -396$ kJ/mol), responsible for its low reactivity. Thus, the CO_2 thermodynamic stability leads to chemical processes demanding high temperatures and/or heat fluxes for its conversion and then, resulting in high energy intensity. In order to address this energy intensity issue, energy efficiency and effectiveness have been focused. Catalysis [16] together with process intensification [17] and the use of low-carbon energy sources play important roles in this search for more efficient, effective, and intensified process technologies. On one side, the development of better catalysts needs to be based on the fundamental knowledge of reaction pathways and mechanisms, as well as on the overcoming of identified technical barriers and limitations [18].

This work revises relevant literature to support a proposal for a methodology to eco-design configurations of a CO_2 refinery, to warrant a sustainable carbon cycle (in terms of energy, environment, and economy) and to change the ways for producing fuels, chemicals, and materials. That configuration of the CO_2 refinery efficiently and effectively integrates chemical process technologies to upgrade emitted CO_2. Since the developmental stage and maturity of these chemical processes differ from each other, a technology pipeline consisting of a database of these processes and the technology market status needs to be defined based on published scientific results and patents. The lessons learned from the historical development or configuration design of oil refineries and biomass refineries (biorefineries) were also incorporated in the conceptualization of the methodology.

2. Technology Integration towards Carbon Dioxide Valorization

The valorization of emitted CO_2 would require its capture before its subsequent utilization, which for the present work will be focused on its conversion. Clearly then, CC plays a vital role in whether the carbon gets sequestered or converted into value-added products. However, according to the Intergovernmental Panel on Climate Change (IPCC), CCS will not be enough to achieve the net zero goals and additional components should be added to the strategy, such as reduction of energy demand, improvements in energy efficiency, and deploying of innovative conversion processes [19]. Although IPCC [19,20] and IEA [21] projections studies showed different trends in the carbon and energy intensities, their models and scenarios assume a predominant role in efficiency improvements, demand reduction measures, electrification, and increased CCS deployment. For emissions reduction purposes, the relative importance of the recommended approaches differs in their respective predictions on the deployment of CCS, in the level of fuel switching and efficiency improvements, and the effect of structural and behavioral changes. Nevertheless, some emissions have been recognized as being difficult to cost-effectively avoid, such as from the aviation sector; long-distance freight by ships; industrial process emissions (e.g., cement, steel, refining, etc.); high-temperature heat (e.g., >1000 °C); etc. [22]. Although technological solutions exist for these cases, these technologies are unsustainable, absurdly expensive, or have not reached commercial scale [23]. In this regard then, the well-accepted role of CCS in decarbonization can be complemented with CU to valorize CO_2, create revenues, and balance economic sustainability. Additionally, CU could be seen as the integrating vehicle that could close the C-loop in the anthropogenic C-cycle, as represented in Figure 3, even though sustainability indicators and metrics must be kept in mind permanently. Probably, closing the carbon cycle might be the most challenging aspect of establishing a CCE. However, circularity per se does not warrant sustainability: other measures need to be put in place, together with tools and methods for assessing, monitoring, and measuring the implementation of the circularity strategy [24].

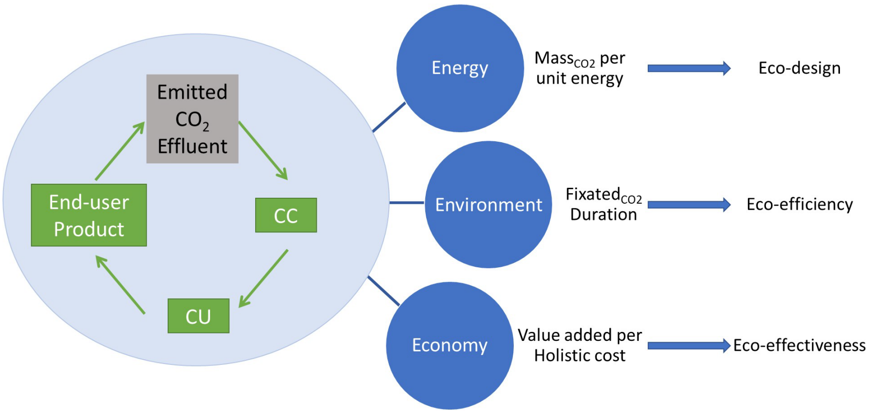


Figure 3. CU as a C-loop closing step and sustainability metrics (adapted from [24]).

The 17 Sustainable Development Goals (SDGs) of the 2030 Agenda were defined by the UN, in 2015 [25]. The four pillars of sustainability namely, human, economy, environment, and social were articulated to achieve a sustainable future in which human development is promoted. For this work, two of these sustainability pillars will be considered together with energy for its prevalent role in development and its impact on the environment (see Figure 3). Thus, the three considered pillars regard energy consumption, environmental impact, and economic feasibility. Figure 3 also includes some metric indicators to monitor and assess sustainability, for those three pillars. Each of these indicators can be associated with the concepts listed on their right namely, eco-design, eco-efficiency, and eco-effectiveness [26]. Eco-design is defined as the use and application of methods, tools, processes, and/or measures to reduce resource consumption and waste generation. Eco-efficiency is the minimization of volume, flow rate, and toxicity of materials flowing through the systems, per unit energy spent/consumed. Eco-effectiveness is the transformation of products and their associated material flows without impact on ecological systems or economic growth. In summary, these concepts represent the principles framework to support sustainability. These principles include (i) resource optimization, (ii) efficiency optimization, (iii) effectiveness optimization, and (iv) waste prevention. Regarding (i) and (iv), maximizing the volume of CO_2 consumed and minimizing its emissions call for the use of low-carbon energy sources and the production of long-lasting products (not fuels). In the case of CO_2, new eco-efficient chemical processes enabling its valorization are needed, making CCE an urgent essential that cannot be prolonged into a future prospect. The total substitution of today's linear "take, make, dispose" economy, by eco-efficient/eco-effective closed-loop approaches to production processes has to be emphasized [10].

The 2018 energy demand of more than 175 EJ by the industrial sector led to 30% of the global CO_2 emissions (~11 Gton) [27]. Approximately 60% of this industrial energy demand comes from energy-intense, C-intense, or both industries, such as steel, cement, chemicals, oil and gas, etc. [28]. Their share of direct CO_2 emissions is even higher, close to 70% [29]. By 2023, according to the International Energy Agency (IEA), the situation has worsened to make industry the most energy-consuming and CO_2-emitting end-use sector. It accounts for 38% of total final energy consumption and 47% of CO_2 global emissions [30]. Industrial heat and steam generation are the main responsible for this level of emissions since energy is provided from the combustion of fossil fuels [31]. The vast majority of the industrial emissions correspond to streams with CO_2 concentration lower than 15%, and only a few industries (<2%) emit streams that exceed 95% of CO_2 concentration [32]. In summary, the industrial and energy sectors are the main ones responsible for CO_2 emissions, which could be an unlimited source of carbon-based feedstock. However, the industry seems to believe that the individual factors defining the emissions are responsible for the above-described mismatches of the CO_2 resources. The magnitude of the emitted volumes, their CO_2 concentration, and even their transportation feasibility are defined by different factors, such as the origin of fossil sources of electricity and of fossil-derived heat, the high-temperature heating requirements, energy inefficiencies, energy intensity or high consumption, fossil or carbon-containing raw materials, inefficient and ineffective material flow, waste generation and/or disposal, etc. On the other hand, most of the published literature on CO_2 conversion does not consider real feedstocks (emitted streams), nor surrogate mixtures of the real feeds, or even the effect of potential contaminants present in these feeds. If during development and scaling up these processes do not fill these gaps, then, for demonstration or implementation purposes, any of them would need to be considered in conjunction with either a recovery process that yields a concentrated CO_2 stream or a pretreatment step that removes undesired contaminants.

Valorizing technologies to convert massive amounts of CO_2 into value-added products are preferred for the already mentioned benefits: (i) the large consumption of this noxious compound, (ii) being retained in a long lifecycle material, and/or (iii) the economy of scale. In addition to CO_2 consumption, the energy intensity of the current process-producing technology should be considered as well since most processes for CO_2 conversion are typically energy-intense [33]. In this regard, The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) published an analysis study reporting the energy intensity and the domestic production of 74 individual chemicals [34]. Then, based on different rationalized reasons, 10 of those chemicals were excluded. A summary is presented in Table 1 to show the top 20 chemicals that can be directly or indirectly produced or derived from CO_2. Thus, Table 1A lists these chemicals in decreasing order of energy intensity while Table 1B lists those in decreasing order of production.

Table 1. Top 20 chemicals with higher (A) energy intensity and (B) production capacity in the United States (data from [34]).

A			B		
Chemical	**Energy Intensity (kJ/kg)**	**Production (ton/y)**	**Chemical**	**Energy Intensity (kJ/kg)**	**Production (ton/y)**
Benzene	18289	6	**Ethanol**	10799	30
Ethylene	16436	24	**Ethylene**	16436	24
Polycarbonate	15590	1	**Propylene**	3140	14
Ammonia	13591	10	**Ammonia**	13591	10
Methanol	11392	1	**Polypropylene**	1432	8
Ethanol	10799	30	**Polyethylene, HD**	2410	8
Carbon Black	8937	2	**Polyethylene, LLD**	2025	6
Styrene	8779	4	**Benzene**	18289	6
Phenol	8510	2	**Urea**	1959	5
Xylenes, Paraxylene	5906	3	**Ethylbenzene**	2729	4

Table 1. (*Continued*)

PET	5325	4	**PET**	5325	4
Polystyrene	5262	2	**Styrene**	8779	4
Terephthalic Acid	5153	3	**Isobutylene**	7580	4
Propylene	3140	14	**Cumene**	1209	3
Ethylbenzene	2729	4	**Xylenes, Paraxylene**	5906	3
Polyethylene, LD	2657	3	**Terephthalic Acid**	5153	3
Polyethylene, HD	2410	8	**Polyethylene, LD**	2657	3
Hydrogen	2206	3	**Hydrogen**	2206	3
Polyethylene, LLD	2025	6	**Ethylene Oxide**	4454	3
Urea	1959	5	**Polystyrene**	5262	2
Polystyrene	1478	1	**Phenol**	8510	2

From Table 1, among the top five compounds, ethylene is the only carbon-containing compound in both A and B lists. Therefore, ethylene was selected, to exemplify one of the current technologies that should be replaced by another one converting CO_2 into a product that not only has a large market but also the current producing process is within the top five in energy intensity. Thus, regarding ethylene, it could be produced through thermocatalytic (e.g., [35–43]) or electrocatalytic (e.g. [44–50]) hydrogenation of CO_2, by the reaction shown below:

$$CO_2 + 3H_2 \rightarrow \tfrac{1}{2}C_2H_4 + 2H_2O$$

Global demand for ethylene is about 150 Mton/year [51]. Therefore, about 500 Mton/year of CO_2 would be consumed to satisfy the entire ethylene global market, if it is produced through this reaction. Consequently, the production of one of the largest market-demanded single products represents just 1.3% of the consumption of the current 37 GtonCO_2/year of global emissions [2]. Since it cannot be expected that current producers would shut down their existing facilities, nor that the olefins market would grow to catch up on the CO_2 emissions to consume the remaining 36.5 GtonCO_2/year then, it is clear that more than one conversion technology is needed for valorizing the massive quantities of emitted CO_2 and for rendering a larger variety of products and to satisfy broader market needs. Therefore, a suite of process technologies is needed for producing this wide variety of value-added products, from the immense source of carbon, emitted as CO_2 from static facilities.

Numerous reactions leading either to value-added products or to render a service or application of CO_2 have been proposed, studied, and developed. Production of fuels, bulk or commodity chemicals including inorganic materials and specialty products with biological activity such as health products and medicines have been suggested. Additionally, the production of functionalized polymeric materials in which carbon is fixated during prolonged times has been studied to a lesser extent though besides the economic benefits will bring environmental advantages, as well. These reactions and in general, CU and/or CO_2 conversion have been the subject of multiple review articles, chapters, and books [5,9,52–97]. In Table 2, relevant examples are given to emphasize the number and type of reactions studied, the level of progress or maturity [98] and the covered time. Some references for patents and patent applications are also included, though these are just a few examples and cannot be taken as a measure of intellectual property efforts.

Table 2. Some examples of chemical reactions of CO_2 and their marketable products.

Product	**Reaction**	**Chemical Reaction**	**References**	**Patents (e.g.)**
Carbon Monoxide	RWGS	$CO_2 + H_2 \rightarrow CO + H_2O$	[99–116]	[117]
	Electrocatalytic reduction		[118–150]	[151–162]
	Reversed Boudouard	$C + CO_2 \rightarrow 2CO$	[163,164]	
Carbon	Sorption Enhanced Boudouard	$CaO + CO_2 \leftrightarrow CaCO_3$	[165]	
		$CaO + 2CO \leftrightarrow CaCO_3 + C$		
	Boudouard	$2CO \rightarrow C + CO_2$	[163–165]	

Table 2. (*Continued*)

Syngas	Dry Reforming	$CO_2 + CH_4 \rightarrow 2CO + 2H_2$	[166–219]	[220,221]
	Via Chemical Looping (1)	$CH_4 (CO, H_2) + MeO \rightarrow CO_2 + H_2O (CO_2, H_2O) + Me$	[222–225]	
		$Me + \frac{1}{2}O_2 \rightarrow MeO$		
	Via Chemical Looping (2) w/integrated CC	$4MeO + CH_4 \rightarrow 4Me + CO_2 + 2H_2O$	[56,226–254]	
		$2Me + 2CO_2 \rightarrow 2MeO + 2CO$		
		$2Me + 2H_2O \rightarrow 2MeO + 2H_2$		
		$CH_4 + CO_2 \rightarrow 2CO + 2H_2$		
		$2Me + O_2 \rightarrow 4MeO$		
	Iron looping	$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2$	[255,256]	
		$3Fe + 4H_20 \rightarrow Fe_3O_4 + 4H_2$		
		$4 Fe_3O_4 + O_2 \rightarrow 6 Fe_2O_3$		
	($X + CO_2$) Co-electrolysis or Combined electrocatalytic		[130,257–280]	[153,281–293]
Methane	Sabatier	$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	[88,294–371]	[372,373]
	Hydrogenation w/steam	$CO_2 + 2H_2O \rightarrow CH_4 + 2O_2$	[374–376]	
Methanol	Catalytic Hydrogenation	$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$	[80,87,377–459]	[460–468]
	Electrocatalytic		[469–500]	[283,284,460,501–503]
DMC & Organic Carbonates	Carboxylation	$CO_2 + 2ROH \rightarrow RO\text{-}COO\text{-}R + H_2O$	[504–519]	
Polycarbonates	DMC Polymerization		[6,520–539]	
Polyurethanes			[528,540–545]	
Carboxylic acids or Esters	Hydrocarboxylation of olefins or alcohols		[546]	
Polyacids or Polyesters	Polymerization		[547,548]	
Inorganic carbonates	Carbonation	$2H^+ + H_2O + (Ca, Mg, Fe)SiO_3 \rightarrow Ca^{2+}, Mg^{2+}, Fe^{2+} + H_4SiO_4$	[55,549–575]	[576–580]
		$H_2CO_3 + Me^{2+} \rightarrow MeCO_3 + 2H^+$		
		$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2$		
		$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$		
		$Ca_2SiO_4 + 2CO_2 \rightarrow 2CaCO_3 + SiO_2$		
		$CO_2 + NH_3 + H_2O \rightarrow (NH_4)HCO_3$		
Urea	Two steps process	$2NH_3 + CO_2 \rightleftharpoons H_2N\text{-}COONH_4$	[581–586]	[587–591]
		$H_2N\text{-}COONH_4 \rightleftharpoons (NH_2)_2CO + H_2O$		
Urea polymers	Polymerization	w/CH_2O	[592–605]	
		w/melamine	[588–591,606–615]	

The current trend (not necessarily reflected in Table 2) of devoted R&D efforts [616] is mainly associated with reactions of the CO_2-H_2 pair [617] and the development of electrocatalytic processes [485,618]. The technical advances reached in most of the reactions collected in Table 2 were summarized in [619], including the identified gaps, needs, and challenges. The Technology Readiness Level (TRL) of CCUS and CU technologies was reviewed in [98] and [97], respectively. In the case of the CU, there was a high degree of uncertainty in TRL determination. As can be concluded from the examination of Table 2, the amplitude of the CU technology portfolio based on CO_2 conversion reactions is quite large though currently, most of these products cannot yet reach the market since the low TRL of the corresponding technologies. A graphical representation of this technologies maturity, spanning from TRL 1 through TRL 9 [97,98] is presented in Figure 4, along the curse of the S-curve of technology research, development and demonstration (RD&D). Only a few products (methanol, CO_2-based polycarbonates, polyols, polyurethanes, salicylic acids, and urea) and some inorganic carbonates have reached TRL 9, particularly for cases where CO_2 is used in the production of intermediates. Methanol from CO_2

is an exception since a commercial demonstration plant has been operating in Iceland for almost two decades [620,621]. The other exceptions are urea and salicylic acid, which together with polycarbonates consume 26% (130 MtonCO_2/year) [622] out of the reported utilized 500 MtonCO_2/year.

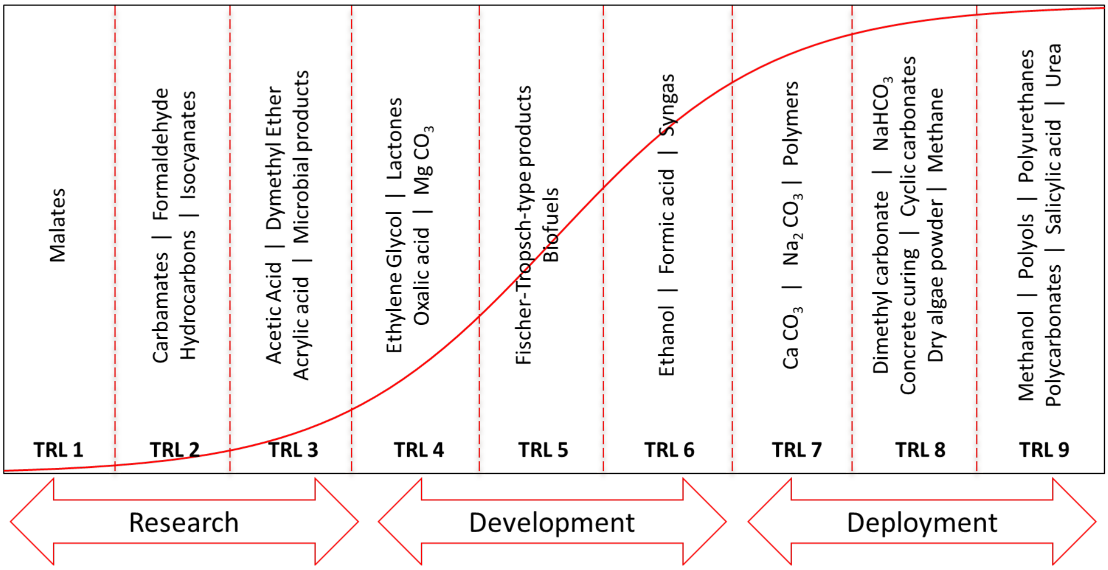


Figure 4. TRL status of technologies rendering referred products (from the information reported in [97]).

As can be deduced, the reaction options are quite broad but the reported efforts and results on these reactions are even larger since only references relevant to this work have been included in this table. Thus, the examination of this vast literature cited indicates the three particular trends within the R&D efforts that could be emphasized, namely, (i) synthesis of highly demanded compounds, (ii) pathways (reactions) that may consume large CO_2 amounts, and (iii) products that may retain CO_2 moiety for long periods (i.e., fuels production/uses are avoided).

The much greater impact of large-scale production based on CO_2 conversion, as summarized in Table 2, on the overall emissions reduction, has been recognized by Dziejarski et al. [98]. The incorporation of CU or CO_2 valorization, for the effective closure of the C-cycle requires the articulation of several strategies, among which become relevant to this work: wastes valorization, effective treatment and/or processing of flue gases, generation of high value-added products for diverse applications, integrated approach to multi-waste treatment as green solutions, business models based on industrial eco-designed parks and eco-effective integration for zero waste ([623] and references therein). Within the approaches followed to achieve decarbonization, three particular cases could interplay favorably towards a sustainable closure of the C-cycle: (1) long-lasting products immobilizing CO_2; (2) improvements in process efficiency; (3) deployment of decarbonized (renewable or low-C) energy, including electricity and fuels. Examples of CU falling within these approaches might include industrial wastes for carbonation, CO_2 hydrogenation, and electrochemical processes [624]. Therefore, new more efficient and effective chemical processes, for CO_2 conversion into longer lifecycle products need to be developed. Ideally, these processes would convert massive volumes of CO_2, with high selectivity. The optimal use of resources points towards the integration of processes and energy. These highly integrated plants for the processing of large volumes of CO_2, yielding a product slate that satisfies a broad range of market demands, fall in the category of a refinery, i.e., a CO_2 refinery.

3. Sustainability Considerations

In regards to sustainability, Artz et al. [8] presented two ways of addressing this topic. Typically, CU is seen as a way to mitigate CO_2 emissions by reducing its flow to the atmosphere from the emitting facility. On the other hand, the carbon balance and other critical environmental factors could be greatly improved by implementing CO_2-based chemistry for the production of fuels, chemicals, and materials to substitute those of fossil origin. This review article questioned the rare appearance of life cycle assessment (LCA), for evaluating the potentialities of the studied conversion pathways and stressed the importance, relevance, and complexity of this type of analysis. Although they concluded that the highest potential of CO_2 conversion resides in the replacement of energy-intensive feedstocks by CO_2, here the energy intensity of CO_2 activation and reaction should be recognized and will rather point towards lowering the energy intensity of the conversion process and improvements in their energy efficiency.

Recently, a concept of a CO_2 biorefinery for the production of fuels and bulk chemicals has been proposed and found financially attractive and environmentally beneficial [625,626]. The first work proposes and discusses multiple pathways to be considered for CO_2 upgrading [625]. A brief mention of the chemical conversion routes (thermochemical, photochemical, and electrochemical) focuses on methanol production. Most of the work discusses biological means for both fixation and conversion, by terrestrial plants, microalgae, and microorganisms. The authors identified challenges closely related to the lack of sustainability of the reported and discussed results, which emphasized the importance of attaining technical and economic feasibility. These challenges include the development of high-performance catalysts and overcoming the high cost of conversion process into biofuels [625]. The second CO_2 biorefinery concept was centered on two core pathways described as Schemes 1 and 2 in [626]. The reactions considered in Scheme 1 include CO_2 reduction and hydrogenation, into fuels or fuel precursors, via catalytic and electrocatalytic processes. Meanwhile, Scheme 2 considers the production of bulk chemicals by reactions with basic molecules such as ammonia or small organic compounds. Most of the chemical processes considered in Scheme 2 have reached commercial demonstration and/or implementation while those in Scheme 1 are mostly bench-top proof of concept. Scheme 1 has the potential of consuming nearly 30% of the global CO_2 emissions but to produce fuels, which in turn will be responsible for equivalent CO_2 emissions. In terms of CO_2 consumption, Scheme 2 might take 3–4% of the global emissions though it might be more economically favorable due to the higher value of the products [626]. Neither of these CO_2 refinery concepts incorporates sustainability considerations, which have to be brought to the plate early, i.e., during the definition of the configuration. A third CO_2 biorefinery concept has been suggested to be an electro-biorefinery and be centered on microbial electrochemical synthesis (MES) [627]. Although this work offers to describe and discuss the potentialities of a CO_2 electro-biorefinery, it rather describes the R&D status of the MES process and identifies the existing needs and gaps within its scaling up towards industrialization. Furthermore, the status of the development precluded the authors from concluding whether MES could be the core process of a CO_2 electro-biorefinery or just a process in any other type of CO_2 refinery.

In fact, configuring the CO_2 refineries could advantageously apply the principles derived from the eco-design, eco-efficiency, and eco-effectiveness concepts, delineated above. Additionally, the historical growth of oil refining as well as the experience gained from the failures during the commercialization of second-generation (2G) biorefineries offer many lessons learned that should be considered and examined. In both cases, refining [628] and biorefining [629] configurations have been defined following a bottom-up approach (Figure 5a).

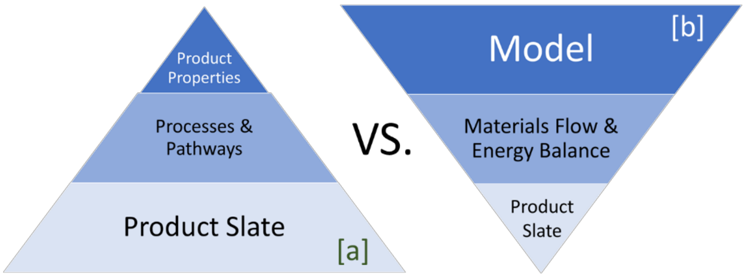


Figure 5. Approaches for refinery configuration design: (**a**) Bottom-up vs. (**b**) Top-down.

In the bottom-up approach, process technologies are first developed to render product(s) either to satisfy a market need or to resolve an end-user problem. Then, these process technologies are integrated to attain viability, technical, and in some instances economical, at least in [628]. Regarding the economy, 2G-biorefining has not been proven to be economically sustainable [630] and oil refining has passed through margin struggling periods [631]. Furthermore, both biorefineries [78] and oil refineries are CO_2 emitters, resulting in environmentally unsustainable or at least with some environmental limitations [632,633]. Moreover, the urgency imposed on decarbonization and the immediate need for increasing the magnitude of CU are driving forces that cannot wait for the historical evolution of concepts and models to start configuring and designing CO_2 refineries. The process technologies should be integrated using eco-efficient and eco-design criteria to fulfill net-zero goals. Additionally, a sustainably designed refinery would optimize the management of the carbon resources to make sure of optimum settings for carbon efficiency, energy efficiency, levelized costs, durability, and robustness. The CO_2 refinery configuration could be eco-designed by following a top-down approach, from a model underpinned by eco-efficiency and eco-effectiveness criteria (Figure 5b). Contrary to the bottom-up approach, the top-down approach is centered on circularization and starts with the development of an integral TEA-LCA model. The model would allow to perform materials flow analysis to identify uses, applications, and post-processing of intermediate and stranded streams, and to define potential circular configurations. The definition of key economic, social, and environmental performance metrics for technology comparison will be key in evaluating sustainability metrics, e.g., water footprint, life cycle cost, global warming potential, ecological footprint, and health-adjusted life years. Selected eco-design configurations can be compared based on TEA-LCA assessments to quantify technology performance, identify technical gaps, and forecast improvements. Applying the three principles (eco-design, eco-efficiency, eco-effectiveness) will promote technologies and practices that minimize resource squandering and waste generation, maximize value creation, and design for reintegration of materials into natural bio-, geo- or chemical processes at their end-of-life. Circularization through eco-design is based on the "dematerialization" transformative change, replacing current practices with measures, policies, or technologies to decrease the quantity of consumed resources and minimize waste generation. The strong need for dematerialization practices has been stressed since improved cleaner technologies, resource recovery, more efficient conservation, and recycling will not be enough to achieve sustainability.

For the CO_2 refinery, the required energy should be provided by a low-carbon power plant and the feed can be supplied either from static emitting sources (biorefinery, oil refinery, power plant, etc.) either through a pipeline network or by integration (chemical or physical). Construction of pipeline networks to interconnect and collect multiple emissions from different emitting facilities has started already. In the case of the U.S., about 8500 km of pipelines were already constructed by 2021, which were transporting an average of 80 MtonCO_2/year [634] (globally a capacity for transporting more than 240 MtonCO_2/year has been built or is under advanced development [14]). The defined infrastructure plans have been based on the analyses of different scenarios, mostly connected either to sequestration or to enhanced oil recovery (EOR). Some of these plans and scenarios consider the construction of 20,000–110,000 km of pipelines, connecting the emitting facility to the sequestration or utilization field [635]. Nevertheless, it is worth mentioning that feeding a CO_2 refinery from pipeline networks would underpin larger capacity refineries, in a preferred scenario benefitted from the economy of scale. Since a refinery can be built at a more convenient location, the issues derived from the logistic mismatch could be minimized and even overcome.

The products manufactured in this wholly integrated CO_2 refinery will contribute to fulfilling the net-zero goals set by the "The 26th UN Climate Change Conference (COP26)" [1] and to achieve sustainability. Preferred process technologies fall within the definition of the so-called "negative emission technologies, NETs". Each of the conversion processes listed in Table 2 are not necessarily NETs though technologies consuming large volumes of CO_2 to convert it to long-lasting products, using low-carbon energy sources have great potential for becoming NETs. However, the needed measures within a net-zero scenario, at a close approach to COP26 2050 committed goals require that the implementation of the developed technologies takes place with the sustainability principles of a circular economy (eco-design, eco-efficiency, and eco-effectiveness criteria, as mentioned above).

The R&D attention for CCUS technologies development has been diverted to specific topics, due to the broad range of composition of industrial emissions (one of the mismatches mentioned above). The variability of these streams brings about different scenarios and situations, for which no universal solution exists. As per similarity with oil refining, a given scenario—situation would be solved with an optimal configuration, constituted by a specific NETs portfolio. Feasibility, effectiveness, and side impacts considered holistically are the critical performance parameters to be assessed. In the bioenergy technologies portfolio, it has been found that only *an optimized technology portfolio timely deployed* will sustainably contribute to mitigating climate change [636]. In this case, suboptimal solutions resulted in infeasible, ineffective, and even created larger problems. In this study, the most promising NETs in the area were evaluated: afforestation and reforestation, biochar, bioenergy with CCS, direct air carbon capture and storage, enhanced weathering on land and in oceans, ocean fertilization, and soil carbon sequestration [636].

As mentioned above, and according to several discussions and revisions [4,5,9,53,54,69,97,98], the developed process technologies have reached different levels of research, development, and maturity, and clearly, gaps and needs for further R&D in the corresponding topics still exist. For these reasons, it is necessary to establish a technology pipeline that positions the processes' availability in terms of a timeframe. The definition of this technology pipeline starts with a technology analysis based on the published patent literature. The importance of this type of analysis has been indicated by Bisotti et. al. [394] though their study concerns the conventional methanol synthesis technology and the development of a better kinetic model for such reaction, which falls outside the scope of the present work. Additionally, their technology analysis associates technological evolution with the results of a bibliometrics analysis of the patents. Furthermore, the high number of new catalysts developed was associated with the growth of the methanol market. One of the first remarks that should be made is that the technology market is not the market of the technology product(s). Then, it is fair to say that the vast majority of patented catalysts rarely reach commercial scale. Finally, according to technology licensors and/or catalysts vendors, the commercially available methanol synthesis catalysts have been optimized to perform and to last for their corresponding process. Many of these catalysts are part of the technology package that the licensor offers to the user and the process operator cannot change it without losing the guarantees. The reader interested in the real status of the technologies for methanol synthesis from CO_2 could refer to [9,33]. Further details of the thermocatalytic and electrocatalytic work for these processes can be found in the references cited in Table 2 (85 articles and 15 patents or applications). The tech pipeline consists of a database of the processes with potential for integration within a CO_2 refinery. It should contain the description and state of the art of the technology market as well as their relevant data for the design and development of the proposed model to configure CO_2 refineries. Particular emphasis should be placed on technical data concerning carbon-efficiency (conversion, product slate, and yields), energy efficiency (consumption, balance, and losses), and material balances (waste generation, losses, and by-products). Besides building the model, the collected information could also be used to identify needs, challenges, and gaps to guide R&D, e.g., to accelerate or kill a given development attempt.

An integral model combining TEA, LCA, and optimization tools is desirable to understand the performance and benefits of the different configurations and to generate insights into the impact on the sustainability of feedstock compositions (see Figure 6). Several issues have been reported on C-accounting that invalidate the C-intensity and efficiency results [637], stressing the importance of method selection, i.e., consequential or attributional, which are key for carbon and GHG accounting, and for life cycles. The issues associated with C-accounting for NETs have been pointed out since these technologies not only remove carbon but also, they might emit it. The recommendation was to report emissions and removals when and where they actually occur, providing the appropriate accounting method is used. Thus, for NETs incentivization or for supporting decision-making consequential methods were recommended while attributional methods were better employed in the descriptions of possible net zero static scenarios [637]. As mentioned already, addressing the magnitude of the CO_2 emissions calls for multiple gigaton solutions. Examples of the "removal" capabilities (or emissions reduction capability) of some technologies were provided by Pacala & Socolow [638], for instance, reduction of 1 Gton of CO_2 emissions can be attained with 1000 zero-emission 500 MW coal-fired power plant with CCS, by installing 50 times the current global capacity of wind energy or by planting energy crops 15 times the size of Iowa. Net zero goals require 37 times these types of solutions, leading to the cost-effectiveness barriers found in the implementation and deployment of CCS solutions [639].

Configuration complexity, a well-known term in oil refining, needs to be defined and assessed for the newly introduced CO_2 refinery concept. The degrees of freedom increase with complexity. Likewise, feedstock flexibility and product slate broadening also increase with complexity. Therefore, it could be expected that complexity would impact the sustainability indicators. Regarding feedstock flexibility, the real composition of industrial emissions is practically unknown. Their chemical characterization, as well as their volumetric quantification, are needed for the most concerning CO_2-containing industrial feedstocks particularly, from the larger emitters, e.g., (fossil-fired) power plants, cement, steel, and/or refining. The optimum management of materials involves the full valorization of the feedstock, even including contaminants. Closing all material flow loops warrants zero waste processing and maximizes eco-efficiency. Feedstock composition

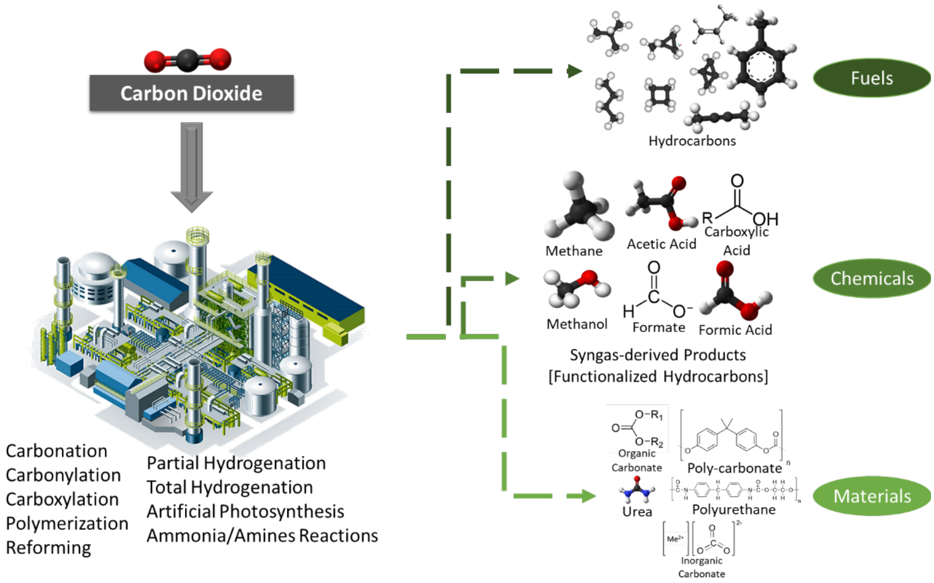


Figure 6. Value-added products from the conversion of CO_2 in an eco-designed refinery.

also determines the need for pretreatment, separation, and/or conversion units that might turn into increasing complexity. Further increments in the number and type of compounds present in the feedstock lead to increases in refinery complexity. Additional increases in complexity might arise from product slate broadening and from producing materials with a longer lifecycle or service life. Even though increasing the configuration complexity will bring technical advantages, it will nonetheless impact the economy of the refinery. A simple configuration of a CO_2 refinery has been recently economically and environmentally evaluated [640]. This configuration was defined following a bottom-up approach and includes methanol synthesis, from DAC-CO_2 as feed, integrated to methanol-to-olefins (MTO) and methanol-to-aromatics (MTA). The quantified refinery benefits were highly limited by the high cost of green hydrogen and the atmospheric CO_2 [640]. Furthermore, these results can be also taken as an indication of the failure of the bottom-up approach, and of the need for incorporation of the three eco-principles and for a circularization strategy that optimizes resource use and minimizes waste generation. Finally, although it shows the advantages of the early conceptualizing of the configuration, that concept missed the relevance of maximizing the volume of CO_2 consumed, the inclusion of long-lasting products (not fuels), and the use of a low-carbon energy source and/or more energy-efficient processes.

The application of "the one problem-one solution approach" requires tailor-made solutions for each emitting facility, which is far from sustainable. Meanwhile, few CO_2 refineries, such as the one proposed here might be more prompt to attain the COP26 goals and become sustainable, particularly when the configuration has been eco-designed following eco-efficiency and eco-effectiveness criteria, with the top-down suggested approach and the considerations discussed above.

4. Final Remarks

In order to close the gap between carbon dioxide (CO_2) emissions (Gton/year) and its utilization (Mton/year), neither a single product nor an exclusive pathway are holistic solution. Instead, processes consuming massive CO_2 volumes, exhibiting lower intensity in carbon- (C-) and energy, and rendering products or services with longer longevity or lifecycle are needed. Therefore, a suite of process technologies should be configured efficiently and effectively, into an integrated CO_2 refinery, to change the way and pathways for producing fuels, chemicals, and materials (Figure 6), from the unlimited source of carbon, emitted as CO_2. The knowledge and learnings from refining and biorefining can be applied together with the novel concepts of eco-design, eco-efficiency, and eco-effectiveness to configure such CO_2 refineries. This work presents and discusses the author's views on an innovative top-down methodology that could lead to a sustainable carbon cycle (in terms of energy, environment, and economy). Research and development gaps and needs could be identified using the suggested methodology before any further investment. Therefore, eventually, a sustainable CO_2 refinery will be the vehicle to close the carbon cycle of a CCE and underpin a decarbonized chemical industry.

In summary, this review has served to establish that (i) CU complements CCS, (ii) CCS and CU are not enough to fulfill net-zero goals, (iii) CU and CCS can be integrated to create a "Circular Carbon Economy, CCE", (iv) circularization is not a warranty for sustainability, (v) CU should focus on the use of massive volumes of CO_2, (vi) conversion into value-added products create revenues, (vii) manufacture of long-lasting products can mitigate atmospheric accumulation, and (viii) eco-principles could lead to sustainable technological solutions. Therefore, the proposed CO_2 refinery can holistically be seen as a "negative emission technology package". Hopefully, the application of the eco-principles, the circularization, and the conversion of massive volumes of CO_2 into long-lasting/value-added products, using low-C energy sources would all sum up to an effective carbon reduction strategy, underpinning a CCE.

Funding

The author acknowledges the financial support for the elaboration of this manuscript to the Laboratory Directed Research & Development (LDRD) Program of Battelle Energy Alliance, LLC under DOE Idaho Operations Office contract No. DE-AC07-05ID14517.

Data Availability

No new data were created or analyzed in this work. Data sharing is not applicable to this article.

Conflicts of Interest

The author has no conflict of interest to declare.

References

1. United Nations. (2021). *COP26: Decision -/CMA.3. Glasgow climate pact.* https://unfccc.int/sites/default/files/resource/cma3_auv_2_cover%2520decision.pdf (accessed 16 February 2023).
2. Global Carbon Project. (2022). *Global carbon atlas: CO_2 emissions.* http://www.globalcarbonatlas.org/en/CO2-emissions (accessed 10 May 2023).
3. International Energy Agency (IEA). (2020). *Global energy review.*
4. Chauvy, R., Meunier, N., Thomas, D., & De Weireld, G. (2019). Selecting emerging CO_2 utilization products for short-to mid-term deployment. *Applied Energy*, *236*, 662–680. https://doi.org10.1016/j.apenergy.2018.11.096
5. Aresta, M. (Ed.). (2010). *Carbon dioxide as chemical feedstock.* John Wiley & Sons. https://doi.org/10.1002/9783527629916
6. Dibenedetto, A., Angelini, A., & Stufano, P. (2014). Use of carbon dioxide as feedstock for chemicals and fuels: homogeneous and heterogeneous catalysis. *Journal of Chemical Technology & Biotechnology*, *89*(3), 334–353. https://doi.org/10.1002/jctb.4229
7. Müller, L. J., Kätelhön, A., Bringezu, S., McCoy, S., Suh, S., Edwards, R., et al. (2020). The carbon footprint of the carbon feedstock CO_2. *Energy & Environmental Science*, *13*(9), 2979–2992. https://doi.org/10.1039/d0ee01530j
8. Artz, J., Müller, T. E., Thenert, K., Kleinekorte, J., Meys, R., Sternberg, A., et al. (2018). Sustainable conversion of carbon dioxide: an integrated review of catalysis and life cycle assessment. *Chemical Reviews*, *118*(2), 434–504. https://doi.org/10.1021/acs.chemrev.7b00435
9. Ramirez-Corredores, M. M., Goldwasser, M. R., & Falabella de Sousa Aguiar, E. (2023). *Decarbonization as a Route Towards Sustainable Circularity*. Springer, Cham. https://doi.org/10.1007/978-3-031-19999-8
10. Covestro. (2016). *Pure facts – why the circular economy matters*. https://www.covestro.com/-/media/covestro/country-sites/global/documents/k-2016/7_pur_pure_facts_circular_economy_engl.pdf?la=en&hash=CAC6CB692A27D5C4902873B62ED0AC17FF396F6A (accessed 22 July 2023).
11. US EPA. (2023). Carbon dioxide emissions. *Greenhouse Gas Reporting Program (GHGRP)*. https://www.epa.gov/ghgreporting/ghgrp-emissions-location (accessed 22 July 2023).
12. Parsons Brinckerhoff. (2011). *Accelerating the uptake of CCS: Industrial use of captured carbon dioxide.* Global CCS Institute.
13. Global Carbon Project. (2020). *Global carbon atlas: CO_2 emissions.* http://www.globalcarbonatlas.org/en/CO2-emissions (accessed 21 February 2021).
14. Steyn, M., Oglesby, J., Turan, G., Zapantis, A., & Gebremedhin, R. (2022). *Global status of CCS.* Global CCS Institute. https://status22.globalccsinstitute.com (accessed 12 May 2023).
15. Centi, G., Perathoner, S., Salladini, A., & Iaquaniello, G. (2020). Economics of CO_2 utilization: a critical analysis. *Frontiers in Energy Research*, *8*, 567986. https://doi.org/10.3389/fenrg.2020.567986
16. Centi, G., & Perathoner, S. (2009). Catalysis: role and challenges for a sustainable energy. *Topics in Catalysis*, *52*, 948–961. https://doi.org/10.1007/s11244-009-9245-x
17. De Luna, P., Hahn, C., Higgins, D., Jaffer, S. A., Jaramillo, T. F., & Sargent, E. H. (2019). What would it take for renewably powered electrosynthesis to displace petrochemical processes? *Science*, *364*(6438), eaav3506. https://doi.org/10.1126/science.aav3506
18. Klankermayer, J., & Leitner, W. (2016). Harnessing renewable energy with CO_2 for the chemical value chain: challenges and opportunities for catalysis. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *374*(2061), 20150315. https://doi.org/10.1098/rsta.2015.0315
19. IPCC. (2018). *Global warming of 1.5 °C.* Cambridge University Press. https://www.ipcc.ch/sr15 (accessed 25 January 2024).

20. Riahi, K., Schaeffer, R., Arango, J., Calvin, K., Guivarch, C., Hasegawa, T., et al. (2023). Mitigation Pathways Compatible with Long-term Goals. In *Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 295–408). Cambridge University Press. https://doi.org/10.1017/9781009157926.005
21. IEA. (2023). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach (accessed 25 March 2024).
22. Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., et al. (2018). Residual fossil CO_2 emissions in 1.5–2 °C pathways. *Nature Climate Change*, *8*(7), 626–633. https://doi.org/10.1038/s41558-018-0198-6
23. Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W. R., III, Zhou, N., et al. (2020). Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Applied Energy*, *266*, 114848. https://doi.org/10.1016/j.apenergy.2020.114848
24. Ramirez-Corredores, M. M., Goldwasser, M. R., & Falabella de Sousa Aguiar, E. (2023). Sustainable circularity. In *Decarbonization as a route towards sustainable circularity* (pp. 103–125). Springer, Cham. https://doi.org/10.1007/978-3-031-19999-8_3
25. United Nations. (2015). *2030 agenda for sustainable development*. Brussels, Belgium. https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E (accessed 13 March 2021).
26. Borrello, M., Pascucci, S., & Cembalo, L. (2020). Three propositions to unify circular economy research: A review. *Sustainability*, *12*(10), 4069. https://doi.org/10.3390/SU12104069
27. Pee, A. D., Pinner, D., Roelofsen, O., & Somers, K. (2018). *Decarbonization of industrial sectors: The next frontier*. McKinsey.
28. IEA. (2017). *Energy technology perspectives 2017: Catalysing energy technology transformations*. https://www.iea.org/reports/energy-technology-perspectives-2017 (accessed 13 March 2021).
29. IPCC. (2014). *Climate change 2014: Mitigation of climate change*. https://www.ipcc.ch/report/ar5/wg3 (accessed 13 March 2021).
30. IEA. (2023). *Global energy and climate model documentation*. https://iea.blob.core.windows.net/assets/ff3a195d-762d-4284-8bb5-bd062d260cc5/GlobalEnergyandClimateModelDocumentation2023.pdf (accessed 25 March 2024).
31. Johansson, T. B., Patwardhan, A. P., Nakićenović, N., & Gomez-Echeverri, L. (Eds.). (2012). *Global energy assessment: toward a sustainable future*. Cambridge University Press.
32. IPCC. (2005). *Carbon dioxide capture and storage*. Cambridge University Press.
33. Ramirez-Corredores, M. M., Diaz, L. A., Gaffney, A. M., & Zarzana, C. A. (2021). Identification of opportunities for integrating chemical processes for carbon (dioxide) utilization to nuclear power plants. *Renewable and Sustainable Energy Reviews*, *150*, 111450. https://doi.org/10.1016/j.rser.2021.111450
34. Brueske, S., Kramer, C., & Fisher, A. (2015). *Chemical bandwidth study*. U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/iedo/articles/bandwidth-study-us-chemical-manufacturing (accessed 13 March 2021).
35. Liu, J., Li, B., Cao, J., Song, C., & Guo, X. (2022). Effects of indium promoter on iron-based catalysts for CO_2 hydrogenation to hydrocarbons. *Journal of CO2 Utilization*, *65*, 102243. https://doi.org/10.1016/j.jcou.2022.102243
36. Wang, H., Nie, X., Liu, Y., Janik, M. J., Han, X., Deng, Y., et al. (2022). Mechanistic insight into hydrocarbon synthesis via CO_2 hydrogenation on χ-Fe_5C_2 catalysts. *ACS Applied Materials & Interfaces*, *14*(33), 37637–37651. https://doi.org/10.1021/acsami.2c07029
37. Liu, J., Song, Y., Guo, X., Song, C., & Guo, X. (2022). Recent advances in application of iron-based catalysts for CO_x hydrogenation to value-added hydrocarbons. *Chinese Journal of Catalysis*, *43*(3), 731–754. https://doi.org/10.1016/S1872-2067(21)63802-0
38. Liu, J., Zhang, G., Jiang, X., Wang, J., Song, C., & Guo, X. (2021). Insight into the role of Fe_5C_2 in CO_2 catalytic hydrogenation to hydrocarbons. *Catalysis Today*, *371*, 162–170. https://doi.org/10.1016/j.cattod.2020.07.032
39. Liu, J., Li, K., Song, Y., Song, C., & Guo, X. (2021). Selective hydrogenation of CO_2 to hydrocarbons: effects of Fe_3O_4 particle size on reduction, carburization, and catalytic performance. *Energy & Fuels*, *35*(13), 10703–10709. https://doi.org/10.1021/acs.energyfuels.1c01265
40. Yuan, F., Zhang, G., Zhu, J., Ding, F., Zhang, A., Song, C., et al. (2021). Boosting light olefin selectivity in CO_2 hydrogenation by adding Co to Fe catalysts within close proximity. *Catalysis Today*, *371*, 142–149. https://doi.org/10.1016/j.cattod.2020.07.072
41. Su, C. Y., Tan, J. Q., & Wang, C. X. (2013). Study on CO_2 Hydrogenation to Ethylene with Iron-Based Catalyst. *Advanced Materials Research*, *791*, 112–115. https://doi.org/10.4028/www.scientific.net/AMR.791-793.112
42. Dang, S., Gao, P., Liu, Z., Chen, X., Yang, C., Wang, H., et al. (2018). Role of zirconium in direct CO_2 hydrogenation to lower olefins on oxide/zeolite bifunctional catalysts. *Journal of Catalysis*, *364*, 382–393. https://doi.org/10.1016/j.jcat.2018.06.010
43. Corva, M., Feng, Z., Dri, C., Salvador, F., Bertoch, P., Comelli, G., et al. (2016). Carbon dioxide reduction on Ir (111): stable hydrocarbon surface species at near-ambient pressure. *Physical Chemistry Chemical Physics*, *18*(9), 6763–6772. https://doi.org/10.1039/c5cp07906c
44. Roberts, F. S., Kuhl, K. P., & Nilsson, A. (2015). High selectivity for ethylene from carbon dioxide reduction over copper nanocube electrocatalysts. *Angewandte Chemie*, *127*(17), 5268–5271. https://doi.org/10.1002/anie.201412214
45. Loiudice, A., Lobaccaro, P., Kamali, E. A., Thao, T., Huang, B. H., Ager, J. W., et al. (2016). Tailoring copper nanocrystals towards C_2 products in electrochemical CO_2 reduction. *Angewandte Chemie International Edition*, *55*(19), 5789–5792. https://doi.org/10.1002/anie.201601582
46. Kas, R., Kortlever, R., Yılmaz, H., Koper, M. T., & Mul, G. (2015). Manipulating the hydrocarbon selectivity of copper nanoparticles in CO_2 electroreduction by process conditions. *ChemElectroChem*, *2*(3), 354–358. https://doi.org/10.1002/celc.201402373
47. Dinh, C. T., Burdyny, T., Kibria, M. G., Seifitokaldani, A., Gabardo, C. M., García de Arquer, F. P., et al. (2018). CO_2 electroreduction to ethylene via hydroxide-mediated copper catalysis at an abrupt interface. *Science*, *360*(6390), 783–787. https://doi.org/10.1126/science.aas9100
48. García de Arquer, F. P., Dinh, C. T., Ozden, A., Wicks, J., McCallum, C., Kirmani, A. R., et al. (2020). CO_2 electrolysis to multicarbon products at activities greater than 1 A cm^{-2}. *Science*, *367*(6478), 661–666. https://doi.org/10.1126/science.aay4217

49. Tan, Y. C., Lee, K. B., Song, H., & Oh, J. (2020). Modulating local CO_2 concentration as a general strategy for enhancing C–C coupling in CO_2 electroreduction. *Joule*, *4*(5), 1104–1120. https://doi.org/10.1016/j.joule.2020.03.013
50. Ma, W., Xie, S., Liu, T., Fan, Q., Ye, J., Sun, F., et al. (2020). Electrocatalytic reduction of CO_2 to ethylene and ethanol through hydrogen-assisted C–C coupling over fluorine-modified copper. *Nature Catalysis*, *3*(6), 478–487. https://doi.org/10.1038/s41929-020-0450-0
51. IEA. (2018). *The future of petrochemicals. Towards more sustainable plastics and fertilisers*. https://www.iea.org/reports/the-future-of-petrochemicals (accessed 13 March 2021).
52. Aresta, M., Dibenedetto, A., & Quaranta, E. (2016). *Reaction mechanisms in carbon dioxide conversion*. Springer. https://doi.org/0.1007/978-3-662-46831-9
53. Aresta, M., Karimi, I., & Kawi, S. (Eds.). (2019). *An economy based on carbon dioxide and water, potential of large scale carbon dioxide utilization*. Springer, Cham. https://doi.org/10.1007/978-3-030-15868-2
54. Centi, G., & Perathoner, S. (Eds.). (2014). *Green carbon dioxide: advances in CO_2 utilization*. John Wiley & Sons. https://doi.org/10.1002/9781118831922
55. Chiang, P.-C., & Pan, S.-Y. (2017). *Carbon dioxide mineralization and utilization*. Springer.
56. Fennell, P., & Anthony, B. (2015). *Calcium and chemical looping technology for power generation and carbon dioxide (CO_2) capture*. Woodhead Publishing.
57. Fink, J. K. (2013). *Reactive polymers fundamentals and applications: A concise guide to industrial polymers* (2nd ed.). Elsevier. https://doi.org/10.1016/C2012-0-02516-1
58. Karamé, I., Shaya, J., & Srour, H. (2018). *Carbon dioxide chemistry, capture and oil recovery*. InTechOpen.
59. Klitkou, A., Fevolden, M., & Capasso, M. (Eds.). (2019). *From waste to value: Valorisation pathways for organic waste streams in circular bioeconomies*. Taylor & Francis. https://doi.org/10.4324/9780429460289
60. Michael, N., & Peter, S. (2019). *Carbon dioxide utilization* (Vol. 1). De Gruyter. https://doi.org/10.1515/9783110563191
61. Muradov, N. (2014). *Liberating energy from carbon: Introduction to decarbonization* (Vol. 22). Springer. https://doi.org/10.1007/978-1-4939-0545-4
62. National Academies of Sciences-Engineering-Medicine. (2019). *Gaseous carbon waste streams utilization: Status and research needs*. The National Academies Press. https://doi.org/10.17226/25232
63. National Academies of Sciences-Engineering-Medicine. (2019). *Negative emissions technologies and reliable sequestration: A research agenda.* The National Academies Press. https://doi.org/10.17226/25259
64. National Academies of Sciences-Engineering-Medicine. (2021). *Accelerating decarbonization of the U.S. Energy system*. The National Academies Press. https://doi.org/10.17226/25932
65. National Research Council. (2001). *Carbon management: Implications for R&D in the chemical sciences and technology*. The National Academies Press. https://doi.org/10.17226/10153
66. Olah, G. A., Goeppert, A., & Prakash, G. K. S. (2009). *Beyond oil and gas: The methanol economy* (2nd ed.). Wiley-VCH. https://doi.org/10.1002/9783527627806
67. Shi, F., & Morreale, B. (2015). *Novel materials for carbon dioxide mitigation technology* (pp. 207–229). Elsevier.
68. Song, C., Gaffney, A. F., & Fujimoto, K. (Eds.). (2002). *CO_2 conversion and utilization* (ACS Symposium Series No. 809). American Chemical Society (ACS).
69. Styring, P., Quadrelli, E. A., & Armstrong, K. (2015). *Carbon dioxide utiiisation: Closing the carbon cycle*. Elsevier.
70. Suib, S. L. (2013). *New and future developments in catalysis. Activation of carbon dioxide*. Elsevier. https://doi.org/10.1016/C2010-0-68570-1
71. Aresta, M. (2006). *Carbon dioxide reduction and uses as a chemical feedstock*, in *Activation of small molecules: Organometallic and bioinorganic perspectives* (pp. 1–41). John Wiley & Sons. https://doi.org/10.1002/9783527609352.ch1
72. Aresta, M. (2010). Carbon dioxide: Utilization options to reduce its accumulation in the atmosphere. In *Carbon dioxide as chemical feedstock* (pp. 1–13). Wiley-VCH. https://doi.org/10.1002/9783527629916.ch1
73. Aresta, M. (2019). Preface: The carbon dioxide problem. In M. Aresta, I. Karimi, & S. Kawi (Eds.), *An economy based on carbon dioxide and water, potential of large scale carbon dioxide utilization*. Springer.
74. Aresta, M., & Dibenedetto, A. (2007). Artificial carbon sinks: Utilization of carbon dioxide for the synthesis of chemicals and technological applications. In *Greenhouse gas sinks* (pp. 98–114). CABI Publishing.
75. Aresta, M., & Dibenedetto, A. (2010). Industrial utilization of carbon dioxide (CO_2). In *Developments and innovation in carbon dioxide (CO_2) capture and storage technology* (pp. 377–410). Elsevier. https://doi.org/10.1533/9781845699581.4.377
76. Aresta, M., & Dibenedetto, A. (2013). Carbon dioxide: A valuable source of carbon for chemicals, fuels and materials. In *Catalytic process development for renewable materials* (pp. 355–385). Wiley-VCH. https://doi.org/10.1002/9783527656639.ch13
77. Aresta, M., & Nocito, F. (2019). Large scale utilization of carbon dioxide: From its reaction with energy rich chemicals to (Co)-processing with water to afford energy rich products. Opportunities and barriers. In M. Aresta, I. Karimi, & S. Kawi (Eds.), *An economy based on carbon dioxide and water, potential of large scale carbon dioxide utilization* (pp. 2–34). Springer.
78. Centi, G., & Perathoner, S. (2013). Catalytic transformation of CO_2 to fuels and chemicals, with reference to biorefineries. In K. S. Triantafyllidis, A. A. Lappas, & M. Stöcker (Eds.), *The role of catalysis for the sustainable production of bio-fuels and bio-chemicals* (pp. 529–555). Elsevier. https://doi.org/10.1016/B978-0-444-56330-9.00016-4
79. Hall, P. J., Wilson, I. a. G., & Rennie, A. (2015). CO_2-derived fuels for energy storage. In P. Styring, E. A. Quadrelli, & K. Armstrong (Eds.), *Carbon dioxide utiiisation: Closing the carbon cycle* (pp. 33–44). Elsevier.
80. Kiss, A. A., Pragt, J. J., Vos, H. J., Bargeman, G., & De Groot, M. T. (2016). Enhanced process for methanol production by CO_2 hydrogenation. In *Computer aided chemical engineering* (Vol. 38, pp. 985–990). Elsevier. https://doi.org/10.1016/B978-0-444-63428-3.50169-7
81. Langanke, J., Wolf, A., & Peters, M. (2015). Polymers from CO_2—an industrial perspective. In P. Styring, E. A. Quadrelli, & K. Armstrong (Eds.), *Carbon dioxide utiiisation: Closing the carbon cycle* (pp. 59–71). Elsevier. https://doi.org/10.1016/B978-0-444-62746-9.00005-0
82. Leonzio, G. (2022). State-of-the-art overview of CO_2 conversions. In *Carbon dioxide utilization to sustainable energy and fuels* (pp. 335–353). Springer Nature. https://doi.org/10.1007/978-3-030-72877-9_18
83. Mahajan, D., Song, C., & Scaroni, A. W. (2002). Catalytic reduction of CO_2 into liquid fuels: Simulating reactions under geologic formation conditions. In *CO_2 conversion and utilization* (pp. 166–180). American Chemical Society. https://doi.org/10.1021/bk-2002-0809.ch011

84. IPCC. (2005). Mineral carbonation and industrial uses of carbon dioxide. In *Special report on carbon dioxide capture and storage* (pp. 319–338). Cambridge University Press.
85. Nakagawa, Y., Honda, M., & Tomishige, K. (2014). Direct synthesis of organic carbonates from CO_2 and alcohols using heterogeneous oxide catalysts. In *Green carbon dioxide: Advances in CO_2 utilization* (pp. 119–148). Wiley Blackwell. https://doi.org/10.1002/9781118831922.ch5
86. Rafiee, A., Khalilpour, K. R., & Milani, D. (2019). CO_2 conversion and utilization pathways. In K. R. Khalilpour (Ed.), *Polygeneration with polystorage for chemical and energy hubs* (213–245). Academic Press. https://doi.org/10.1016/B978-0-12-813306-4.00008-2
87. Gielen, D., Podkanski, J., & Unander, F. (2006). Prospects for CO_2 capture and storage. International Energy Agency.
88. Seemann, M., & Thunman, H. (2019). Methane synthesis. In M. Materazzi & P. U. Foscolo (Eds.), *Substitute natural gas from waste* (pp. 221–243). Academic Press. https://doi.org/10.1016/B978-0-12-815554-7.00009-X
89. Siddique, M. H., Maqbool, F., Shahzad, T., Waseem, M., Rasul, I., Hayat, S., et al. (2023). Recent advances in carbon dioxide utilization as renewable energy. In *Green Sustainable Process for Chemical and Environmental Engineering and Science* (pp. 197–210). Elsevier. https://doi.org/10.1016/B978-0-323-99429-3.00032-1
90. Song, C. (2002). CO_2 conversion and utilization: An overview. In *CO_2 conversion and utilization* (ACS Symposium Series, pp. 2–30). American Chemical Society (ACS).
91. Ushikoshi, K., Moria, K., Watanabe, T., Takeuchi, M., & Saito, M. (1998). A 50 kg/day class test plant for methanol synthesis from CO_2 and H_2. In *Studies in surface science and catalysis* (Vol. 114, pp. 357–362). Elsevier. https://doi.org/10.1016/S0167-2991(98)80770-2
92. Budzianowski, W. M. (2010). Mass-recirculating systems in CO_2 capture technologies: A review. *Recent Patents on Engineering*, *4*(1), 15–43. https://doi.org/10.2174/187221210790244758
93. Gattrell, M., Gupta, N., & Co, A. (2006). A review of the aqueous electrochemical reduction of CO_2 to hydrocarbons at copper. *Journal of Electroanalytical Chemistry*, *594*(1), 1–19. https://doi.org/10.1016/j.jelechem.2006.05.013
94. Ma, J., Sun, N., Zhang, X., Zhao, N., Xiao, F., Wei, W., et al. (2009). A short review of catalysis for CO_2 conversion. *Catalysis Today*, *148*(3–4), 221–231. https://doi.org/10.1016/j.cattod.2009.08.015
95. Mikkelsen, M., Jørgensen, M., & Krebs, F. C. (2010). The teraton challenge. A review of fixation and transformation of carbon dioxide. *Energy & Environmental Science*, *3*(1), 43–81. https://doi.org/10.1039/b912904a
96. Huijgen, W. J. J., & Comans, R. N. J. (2003). *Carbon dioxide sequestration by mineral carbonation: Literature review* (ECN-C--03-016 Report). Energy Research Centre of the Netherlands.
97. Chauvy, R., & De Weireld, G. (2020). CO_2 utilization technologies in Europe: a short review. *Energy Technology*, *8*(12), 2000627. https://doi.org/10.1002/ente.202000627
98. Dziejarski, B., Krzyżyńska, R., & Andersson, K. (2023). Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment. *Fuel*, *342*, 127776. https://doi.org/10.1016/j.fuel.2023.127776
99. Abidin, V., Bouallou, C., & Clodic, D. (2011). Valorization of CO_2 emissions into ethanol by an innovative process. *Chemical Engineering Transactions*, *25*, 1–6. https://doi.org/10.3303/CET1125001
100. Anicic, B., Trop, P., & Goricanec, D. (2014). Comparison between two methods of methanol production from carbon dioxide. *Energy*, *77*, 279–289. https://doi.org/10.1016/j.energy.2014.09.069
101. Chein, R. Y., & Yu, C. T. (2017). Thermodynamic equilibrium analysis of water-gas shift reaction using syngases-effect of CO_2 and H_2S contents. *Energy*, *141*, 1004–1018. https://doi.org/10.1016/j.energy.2017.09.133
102. Daza, Y. A., & Kuhn, J. N. (2016). CO_2 conversion by reverse water gas shift catalysis: Comparison of catalysts, mechanisms and their consequences for CO_2 conversion to liquid fuels. *RSC Advances*, *6*(55), 49675–49691. https://doi.org/10.1039/c6ra05414e
103. Dijkstra, J. W., Raju, G., Peppink, G., & Jansen, D. (2011). Techno-economic evaluation of membrane technology for pre-combustion decarbonisation: water-gas shift versus reforming. *Energy Procedia*, *4*, 723–730. https://doi.org/10.1016/j.egypro.2011.01.111
104. Gao, J., Wu, Y., Jia, C., Zhong, Z., Gao, F., Yang, Y., et al. (2016). Controllable synthesis of α-MoC1-x and β-Mo_2C nanowires for highly selective CO_2 reduction to CO. *Catalysis Communications*, *84*, 147–150. https://doi.org/10.1016/j.catcom.2016.06.026
105. Hu, J., Brooks, K. P., Holladay, J. D., Howe, D. T., & Simon, T. M. (2007). Catalyst development for microchannel reactors for martian in situ propellant production. *Catalysis Today*, *125*(1–2), 103–110. https://doi.org/10.1016/j.cattod.2007.01.067
106. Jadhav, S. G., Vaidya, P. D., Bhanage, B. M., & Joshi, J. B. (2016). Kinetics of reverse water-gas shift reaction over Pt/Al_2O_3 catalyst. *The Canadian Journal of Chemical Engineering*, *94*(1), 101–106. https://doi.org/10.1002/cjce.22370
107. Jo, S. B., Woo, J. H., Lee, J. H., Kim, T. Y., Kang, H. I., Lee, S. C., et al. (2020). CO_2 green technologies in CO_2 capture and direct utilization processes: methanation, reverse water-gas shift, and dry reforming of methane. *Sustainable Energy & Fuels*, *4*(11), 5543–5549. https://doi.org/10.1039/d0se00951b
108. Kunkes, E. L., Studt, F., Abild-Pedersen, F., Schlögl, R., & Behrens, M. (2015). Hydrogenation of CO_2 to methanol and CO on $Cu/ZnO/Al_2O_3$: Is there a common intermediate or not? *Journal of Catalysis*, *328*, 43–48. https://doi.org/10.1016/j.jcat.2014.12.016
109. Lindenthal, L., Popovic, J., Rameshan, R., Huber, J., Schrenk, F., Ruh, T., et al. (2021). Novel perovskite catalysts for CO_2 utilization-Exsolution enhanced reverse water-gas shift activity. *Applied Catalysis B: Environmental*, *292*, 120183. https://doi.org/10.1016/j.apcatb.2021.120183
110. Rezaei, E., & Dzuryk, S. (2019). Techno-economic comparison of reverse water gas shift reaction to steam and dry methane reforming reactions for syngas production. *Chemical Engineering Research and Design*, *144*, 354–369. https://doi.org/10.1016/j.cherd.2019.02.005
111. Rodrigues, M. T., Zonetti, P. C., Alves, O. C., Sousa-Aguiar, E. F., Borges, L. E., & Appel, L. G. (2017). RWGS reaction employing Ni/Mg(Al,Ni)O − The role of the O vacancies. *Applied Catalysis A: General*, *543*, 98–103. https://doi.org/10.1016/j.apcata.2017.06.026
112. Saeidi, S., Najari, S., Fazlollahi, F., Nikoo, M. K., Sefidkon, F., Klemeš, J. J., et al. (2017). Mechanisms and kinetics of CO2 hydrogenation to value-added products: A detailed review on current status and future trends. *Renewable and Sustainable Energy Reviews*, *80*, 1292–1311. https://doi.org/10.1016/j.rser.2017.05.204
113. Sun, H., Wang, J., Zhao, J., Shen, B., Shi, J., Huang, J., et al. (2019). Dual functional catalytic materials of Ni over Ce-modified CaO sorbents for integrated CO_2 capture and conversion. *Applied Catalysis B: Environmental*, *244*, 63–75. https://doi.org/10.1016/j.apcatb.2018.11.040

114. Wang, J., Liu, C. Y., Senftle, T. P., Zhu, J., Zhang, G., Guo, X., et al. (2019). Variation in the In_2O_3 crystal phase alters catalytic performance toward the reverse water gas shift reaction. *ACS Catalysis*, *10*(5), 3264–3273. https://doi.org/10.1021/acscatal.9b04239
115. Yang, L., Pastor-Pérez, L., Gu, S., Sepúlveda-Escribano, A., & Reina, T. R. (2018). Highly efficient Ni/CeO_2-Al_2O_3 catalysts for CO_2 upgrading via reverse water-gas shift: Effect of selected transition metal promoters. *Applied Catalysis B: Environmental*, *232*, 464–471. https://doi.org/10.1016/j.apcatb.2018.03.091
116. Zhu, J., Zhang, G., Li, W., Zhang, X., Ding, F., Song, C., et al. (2020). Deconvolution of the particle size effect on CO2 hydrogenation over iron-based catalysts. *ACS Catalysis*, *10*(13), 7424–7433. https://doi.org/10.1021/acscatal.0c01526
117. Kurz, G., & Von Linde, J. (1994). *Process for obtaining carbon monoxide* (Patent No. DE3617280A1). German Patent and Trade Mark Office.
118. Xi, W., Yang, P., Jiang, M., Wang, X., Zhou, H., Duan, J., et al. (2023). Electrochemical CO_2 reduction coupled with alternative oxidation reactions: electrocatalysts, electrolytes, and electrolyzers. *Applied Catalysis B: Environmental*, *341*, 123291. https://doi.org/10.1016/j.apcatb.2023.123291
119. Van Daele, S., Hintjens, L., Hoekx, S., Bohlen, B., Neukermans, S., Daems, N., et al. (2024). How flue gas impurities affect the electrochemical reduction of CO_2 to CO and formate. *Applied Catalysis B: Environmental*, *341*, 123345. https://doi.org/10.1016/j.apcatb.2023.123345
120. Liu, Y., & Tang, Y. (2024). Low Overpotential Electroreduction of CO_2 on Porous SnO_2/ZnO Catalysts. *Journal of Electrochemical Energy Conversion and Storage*, *21*, 021001. https://doi.org/10.1115/1.4062618
121. Liu, Z., Qian, J., Zhang, G., Zhang, B., & He, Y. (2024). Electrochemical CO_2-to-CO conversion: A comprehensive review of recent developments and emerging trends. *Separation and Purification Technology*, *330*, 125177. https://doi.org/10.1016/j.seppur.2023.125177
122. Liu, Y., Lyu, S., Wen, F., Nie, W., & Wang, S. (2023). Polymer-encapsulated metal complex catalysts: An emerging and efficient platform for electrochemical CO_2 reduction. *Journal of Materials Science & Technology*, *172*, 33–50. https://doi.org/10.1016/j.jmst.2023.08.002
123. Li, S., Li, S., Wu, Z., Qin, L., Liu, J., Zhou, W., et al. (2024). Rational design of highly efficient carbon-based materials for electrochemical CO_2 reduction reaction. *Fuel*, *357*, 129760. https://doi.org/10.1016/j.fuel.2023.129760
124. Zhang, D., Zhou, J., Luo, Y., Wang, Y., Zhang, X., Chen, X., et al. (2023). Robust cobalt-free perovskite type electrospun nanofiber cathode for efficient electrochemical carbon dioxide reduction reaction. *Journal of Power Sources*, *587*, 233705. https://doi.org/10.1016/j.jpowsour.2023.233705
125. Yusufoğlu, M., Tafazoli, S., Balkan, T., & Kaya, S. (2023). Enhancement in CO Selectivity by Modification of ZnO with Cu x O for Electrochemical Reduction of CO_2. *Energy Technology*, *11*(11), 2300542. https://doi.org/10.1002/ente.202300542
126. Yamaguchi, N., Nakazato, R., Matsumoto, K., Kakesu, M., Rosero-Navarro, N. C., Miura, A., et al. (2023). Electrocatalytic property of Zn-Al layered double hydroxides for CO_2 electrochemical reduction. *Journal of Asian Ceramic Societies*, *11*(3), 406–411. https://doi.org/10.1080/21870764.2023.2236441
127. Ampelli, C., Tavella, F., Giusi, D., Ronsisvalle, A. M., Perathoner, S., & Centi, G. (2023). Electrode and cell design for CO_2 reduction: A viewpoint. *Catalysis Today*, *421*, 114217. https://doi.org/10.1016/j.cattod.2023.114217
128. Proietto, F., Li, S., Loria, A., Hu, X. M., Galia, A., Ceccato, M., et al. (2022). High-pressure synthesis of CO and syngas from CO_2 reduction using Ni−N-doped porous carbon electrocatalyst. *Chemical Engineering Journal*, *429*, 132251. https://doi.org/10.1016/j.cej.2021.132251
129. Li, Y., Adli, N. M., Shan, W., Wang, M., Zachman, M. J., Hwang, S., et al. (2022). Atomically dispersed single Ni site catalysts for high-efficiency CO_2 electroreduction at industrial-level current densities. *Energy & Environmental Science*, *15*(5), 2108–2119. https://doi.org/10.1039/d2ee00318j
130. Li, L., Yang, J., Li, L., Huang, Y., & Zhao, J. (2022). Electrolytic reduction of CO_2 in $KHCO_3$ and alkanolamine solutions with layered double hydroxides intercalated with gold or copper. *Electrochimica Acta*, *402*, 139523. https://doi.org/10.1016/j.electacta.2021.139523
131. Kim, J. Y., & Youn, D. H. (2022). Electrochemical Reduction of Gaseous CO_2 at Low-Intermediate Temperatures Using a Solid Acid Membrane Cell. *Catalysts*, *12*(12), 1504. https://doi.org/10.3390/catal12121504
132. Xie, L., Liang, J., Priest, C., Wang, T., Ding, D., Wu, G., et al. (2021). Engineering the atomic arrangement of bimetallic catalysts for electrochemical CO_2 reduction. *Chemical Communications*, *57*(15), 1839–1854. https://doi.org/10.1039/D0CC07589B
133. Wuttig, A., Ryu, J., & Surendranath, Y. (2021). Electrolyte competition controls surface binding of CO intermediates to CO_2 reduction catalysts. *Journal of Physical Chemistry C*, *125*(31), 17042–17050. https://doi.org/10.1021/acs.jpcc.1c04337
134. Ahmad, N., Wang, X., Sun, P., Chen, Y., Rehman, F., Xu, J., et al. (2021). Electrochemical CO_2 reduction to CO facilitated by MDEA-based deep eutectic solvent in aqueous solution. *Renewable Energy*, *177*, 23–33. https://doi.org/10.1016/j.renene.2021.05.106
135. Abdinejad, M., da Silva, I. S., & Kraatz, H. B. (2021). Electrografting amines onto silver nanoparticle-modified electrodes for electroreduction of CO_2 at low overpotential. *Journal of Materials Chemistry A*, *9*(15), 9791–9797. https://doi.org/10.1039/d1ta00260k
136. Zhang, X., Guo, S. X., Gandionco, K. A., Bond, A. M., & Zhang, J. (2020). Electrocatalytic carbon dioxide reduction: From fundamental principles to catalyst design. *Materials Today Advances*, *7*, 100074. https://doi.org/10.1016/j.mtadv.2020.100074
137. Sun, L., Reddu, V., Fisher, A. C., & Wang, X. (2020). Electrocatalytic reduction of carbon dioxide: opportunities with heterogeneous molecular catalysts. *Energy & Environmental Science*, *13*(2), 374–403. https://doi.org/10.1039/C9EE03660A
138. Nwabara, U. O., De Heer, M. P., Cofell, E. R., Verma, S., Negro, E., & Kenis, P. J. (2020). Towards accelerated durability testing protocols for CO_2 electrolysis. *Journal of Materials Chemistry A*, *8*(43), 22557–22571. https://doi.org/10.1039/D0TA08695A
139. Liang, S., Altaf, N., Huang, L., Gao, Y., & Wang, Q. (2020). Electrolytic cell design for electrochemical CO_2 reduction. *Journal of CO2 Utilization*, *35*, 90–105. https://doi.org/10.1016/j.jcou.2019.09.007
140. Küngas, R. (2020). Review—electrochemical CO_2 reduction for CO production: Comparison of low- and high-temperature electrolysis technologies. *Journal of The Electrochemical Society*, *167*(4), 044508. https://doi.org/10.1149/1945-7111/ab7099

141. Yin, Z., Peng, H., Wei, X., Zhou, H., Gong, J., Huai, M., et al. (2019). An alkaline polymer electrolyte CO_2 electrolyzer operated with pure water. *Energy & Environmental Science*, *12*(8), 2455–2462. https://doi.org/10.1039/C9EE01204D
142. Tian, Y., Zhang, L., Liu, Y., Jia, L., Yang, J., Chi, B., et al. (2019). A self-recovering robust electrode for highly efficient CO_2 electrolysis in symmetrical solid oxide electrolysis cells. *Journal of Materials Chemistry A*, *7*(11), 6395–6400. https://doi.org/10.1039/C9TA00643E
143. Mun, Y., Lee, S., Cho, A., Kim, S., Han, J. W., & Lee, J. (2019). Cu-Pd alloy nanoparticles as highly selective catalysts for efficient electrochemical reduction of CO_2 to CO. *Applied Catalysis B: Environmental*, *246*, 82–88. https://doi.org/10.1016/j.apcatb.2019.01.021
144. Lu, P., Yang, Y., Yao, J., Wang, M., Dipazir, S., Yuan, M., et al. (2019). Facile synthesis of single-nickel-atomic dispersed N-doped carbon framework for efficient electrochemical CO_2 reduction. *Applied Catalysis B: Environmental*, *241*, 113–119. https://doi.org/10.1016/j.apcatb.2018.09.025
145. Higgins, D., Hahn, C., Xiang, C., Jaramillo, T. F., & Weber, A. Z. (2018). Gas-diffusion electrodes for carbon dioxide reduction: a new paradigm. *ACS Energy Letters*, *4*(1), 317–324. https://doi.org/10.1021/acsenergylett.8b02035
146. Burdyny, T., & Smith, W. A. (2019). CO_2 reduction on gas-diffusion electrodes and why catalytic performance must be assessed at commercially-relevant conditions. *Energy & Environmental Science*, *12*(5), 1442–1453. https://doi.org/10.1039/C8EE03134G
147. Weng, L.-C., Bell, A. T., & Weber, A. Z. (2018). Modeling gas-diffusion electrodes for CO_2 reduction. *Physical Chemistry Chemical Physics*, *20*(25), 16973–16984. https://doi.org/10.1039/C8CP01319E
148. Salvatore, D. A., Weekes, D. M., He, J., Dettelbach, K. E., Li, Y. C., Mallouk, T. E., et al. (2017). Electrolysis of Gaseous CO_2 to CO in a Flow Cell with a Bipolar Membrane. *ACS Energy Letters*, *3*(1), 149–154. https://doi.org/10.1021/acsenergylett.7b01017
149. Hu, X. M., Hval, H. H., Bjerglund, E. T., Dalgaard, K. J., Madsen, M. R., Pohl, M. M., et al. (2018). Selective CO_2 reduction to CO in water using earth-abundant metal and nitrogen-doped carbon electrocatalysts. *ACS Catalysis*, *8*(7), 6255–6264. https://doi.org/10.1021/acscatal.8b01022
150. Dinh, C. T., García de Arquer, F. P., Sinton, D., & Sargent, E. H. (2018). High rate, selective, and stable electroreduction of CO_2 to CO in basic and neutral media. *ACS Energy Letters*, *3*(11), 2835–2840. https://doi.org/10.1021/acsenergylett.8b01734
151. Rosenthal, J., Dimeglio, J. L., & Medina-Ramos, J. (2017). *System and process for electrochemical conversion of carbon dioxide to carbon monoxide* (Patent No. US9624589). U.S. Patent and Trade Mark Office.
152. Rosenthal, J., Medina-Ramos, J., Dimeglio, J. L., & Keane, T. P. (2017). *System and process for electrochemical conversion of carbon dioxide to carbon monoxide* (Patent No. US2017130347). U.S. Patent and Trade Mark Office.
153. Krishnamurthy, K., Gärtner, L.-E., Rupieper, A., & Bostick, D. (2018). *Process and apparatus for manufacturing carbon monoxide* (Patent No. WO2018228723). WIPO.
154. Peschel, A., & Hentschel, B. (2018). *Method and system for producing a gas product containing carbon monoxide* (Patent No. WO2018228718). WIPO.
155. Kushi, T., & Doko, T. (2019). *Carbon monoxide production system* (Patent No. JP2019035102). Japan Patent Office.
156. Stark, K., Baldauf, M., & Hanebuth, M. (2019). *Method and device for the electrochemical utilization of carbon dioxide* (Patent No. US2019062931). U.S. Patent and Trade Mark Office.
157. Hartmann, D., & Krause, R. (2020). *Electrolysis method for carbon dioxide reduction* (Patent No. WO2020143970). WIPO.
158. Peschel, A., & Hentschel, B. (2020). *Method and system for producing a gas product containing carbon monoxide* (Patent No. US2020165732). U.S. Patent and Trade Mark Office.
159. Cao, M., Wu, D., Long, C., & Sun, S. (2021). *Preparation of catalyst for electrocatalytic carbon dioxide reduction* (Patent No. CN214168159). China National Intellectual Property Administration.
160. Kim, W. B., & Park, S. M. (2021). *Cathode composition for carbon dioxide decomposition solid oxide electrolysis cell for carbon dioxide decomposition and manufacturing method for the cathode composition* (Patent No. KR20210033744). Korea Intellectual Property Office.
161. Lu, L., Guan, W., Wang, J., Yang, J., & Liu, W. (2021). *Method for efficient electrocatalytically reducing carbon dioxide* (Patent No. CN113046769). China National Intellectual Property Administration.
162. Shi, J., Shen, F., Song, W., Hua, Y., Wu, S., Zhang, J., et al. (2022). *Bipolar membrane electrolysis method for preparing carbon monoxide by electrolyzing carbon dioxide in organic electrolyte and simultaneously producing chlorine and metal hydroxide as byproducts* (Patent No. CN113913851). China National Intellectual Property Administration.
163. Hunt, J., Ferrari, A., Lita, A., Crosswhite, M., Ashley, B., & Stiegman, A. E. (2013). Microwave-specific enhancement of the carbon–carbon dioxide (Boudouard) reaction. *The Journal of Physical Chemistry C*, *117*(51), 26871–26880. https://doi.org/10.1021/jp4076965
164. Kogler, M., Köck, E. M., Klötzer, B., Schachinger, T., Wallisch, W., Henn, R., et al. (2016). High-temperature carbon deposition on oxide surfaces by CO disproportionation. *The Journal of Physical Chemistry C*, *120*(3), 1795–1807. https://doi.org/10.1021/acs.jpcc.5b12210
165. Rout, K. R., Gil, M. V., & Chen, D. (2019). Highly selective CO removal by sorption enhanced Boudouard reaction for hydrogen production. *Catalysis Science and Technology*, *9*(15), 4100–4107. https://doi.org/10.1039/c9cy00851a
166. Zuber, M., Patriarca, M., Ackermann, S., Furler, P., Conceição, R., Gonzalez-Aguilar, J., et al. (2023). Methane dry reforming via a ceria-based redox cycle in a concentrating solar tower. *Sustainable Energy & Fuels*, *7*(8), 1804–1817. https://doi.org/10.1039/d2se01726a
167. Zhu, L., Lv, Z., Huang, X., Lu, S., Ran, J., & Qin, C. (2023). Development of dual-functional materials for integrated CO_2 capture and utilization by dry reforming of CH_4. *Fuel Processing Technology*, *248*, 107838. https://doi.org/10.1016/j.fuproc.2023.107838
168. Yadav, P. K., Patrikar, K., Mondal, A., & Sharma, S. (2023). Ni/Co in and on CeO_2: a comparative study on the dry reforming reaction. *Sustainable Energy & Fuels*, *7*(16), 3853–3870. https://doi.org/10.1039/d3se00649b
169. Wang, C., Sourav, S., Yu, K., Kwak, Y., Zheng, W., & Vlachos, D. G. (2023). Green Syngas Production by Microwave-Assisted Dry Reforming of Methane on Doped Ceria Catalysts. *ACS Sustainable Chemistry & Engineering*, *11*(36), 13353–13362. https://doi.org/10.1021/acssuschemeng.3c02693
170. Shi, Y., Wang, L., Wu, M., & Wang, F. (2023). Order-of-magnitude increase in rate of methane dry reforming over Ni/CeO_2-SiC catalysts by microwave catalysis. *Applied Catalysis B: Environmental*, *337*, 122927. https://doi.org/10.1016/j.apcatb.2023.122927

171. Ramirez-Corredores, M. M., Rollins, H. W., Morco, R. P., Zarzana, C. A., & Diaz, L. A. (2023). Radiation-induced dry reforming: A negative emission process. *Journal of Cleaner Production*, *429*, 139539. https://doi.org/10.1016/j.jclepro.2023.139539
172. Ou, Z., Ran, J., Qiu, H., Huang, X., & Qin, C. (2023). Uncovering the effect of surface basicity on the carbon deposition of Ni/CeO_2 catalyst modified by oxides in DRM. *Fuel*, *335*, 126994. https://doi.org/10.1016/j.fuel.2022.126994
173. Kumari, R., & Sengupta, S. (2023). $MgAl_2O_4$ with CaO in supported Ni and Ni–Co catalysts–impact on CO_2 reforming of CH4. *Indian Chemical Engineer*, *65*(6), 574–586. https://doi.org/10.1080/00194506.2023.2232792
174. Dong, J., Peng, Y., Li, J., Liu, Z. W., & Hu, R. (2023). CO_2 capture and conversion to syngas via dry reforming of C_3H_8 over a Pt/ZrO_2–CaO catalyst. *Catalysis Science & Technology*, *13*(6), 1650–1665. https://doi.org/10.1039/d3cy00049d
175. Cherbański, R., Kotkowski, T., & Molga, E. (2023). Thermogravimetric analysis of coking during dry reforming of methane. *International Journal of Hydrogen Energy*, *48*(20), 7346–7360. https://doi.org/10.1016/j.ijhydene.2022.11.106
176. Ahasan, M. R., Hossain, M. M., Barlow, Z., Ding, X., & Wang, R. (2023). Low-Temperature Plasma-Assisted Catalytic Dry Reforming of Methane over CeO_2 Nanorod-Supported NiO Catalysts in a Dielectric Barrier Discharge Reactor. *ACS Applied Materials & Interfaces*, *15*(38), 44984–44995. https://doi.org/10.1021/acsami.3c09349
177. Zhang, X., Deng, J., Lan, T., Shen, Y., Qu, W., Zhong, Q., et al. (2022). Coking-and sintering-resistant Ni nanocatalysts confined by active BN edges for methane dry reforming. *ACS Applied Materials & Interfaces*, *14*(22), 25439–25447. https://doi.org/10.1021/acsami.2c04149
178. Yoon, Y., You, H. M., Kim, H. J., Curnan, M. T., Kim, K., & Han, J. W. (2022). Computational catalyst design for dry reforming of methane: a review. *Energy & Fuels*, *36*(17), 9844–9865. https://doi.org/10.1021/acs.energyfuels.2c01776
179. Tsiotsias, A. I., Charisiou, N. D., Sebastian, V., Gaber, S., Hinder, S. J., Baker, M. A., et al. (2022). A comparative study of Ni catalysts supported on Al_2O_3, MgO–CaO–Al_2O_3 and La_2O_3–Al_2O_3 for the dry reforming of ethane. *International Journal of Hydrogen Energy*, *47*(8), 5337–5353. https://doi.org/10.1016/j.ijhydene.2021.11.194
180. Sokefun, Y. O., Trottier, J., Yung, M. M., Joseph, B., & Kuhn, J. N. (2022). Low temperature dry reforming of methane using Ru-Ni-Mg/ceria-zirconia catalysts: Effect of Ru loading and reduction temperature. *Applied Catalysis A: General*, *645*, 118842. https://doi.org/10.1016/j.apcata.2022.118842
181. Huang, L., Li, D., Tian, D., Jiang, L., Li, Z., Wang, H., et al. (2022). Optimization of Ni-based catalysts for dry reforming of methane via alloy design: a review. *Energy & Fuels*, *36*(10), 5102–5151. https://doi.org/10.1021/acs.energyfuels.2c00523
182. Wang, Y. B., He, L., Zhou, B. C., Tang, F., Fan, J., Wang, D. Q., et al. (2021). Hydroxyapatite nanorods rich in [Ca–O–P] sites stabilized Ni species for methane dry reforming. *Industrial & Engineering Chemistry Research*, *60*(42), 15064–15073. https://doi.org/10.1021/acs.iecr.1c02895
183. Taherian, Z., Gharahshiran, V. S., Fazlikhani, F., & Yousefpour, M. (2021). Catalytic performance of Samarium-modified Ni catalysts over Al_2O_3–CaO support for dry reforming of methane. *International Journal of Hydrogen Energy*, *46*(10), 7254–7262. https://doi.org/10.1016/j.ijhydene.2020.11.196
184. Silva, C. G., Passos, F. B., & Teixeira da Silva, V. (2021). Effect of carburization conditions on the activity of molybdenum carbide-supported catalysts promoted by nickel for the dry reforming of methane. *Energy & Fuels*, *35*(21), 17833–17847. https://doi.org/10.1021/acs.energyfuels.1c02110
185. Meng, J., Pan, W., Gu, T., Bu, C., Zhang, J., Wang, X., et al. (2021). One-pot synthesis of a highly active and stable Ni-embedded hydroxyapatite catalyst for syngas production via dry reforming of methane. *Energy & Fuels*, *35*(23), 19568–19580. https://doi.org/10.1021/acs.energyfuels.1c02851
186. Li, R., Xu, W., Deng, J., & Zhou, J. (2021). Coke-resistant Ni–Co/ZrO_2–CaO-based microwave catalyst for highly effective dry reforming of methane by microwave catalysis. *Industrial & Engineering Chemistry Research*, *60*(48), 17458–17468. https://doi.org/10.1021/acs.iecr.1c03164
187. Jensen, C., & Duyar, M. S. (2021). Thermodynamic analysis of dry reforming of methane for valorization of landfill gas and natural gas. *Energy Technology*, *9*(7), 2100106. https://doi.org/10.1002/ente.202100106
188. Dang, C., Luo, J., Yang, W., Li, H., & Cai, W. (2021). Low-temperature catalytic dry reforming of methane over Pd promoted Ni–CaO–$Ca_{12}Al_{14}O_{33}$ multifunctional catalyst. *Industrial & Engineering Chemistry Research*, *60*(50), 18361–18372. https://doi.org/10.1021/acs.iecr.1c04010
189. Wittich, K., Krämer, M., Bottke, N., & Schunk, S. A. (2020). Catalytic dry reforming of methane: insights from model systems. *ChemCatChem*, *12*(8), 2130–2147. https://doi.org/10.1002/cctc.201902142
190. Wang, L., Zhang, J., Huang, J., Cui, Q., Zhu, Y., & Chen, H. (2019). Self-confinement created for a uniform Ir–Ni/SiO_2 catalyst with enhanced performances on CO_2 reforming of methane. *Energy & Fuels*, *34*(1), 111–117. https://doi.org/10.1021/acs.energyfuels.9b03083
191. Sun, H., Zhang, Q., Wen, J., Tang, T., Wang, H., Liu, M., et al. (2020). Insight into the role of CaO in coke-resistant over Ni-HMS catalysts for CO_2 reforming of methane. *Applied Surface Science*, *521*, 146395. https://doi.org/10.1016/j.apsusc.2020.146395
192. Praserthdam, S., Somdee, S., Rittiruam, M., & Balbuena, P. B. (2020). Computational study of the evolution of Ni-based catalysts during the dry reforming of methane. *Energy & Fuels*, *34*(4), 4855–4864. https://doi.org/10.1021/acs.energyfuels.9b04350
193. Mozammel, T., Dumbre, D., Hubesch, R., Yadav, G. D., Selvakannan, P. R., & Bhargava, S. K. (2020). Carbon dioxide reforming of methane over mesoporous alumina supported Ni (Co), Ni (Rh) bimetallic, and Ni (CoRh) trimetallic catalysts: role of nanoalloying in improving the stability and nature of coking. *Energy & Fuels*, *34*(12), 16433–16444. https://doi.org/10.1021/acs.energyfuels.0c03249
194. Gao, X., Ashok, J., & Kawi, S. (2020). Smart designs of anti-coking and anti-sintering Ni-based catalysts for dry reforming of methane: a recent review. *Reactions*, *1*(2), 162–194. https://doi.org/10.3390/reactions1020013
195. Fertout, R. I., Ghelamallah, M., Kacimi, S., López, P. N., & Corberán, V. C. (2020). Nickel Supported on Alkaline Earth Metal–Doped γ-Al_2O_3–La_2O_3 as Catalysts for Dry Reforming of Methane. *Russian Journal of Applied Chemistry*, *93*, 289–298. https://doi.org/10.1134/S1070427220020196
196. Chen, Q., Wang, D., Gu, Y., Yang, S., Tang, Z., Sun, Y., et al. (2020). Techno-economic evaluation of CO_2-rich natural gas dry reforming for linear alpha olefins production. *Energy Conversion and Management*, *205*, 112348. https://doi.org/10.1016/j.enconman.2019.112348

197. Al Abdulghani, A. J., Park, J. H., Kozlov, S. M., Kang, D. C., AlSabban, B., Pedireddy, S., et al. (2020). Methane dry reforming on supported cobalt nanoparticles promoted by boron. *Journal of Catalysis*, *392*, 126–134. https://doi.org/10.1016/j.jcat.2020.09.015
198. Ugwu, A., Zaabout, A., & Amini, S. (2019). An advancement in CO_2 utilization through novel gas switching dry reforming. *International Journal of Greenhouse Gas Control*, *90*, 102791. https://doi.org/10.1016/j.ijggc.2019.102791
199. Szima, S., & Cormos, C. C. (2019). Techno–economic assessment of flexible decarbonized hydrogen and power co-production based on natural gas dry reforming. *International Journal of Hydrogen Energy*, *44*(60), 31712–31723. https://doi.org/10.1016/j.ijhydene.2019.10.115
200. Sokefun, Y. O., Joseph, B., & Kuhn, J. N. (2019). Impact of Ni and Mg loadings on dry reforming performance of Pt/ceria-zirconia catalysts. *Industrial & Engineering Chemistry Research*, *58*(22), 9322–9330. https://doi.org/10.1021/acs.iecr.9b01170
201. Rezaei, R., Moradi, G., & Sharifnia, S. (2019). Dry reforming of methane over Ni-Cu/Al_2O_3 catalyst coatings in a microchannel reactor: modeling and optimization using design of experiments. *Energy & Fuels*, *33*(7), 6689–6706. https://doi.org/10.1021/acs.energyfuels.9b00692
202. Park, J. H., Heo, I., & Chang, T. S. (2019). Dry reforming of methane over Ni-substituted CaZrNiOx catalyst prepared by the homogeneous deposition method. *Catalysis Communications*, *120*, 1–5. https://doi.org/10.1016/j.catcom.2018.11.006
203. Khoja, A. H., Tahir, M., & Saidina Amin, N. A. (2019). Evaluating the performance of a Ni catalyst supported on La_2O_3-$MgAl_2O_4$ for dry reforming of methane in a packed bed dielectric barrier discharge plasma reactor. *Energy & Fuels*, *33*(11), 11630–11647. https://doi.org/10.1021/acs.energyfuels.9b02236
204. Hernández, B., & Martín, M. (2019). Optimization of Biogas to Syngas via Combined Super-Dry and Tri-Reforming. Analysis of Fischer-Tropsch Fuels Production. In *Computer Aided Chemical Engineering* (Vol. 46, pp. 193–198). Elsevier. https://doi.org/10.1016/B978-0-12-818634-3.50033-3
205. Chein, R., & Yang, Z. W. (2019). H_2S effect on dry reforming of biogas for syngas production. *International Journal of Energy Research*, *43*(8), 3330–3345. https://doi.org/10.1002/er.4470
206. Barelli, L., Bidini, G., Di Michele, A., Gammaitoni, L., Mattarelli, M., Mondi, F., et al. (2019). Development and validation of a Ni-based catalyst for carbon dioxide dry reforming of methane process coupled to solid oxide fuel cells. *International Journal of Hydrogen Energy*, *44*(31), 16582–16593. https://doi.org/10.1016/j.ijhydene.2019.04.187
207. Wang, Y., Yao, L., Wang, S., Mao, D., & Hu, C. (2018). Low-temperature catalytic CO_2 dry reforming of methane on Ni-based catalysts: A review. *Fuel Processing Technology*, *169*, 199–206. https://doi.org/10.1016/j.fuproc.2017.10.007
208. Wang, H., Duan, X., Liu, X., Ye, G., Gu, X., Zhu, K., et al. (2018). Influence of tubular reactor structure and operating conditions on dry reforming of methane. *Chemical Engineering Research and Design*, *139*, 39–51. https://doi.org/10.1016/j.cherd.2018.09.019
209. Lachén, J., Durán, P., Menéndez, M., Peña, J. A., & Herguido, J. (2018). Biogas to high purity hydrogen by methane dry reforming in TZFBR+MB and exhaustion by Steam-Iron Process. Techno–economic assessment. *International Journal of Hydrogen Energy*, *43*(26), 11663–11675. https://doi.org/10.1016/j.ijhydene.2018.03.105
210. Guharoy, U., Le Saché, E., Cai, Q., Reina, T. R., & Gu, S. (2018). Understanding the role of Ni-Sn interaction to design highly effective CO_2 conversion catalysts for dry reforming of methane. *Journal of CO2 Utilization*, *27*, 1–10. https://doi.org/10.1016/j.jcou.2018.06.024
211. Dama, S., Ghodke, S. R., Bobade, R., Gurav, H. R., & Chilukuri, S. (2018). Active and durable alkaline earth metal substituted perovskite catalysts for dry reforming of methane. *Applied Catalysis B: Environmental*, *224*, 146–158. https://doi.org/10.1016/j.apcatb.2017.10.048
212. Aramouni, N. A. K., Touma, J. G., Tarboush, B. A., Zeaiter, J., & Ahmad, M. N. (2018). Catalyst design for dry reforming of methane: Analysis review. Renewable and Sustainable *Energy Reviews*, *82*, 2570–2585. https://doi.org/10.1016/j.rser.2017.09.076
213. Zubenko, D., Singh, S., & Rosen, B. A. (2017). Exsolution of Re-alloy catalysts with enhanced stability for methane dry reforming. *Applied Catalysis B: Environmental*, *209*, 711–719. https://doi.org/10.1016/j.apcatb.2017.03.047
214. Wang, C., Zhang, Y., Wang, Y., & Zhao, Y. (2017). Comparative studies of non-noble metal modified mesoporous M-Ni-CaO-ZrO_2 (M = Fe, Co, Cu) catalysts for simulated biogas dry reforming. *Chinese Journal of Chemistry*, *35*(1), 113–120. https://doi.org/10.1002/cjoc.201600609
215. Lou, Y., Steib, M., Zhang, Q., Tiefenbacher, K., Horváth, A., Jentys, A., et al. (2017). Design of stable Ni/ZrO_2 catalysts for dry reforming of methane. *Journal of Catalysis*, *356*, 147–156. https://doi.org/10.1016/j.jcat.2017.10.009
216. Elsayed, N. H., Elwell, A., Joseph, B., & Kuhn, J. N. (2017). Effect of silicon poisoning on catalytic dry reforming of simulated biogas. *Applied Catalysis A: General*, *538*, 157–164. https://doi.org/10.1016/j.apcata.2017.03.024
217. Dębek, R., Motak, M., Galvez, M. E., Grzybek, T., & Da Costa, P. (2017). Influence of Ce/Zr molar ratio on catalytic performance of hydrotalcite-derived catalysts at low temperature CO_2 methane reforming. *International Journal of Hydrogen Energy*, *42*(37), 23556–23567. https://doi.org/10.1016/j.ijhydene.2016.12.121
218. Amin, R., Liu, B., Ullah, S., & Biao, H. Z. (2017). Study of coking and catalyst stability over CaO promoted Ni-based MCF synthesized by different methods for CH_4/CO_2 reforming reaction. *International Journal of Hydrogen Energy*, *42*(34), 21607–21616. https://doi.org/10.1016/j.ijhydene.2017.05.036
219. Wolfbeisser, A., Sophiphun, O., Bernardi, J., Wittayakun, J., Föttinger, K., & Rupprechter, G. (2016). Methane dry reforming over ceria-zirconia supported Ni catalysts. *Catalysis Today*, *277*, 234–245. https://doi.org/10.1016/j.cattod.2016.04.025
220. Kurz, G. (1997). *Process and plant for producing synthesis gas by cracking of hydrocarbons* (Patent No. DE3528858). German Patent and Trade Mark Office.
221. Kurz, G., & Von Linde, J. (1991). *Cooling carbon monoxide rich synthesis gas from Boudouard reaction - uses a mixing chamber or venturi to put together hot gas with cooled gas recycled through a heat exchanger* (Patent No. DE3941591). German Patent and Trade Mark Office.
222. Buelens, L. C., Poelman, H., Marin, G. B., & Galvita, V. V. (2019). 110th anniversary: carbon dioxide and chemical looping: current research trends. *Industrial & Engineering Chemistry Research*, *58*(36), 16235–16257. https://doi.org/10.1021/acs.iecr.9b02521
223. Güleç, F., Meredith, W., & Snape, C. E. (2020). Progress in the CO_2 capture technologies for fluid catalytic cracking (FCC) units—a review. *Frontiers in Energy Research*, *8*, 62. https://doi.org/10.3389/fenrg.2020.00062
224. Fan, L. S., & Li, F. (2010). Chemical looping technology and its fossil energy conversion applications. *Industrial & Engineering Chemistry Research*, *49*(21), 10200–10211. https://doi.org/10.1021/ie1005542

225. Fang, H., Haibin, L., & Zengli, Z. (2009). Advancements in development of chemical-looping combustion: a review. *International Journal of Chemical Engineering*, *2009*, 710515. https://doi.org/10.1155/2009/710515
226. Adánez, J., Abad, A., Mendiara, T., Gayán, P., De Diego, L. F., & García-Labiano, F. (2018). Chemical looping combustion of solid fuels. *Progress in Energy and Combustion Science*, *65*, 6–66. https://doi.org/10.1016/j.pecs.2017.07.005
227. Argyris, P. A., de Leeuwe, C., Abbas, S. Z., & Spallina, V. (2022). Mono-dimensional and two-dimensional models for chemical looping reforming with packed bed reactors and validation under real process conditions. *Sustainable Energy & Fuels*, *6*(11), 2755–2770. https://doi.org/10.1039/d2se00351a
228. Bhavsar, S., Najera, M., & Veser, G. (2012). Chemical looping dry reforming as novel, intensified process for CO_2 activation. *Chemical Engineering & Technology*, *35*(7), 1281–1290. https://doi.org/10.1002/ceat.201100649
229. Brandvoll, O., & Bolland, O. (2004). Inherent CO_2 capture using chemical looping combustion in a natural gas fired power cycle. *Journal of Engineering for Gas Turbines and Power*, *126*(2), 316–321. https://doi.org/10.1115/1.1615251
230. Brower, J. C., Hare, B. J., Bhethanabotla, V. R., & Kuhn, J. N. (2020). Mesoporous silica supported perovskite oxides for low temperature thermochemical CO_2 conversion. *ChemCatChem*, *12*(24), 631–6328. https://doi.org/10.1002/cctc.202001216
231. Chen, X., Wang, L., Lin, Y., Zeng, T., Huang, Z., Zhang, Y., et al. (2023). Migration of lattice oxygen during chemical looping dry reforming of methane with $Ca_2Fe_2O_5/Zr_{0.5}Ce_{0.5}O_2$ oxygen carrier. *Fuel Processing Technology*, *244*, 107706. https://doi.org/10.1016/j.fuproc.2023.107706
232. Daza, Y. A., Kent, R. A., Yung, M. M., & Kuhn, J. N. (2014). Carbon dioxide conversion by reverse water–gas shift chemical looping on perovskite-type oxides. *Industrial & Engineering Chemistry Research*, *53*(14), 5828–5837. https://doi.org/10.1021/ie5002185
233. Daza, Y. A., Maiti, D., Kent, R. A., Bhethanabotla, V. R., & Kuhn, J. N. (2015). Isothermal reverse water gas shift chemical looping on $La_{0.75}Sr_{0.25}Co(1-Y)FeYO_3$ perovskite-type oxides. *Catalysis Today*, *258*, 691–698. https://doi.org/10.1016/j.cattod.2014.12.037
234. Han, R., Xing, S., Wang, Y., Wei, L., Li, Z., Yang, C., et al. (2023). Two birds with one stone: MgO promoted Ni-CaO as stable and coke-resistant bifunctional materials for integrated CO_2 capture and conversion. *Separation and Purification Technology*, *307*, 122808. https://doi.org/10.1016/j.seppur.2022.122808
235. Hare, B. J., Maiti, D., Ramani, S., Ramos, A. E., Bhethanabotla, V. R., & Kuhn, J. N. (2019). Thermochemical conversion of carbon dioxide by reverse water-gas shift chemical looping using supported perovskite oxides. *Catalysis Today*, *323*, 225–232. https://doi.org/10.1016/j.cattod.2018.06.002
236. Hu, J., Hongmanorom, P., Chen, J., Wei, W., Chirawatkul, P., Galvita, V. V., et al. (2023). Tandem distributing Ni into CaO framework for isothermal integration of CO_2 capture and conversion. *Chemical Engineering Journal*, *452*, 139460. https://doi.org/10.1016/j.cej.2022.139460
237. Hu, J., Hongmanorom, P., Chirawatkul, P., & Kawi, S. (2021). Efficient integration of CO_2 capture and conversion over a Ni supported CeO_2-modified CaO microsphere at moderate temperature. *Chemical Engineering Journal*, *426*, 130864. https://doi.org/10.1016/j.cej.2021.130864
238. Hu, J., Hongmanorom, P., Galvita, V. V., Li, Z., & Kawi, S. (2021). Bifunctional Ni-Ca based material for integrated CO_2 capture and conversion via calcium-looping dry reforming. *Applied Catalysis B: Environmental*, *284*, 119734. https://doi.org/10.1016/j.apcatb.2020.119734
239. Law, Z. X., & Tsai, D. H. (2023). Efficient calcium looping-integrated methane dry reforming by dual functional aerosol Ca–Ni–Ce nanoparticle clusters. *ACS Sustainable Chemistry & Engineering*, *11*(6), 2574–2585. https://doi.org/10.1021/acssuschemeng.2c06832
240. Miyazaki, S., Li, Z., Li, L., Toyao, T., Nakasaka, Y., Nakajima, Y., et al. (2023). Chemical Looping Dry Reforming of Methane over Ni-Modified WO_3/ZrO_2: Cooperative Work of Dispersed Tungstate Species and Ni over the ZrO_2 Surface. *Energy & Fuels*, *37*(11), 7945–7957. https://doi.org/10.1021/acs.energyfuels.3c00875
241. Najera, M., Solunke, R., Gardner, T., & Veser, G. (2011). Carbon capture and utilization via chemical looping dry reforming. *Chemical Engineering Research and Design*, *89*(9), 1533–1543. https://doi.org/10.1016/j.cherd.2010.12.017
242. Osman, M., Khan, M. N., Zaabout, A., Cloete, S., & Amini, S. (2021). Review of pressurized chemical looping processes for power generation and chemical production with integrated CO_2 capture. *Fuel Processing Technology*, *214*, 106684. https://doi.org/10.1016/j.fuproc.2020.106684
243. Ramos, A. E., Maiti, D., Daza, Y. A., Kuhn, J. N., & Bhethanabotla, V. R. (2019). Co, Fe, and Mn in La-perovskite oxides for low temperature thermochemical CO_2 conversion. *Catalysis Today*, *338*, 52–59. https://doi.org/10.1016/j.cattod.2019.04.028
244. Salaudeen, S. A., Tasnim, S. H., Heidari, M., Acharya, B., & Dutta, A. (2018). Eggshell as a potential CO_2 sorbent in the calcium looping gasification of biomass. *Waste Management*, *80*, 274–284. https://doi.org/10.1016/j.wasman.2018.09.027
245. Shahrestani, M. M., & Rahimi, A. (2014). Evolution, fields of research, and future of chemical-looping combustion (CLC) process: a review. *Environmental Engineering Research*, *19*(4), 299–308. https://doi.org/10.4491/eer.2014.065
246. Shao, B., Wang, Z. Q., Gong, X. Q., Liu, H., Qian, F., Hu, P., et al. (2023). Synergistic promotions between CO_2 capture and in-situ conversion on Ni-CaO composite catalyst. *Nature Communications*, *14*(1), 996. https://doi.org/10.1038/s41467-023-36646-2
247. Shi, H., Bhethanabotla, V. R., & Kuhn, J. N. (2021). Role of Ba in low temperature thermochemical conversion of carbon dioxide with $LaFeO_3$ perovskite oxides. *Journal of CO2 Utilization*, *51*, 101638. https://doi.org/10.1016/j.jcou.2021.101638
248. Shi, H., Bhethanabotla, V. R., & Kuhn, J. N. (2023). Pelletized SiO_2-supported $La_{0.5}Ba_{0.5}FeO_3$ for conversion of CO_2 to CO by a reverse water-gas shift chemical looping process. *Journal of Industrial and Engineering Chemistry*, *118*, 44–52. https://doi.org/10.1016/j.jiec.2022.10.038
249. Tregambi, C., Di Lauro, F., Montagnaro, F., Salatino, P., & Solimene, R. (2019). 110th anniversary: calcium looping coupled with concentrated solar power for carbon capture and thermochemical energy storage. *Industrial & Engineering Chemistry Research*, *58*(47), 21262–21272. https://doi.org/10.1021/acs.iecr.9b03083
250. Ugwu, A., Osman, M., Zaabout, A., & Amini, S. (2022). Carbon Capture Utilization and Storage in Methanol Production Using a Dry Reforming-Based Chemical Looping Technology. *Energy & Fuels*, *36*(17), 9719–9735. https://doi.org/10.1021/acs.energyfuels.2c00620
251. Wei, G. Q., Feng, J., Hou, Y. L., Li, F. Z., Li, W. Y., Huang, Z., et al. (2021). Ca-enhanced hematite oxygen carriers for chemical looping reforming of biomass pyrolyzed gas coupled with CO_2 splitting. *Fuel*, *285*, 119125. https://doi.org/10.1016/j.fuel.2020.119125

252. Wei, L., Han, R., Xing, S., Wang, Y., Li, Z., & Liu, Q. (2023). Calcium-looping coupling methane partial oxidation and dry reforming process for integrated CO_2 capture and conversion: Regulable H_2/CO molar ratio and excellent coke deposition-resistant. *Chemical Engineering Journal*, *474*, 145833. https://doi.org/10.1016/j.cej.2023.145833
253. Law, Z. X., Pan, Y. T., & Tsai, D. H. (2022). Calcium looping of CO_2 capture coupled to syngas production using Ni-CaO-based dual functional material. *Fuel*, *328*, 125202. https://doi.org/10.1016/j.fuel.2022.125202
254. Zhu, L., Jiang, P., & Fan, J. (2015). Comparison of carbon capture IGCC with chemical-looping combustion and with calcium-looping process driven by coal for power generation. *Chemical Engineering Research and Design*, *104*, 110–124. https://doi.org/10.1016/j.cherd.2015.07.027
255. Galvita, V. V., Poelman, H., Bliznuk, V., Detavernier, C., & Marin, G. B. (2013). CeO_2-modified Fe_2O_3 for CO_2 utilization via chemical looping. *Industrial & Engineering Chemistry Research*, *52*(25), 8416–8426. https://doi.org/10.1021/ie4003574
256. Huang, Z., Jiang, H., He, F., Chen, D., Wei, G., Zhao, K., et al. (2016). Evaluation of multi-cycle performance of chemical looping dry reforming using CO_2 as an oxidant with Fe–Ni bimetallic oxides. *Journal of Energy Chemistry*, *25*(1), 62–70. https://doi.org/10.1016/j.jechem.2015.10.008
257. O'Brien, J. E., McKellar, M. G., Stoots, C. M., Herring, J. S., & Hawkes, G. L. (2009). Parametric study of large-scale production of syngas via high-temperature co-electrolysis. *International Journal of Hydrogen Energy*, *34*(9), 4216–4226. https://doi.org/10.1016/j.ijhydene.2008.12.021
258. Stoots, C., O'brien, J., & Hartvigsen, J. (2009). Results of recent high temperature coelectrolysis studies at the idaho national laboratory. *International Journal of Hydrogen Energy*, *34*(9), 4208–4215. https://doi.org/10.1016/j.ijhydene.2008.08.029
259. Stoots, C. M., O'Brien, J. E., Herring, J. S., & Hartvigsen, J. J. (2009). Syngas production via high-temperature coelectrolysis of steam and carbon dioxide. *Journal of Fuel Cell Science and Technology*, *6*(1), 011014. https://doi.org/10.1115/1.2971061
260. Fu, Q., Mabilat, C., Zahid, M., Brisse, A., & Gautier, L. (2010). Syngas production via high-temperature steam/CO_2 co-electrolysis: an economic assessment. *Energy & Environmental Science*, *3*(10), 1382–1397. https://doi.org/10.1039/c0ee00092b
261. O'brien, J. E., McKellar, M. G., Harvego, E. A., & Stoots, C. M. (2010). High-temperature electrolysis for large-scale hydrogen and syngas production from nuclear energy–summary of system simulation and economic analyses. *International Journal of Hydrogen Energy*, *35*(10), 4808–4819. https://doi.org/10.1016/j.ijhydene.2009.09.009
262. Kim, S. W., Kim, H., Yoon, K. J., Lee, J. H., Kim, B. K., Choi, W., et al. (2015). Reactions and mass transport in high temperature co-electrolysis of steam/CO_2 mixtures for syngas production. *Journal of Power Sources*, *280*, 630–639. https://doi.org/10.1016/j.jpowsour.2015.01.083
263. Menon, V., Fu, Q., Janardhanan, V. M., & Deutschmann, O. (2015). A model-based understanding of solid-oxide electrolysis cells (SOECs) for syngas production by H_2O/CO_2 co-electrolysis. *Journal of Power Sources*, *274*, 768–781. https://doi.org/10.1016/j.jpowsour.2014.09.158
264. Li, Y. C., Zhou, D., Yan, Z., Gonçalves, R. H., Salvatore, D. A., Berlinguette, C. P., et al. (2016). Electrolysis of CO_2 to syngas in bipolar membrane-based electrochemical cells. *ACS Energy Letters*, *1*(6), 1149–1153. https://doi.org/10.1021/acsenergylett.6b00475
265. Liu, Z., Masel, R. I., Chen, Q., Kutz, R., Yang, H., Lewinski, K., et al. (2016). Electrochemical generation of syngas from water and carbon dioxide at industrially important rates. *Journal of CO2 Utilization*, *15*, 50–56. https://doi.org/10.1016/j.jcou.2016.04.011
266. Wang, Y., Liu, T., Lei, L., & Chen, F. (2017). High temperature solid oxide H_2O/CO_2 co-electrolysis for syngas production. *Fuel Processing Technology*, *161*, 248–258. https://doi.org/10.1016/j.fuproc.2016.08.009
267. Diaz, L. A., Gao, N., Adhikari, B., Lister, T. E., Dufek, E. J., & Wilson, A. D. (2018). Electrochemical production of syngas from CO_2 captured in switchable polarity solvents. *Green Chemistry*, *20*(3), 620–626. https://doi.org/10.1039/C7GC03069J
268. Chen, P., Jiao, Y., Zhu, Y. H., Chen, S. M., Song, L., Jaroniec, M., et al. (2019). Syngas production from electrocatalytic CO_2 reduction with high energetic efficiency and current density. *Journal of Materials Chemistry A*, *7*(13), 7675–7682. https://doi.org/10.1039/c9ta01932d
269. Li, Y. C., Lee, G., Yuan, T., Wang, Y., Nam, D. H., Wang, Z., et al. (2019). CO_2 electroreduction from carbonate electrolyte. *ACS Energy Letters*, *4*(6), 1427–1431. https://doi.org/10.1021/acsenergylett.9b00975
270. Daiyan, R., Lovell, E. C., Huang, B., Zubair, M., Leverett, J., Zhang, Q., et al. (2020). Uncovering atomic-scale stability and reactivity in engineered zinc oxide electrocatalysts for controllable syngas production. *Advanced Energy Materials*, *10*(28), 2001381. https://doi.org/10.1002/aenm.202001381
271. Gao, N., Quiroz-Arita, C., Diaz, L. A., & Lister, T. E. (2021). Intensified co-electrolysis process for syngas production from captured CO_2. *Journal of CO2 Utilization*, *43*, 101365. https://doi.org/10.1016/j.jcou.2020.101365
272. Zhao, J., Deng, J., Han, J., Imhanria, S., Chen, K., & Wang, W. (2020). Effective tunable syngas generation via CO2 reduction reaction by non-precious Fe-NC electrocatalyst. *Chemical Engineering Journal*, *389*, 124323. https://doi.org/10.1016/j.cej.2020.124323
273. Moreno-Gonzalez, M., Berger, A., Borsboom-Hanson, T., & Mérida, W. (2021). Carbon-neutral fuels and chemicals: Economic analysis of renewable syngas pathways via CO_2 electrolysis. *Energy Conversion and Management*, *244*, 114452. https://doi.org/10.1016/j.enconman.2021.114452
274. Song, G., Wang, L., Yao, A., Cui, X., & Xiao, J. (2021). Technical and economic assessment of a high-quality syngas production process integrating oxygen gasification and water electrolysis: the Chinese case. *ACS Omega*, *6*(42), 27851–27864. https://doi.org/10.1021/acsomega.1c03489
275. Wolf, S. E., Dittrich, L., Nohl, M., Foit, S., Vinke, I., De Haart, L. G. J., et al. (2021). Boundaries of High-Temperature Co-Electrolysis Towards Direct CO2-Electrolysis. *ECS Transactions*, *103*(1), 493. https://doi.org/10.1149/10301.0493ecst
276. Xiao, Y. C., Gabardo, C. M., Liu, S., Lee, G., Zhao, Y., O'Brien, C. P., et al. (2023). Direct carbonate electrolysis into pure syngas. *EES Catalysis*, *1*(1), 54–61. https://doi.org/10.1039/D2EY00046F
277. Vennekötter, J. B., Scheuermann, T., Sengpiel, R., & Wessling, M. (2019). The electrolyte matters: Stable systems for high rate electrochemical CO_2 reduction. *Journal of CO2 Utilization*, *32*, 202–213. https://doi.org/10.1016/j.jcou.2019.04.007
278. Raya-Imbernón, A., Samu, A. A., Barwe, S., Cusati, G., Fődi, T., Hepp, B. M., et al. (2023). Renewable Syngas Generation via Low-Temperature Electrolysis: Opportunities and Challenges. *ACS Energy Letters*, *9*(1), 288–297. https://doi.org/10.1021/acsenergylett.3c02446

279. Hirata, Y., Terasawa, Y., Matsunaga, N., & Sameshima, S. (2009). Development of electrochemical cell with layered composite of the Gd-doped ceria/electronic conductor system for generation of H_2–CO fuel through oxidation–reduction of CH_4–CO_2 mixed gases. *Ceramics International*, *35*(5), 2023–2028. https://doi.org/10.1016/j.ceramint.2008.11.001
280. Dufek, E. J., Lister, T. E., & McIlwain, M. E. (2011). Bench-scale electrochemical system for generation of CO and syn-gas. *Journal of Applied Electrochemistry*, *41*, 623–631. https://doi.org/10.1007/s10800-011-0271-6
281. O'rear, D. J. (2004). *Process for conversion of lpg and CH_4 to syngas and higher valued products* (Patent No. US6774148). U.S. Patent and Trade Mark Office.
282. Johnston, D. A. (2008). *Carbon dioxide absorbed from air and hydrogen from electrolysis of water, for production of carbon monoxide, alcohols, Fischer-Tropsch hydrocarbons & fuels* (Patent No. GB2448685). UK Patent and Trade Mark Office.
283. Olah, G. A., & Prakash, G. K. S. (2010). *Electrolysis of carbon dioxide in aqueous media to carbon monoxide and hydrogen for production of methanol* (Patent No. US7704369). U.S. Patent and Trade Mark Office.
284. Olah, G. A., & Prakash, G. K. S. (2012). *Electrolysis of carbon dioxide in aqueous media to carbon monoxide and hydrogen for production of methanol* (Patent No. US8138380). U.S. Patent and Trade Mark Office.
285. Rüger, D. (2018). *Synthesis gas production from CO_2 and H_2O in a CO-electrolysis* (Patent No. WO2018228643). WIPO.
286. Omersa, K. (2021). *Carbon dioxide conversion using combined fuel cell and electrolysis cell* (Patent No. US2021313608). U.S. Patent and Trade Mark Office.
287. Fontecave, M., Mougel, V., Tran, N. H., Wakerley, D., & Lamaison, S. (2022). *Method for converting carbon dioxide (CO_2) into syngas by an electrolysis reaction* (Patent No. US2022064804). U.S. Patent and Trade Mark Office.
288. Rüger, D. (2022). *Synthesis gas production from CO_2 and H_2O in a CO-electrolysis* (Patent No. US11214488). U.S. Patent and Trade Mark Office.
289. Sivasankar, N., Cole, E. B., & Teamey, K. (2014). *Electrochemical production of synthesis gas from carbon dioxide* (Patent No. US8721866). U.S. Patent and Trade Mark Office.
290. Sivasankar, N., Cole, E. B., & Teamey, K. (2018). *Electrochemical production of synthesis gas from carbon dioxide* (Patent No. US10119196). U.S. Patent and Trade Mark Office.
291. Zhang, C., Pan, L., Guo, H., Xu, X., & Wang, J. (2022). *System for preparing synthesis gas by reducing electrolytic urea-carbon dioxide* (Patent No. CN218115613). China National Intellectual Property Administration.
292. Lister, T. E., Dufek, E. J., Wilson, A. D., Diaz Aldana, L. A., Adhikari, B., & Gao, N. (2019). *Methods and systems for the electrochemical reduction of carbon dioxide using switchable polarity materials* (Patent No. WO2019070526). WIPO.
293. Lister, T. E., Dufek, E. J., Wilson, A. D., Diaz Aldana, L. A., Adhikari, B., & Gao, N. (2021). *Methods and systems for the electrochemical reduction of carbon dioxide using switchable polarity materials* (Patent No. US10975477). U.S. Patent and Trade Mark Office.
294. Kugeler, K., Niessen, H. F., Röth-Kamat, M., Böcker, D., Rüter, B., & Theis, K. A. (1975). Transport of nuclear heat by means of chemical energy (nuclear long-distance energy). *Nuclear Engineering and Design*, *34*(1), 65–72. https://doi.org/10.1016/0029-5493(75)90156-9
295. Vakil, H. B., & Kosky, P. G. (1976). Design analyses of a methane-based chemical heat pipe. In *Proceedings of the 11th Intersoc Energy Convers Eng Conf* (pp. 659–664). AIChE.
296. Arcilla, N. T., & Plumlee, D. E. (1981). Methanation of CO and CO_2 for heat production. In *Proceedings of the Intersociety Energy Conversion Engineering Conference* (pp. 1185–1190). ASME.
297. Höhlein, B., Menzer, R., & Range, J. (1981). High temperature methanation in the long-distance nuclear energy transport system. *Applied Catalysis*, *1*(3–4), 125–139. https://doi.org/10.1016/0166-9834(81)80001-2
298. Suzuki, K., Takaya, H., Araki, M., Ogawa, K., Hosoya, T., & Todo, N. (1982). *Thermally stable nickel-molybdenum alloy catalysts supported on zirconia for high temperature methanation. Journal of The Japan Petroleum Institute*, *25*(5), 323–330. https://doi.org/10.1627/jpi1958.25.323
299. Fraenkel, D., Levitan, R., & Levy, M. (1986). A solar thermochemical pipe based on the CO_2:CH_4 (1:1) system. *International Journal of Hydrogen Energy*, *11*(4), 267–277. https://doi.org/10.1016/0360-3199(86)90187-4
300. Osterle, F. (1988). Thermodynamic analysis of the chemical heat pipe as a closed cycle gas turbine. In *Proceedings of the ASME 1988 International Gas Turbine and Aeroengine Congress and Exposition. Volume 3: Coal, Biomass and Alternative Fuels; Combustion and Fuels; Oil and Gas Applications; Cycle Innovations*. American Society of Mechanical Engineers (ASME). https://doi.org/10.1115/88-GT-122
301. Levitan, R., Levy, M., Rosin, H., & Rubin, R. (1991). Closed-loop operation of a solar chemical heat pipe at the Weizmann Institute solar furnace. *Solar Energy Materials*, *24*(1–4), 464–477. https://doi.org/10.1016/0165-1633(91)90083-W
302. Strumpf, H. J., Chin, C. Y., Lester, G. R., & Homeyer, S. T. (1991). Sabatier carbon dioxide reduction system for long-duration manned space application. *SAE Transactions*, 1734–1745. https://doi.org/10.4271/911541
303. Rubin, R., Levitan, R., Rosin, H., & Levy, M. (1992). Methanation of synthesis gas in a solar chemical heat pipe. *Energy*, *17*(12), 1109–1119. https://doi.org/10.1016/0360-5442(92)90001-G
304. Levy, M., Levitan, R., Rosin, H., & Rubin, R. (1993). Solar energy storage via a closed-loop chemical heat pipe. *Solar Energy*, *50*(2), 179–189. https://doi.org/10.1016/0038-092X(93)90089-7
305. Segal, A., & Levy, M. (1993). Solar chemical heat pipe in closed loop operation: mathematical model and experiments. *Solar Energy*, *51*(5), 367–376. https://doi.org/10.1016/0038-092X(93)90149-I
306. Berman, A., Levitan, R., Epstein, M., & Levy, M. (1996). *Ruthenium methanation and reforming catalysts for solar chemical heat pipe*. American Society of Mechanical Engineers.
307. Brooks, K. P., Hu, J., Zhu, H., & Kee, R. J. (2007). Methanation of carbon dioxide by hydrogen reduction using the Sabatier process in microchannel reactors. *Chemical Engineering Science*, *62*(4), 1161–1170. https://doi.org/10.1016/j.ces.2006.11.020
308. Hoekman, S. K., Broch, A., Robbins, C., & Purcell, R. (2010). CO_2 recycling by reaction with renewably-generated hydrogen. *International Journal of Greenhouse Gas Control*, *4*(1), 44–50. https://doi.org/10.1016/j.ijggc.2009.09.012
309. Aldana, P. U., Ocampo, F., Kobl, K., Louis, B., Thibault-Starzyk, F., Daturi, M., et al. (2013). Catalytic CO_2 valorization into CH4 on Ni-based ceria-zirconia. Reaction mechanism by operando IR spectroscopy. *Catalysis Today*, *215*, 201–207. https://doi.org/10.1016/j.cattod.2013.02.019
310. Barbarossa, V., Bassano, C., Deiana, P., & Vanga, G. (2013). CO_2 conversion to CH_4. In *CO_2: A Valuable Source of Carbon* (pp. 123–145). Springer. https://doi.org/10.1007/978-1-4471-5119-7_8
311. Gruber, M., Harth, S., & Trimis, D. (2013). *Integrated high-temperature electrolysis and methanation (helmeth) technology: The methanation process*. http://www.helmeth.eu/index.php/technologies/methanation-process (accessed 18 March 2022).

312. Müller, K., Fleige, M., Rachow, F., & Schmeißer, D. (2013). Sabatier based CO_2-methanation of flue gas emitted by conventional power plants. *Energy Procedia*, *40*, 240–248. https://doi.org/10.1016/j.egypro.2013.08.028
313. Müller, K., Städter, M., Rachow, F., Hoffmannbeck, D., & Schmeißer, D. (2013). Sabatier-based CO_2-methanation by catalytic conversion. *Environmental Earth Sciences*, *70*, 3771–3778. https://doi.org/10.1007/s12665-013-2609-3
314. Hashimoto, K., Kumagai, N., Izumiya, K., Takano, H., & Kato, Z. (2014). The production of renewable energy in the form of methane using electrolytic hydrogen generation. *Energy, Sustainability and Society*, *4*, 1–9. https://doi.org/10.1186/s13705-014-0017-5
315. Jürgensen, L., Ehimen, E. A., Born, J., & Holm-Nielsen, J. B. (2014). Utilization of surplus electricity from wind power for dynamic biogas upgrading: Northern Germany case study. *Biomass and Bioenergy*, *66*, 126–132. https://doi.org/10.1016/j.biombioe.2014.02.032
316. Manthiram, K., Beberwyck, B. J., & Alivisatos, A. P. (2014). Enhanced electrochemical methanation of carbon dioxide with a dispersible nanoscale copper catalyst. *Journal of the American Chemical Society*, *136*(38), 13319–13325. https://doi.org/10.1021/ja5065284
317. Newton, J. (12–13 March 2014). *Power-to-gas and methanation - pathways to a 'hydrogen economy'*. The 14th Annual Apgtf Workshop, London, UK.
318. Schaaf, T., Grünig, J., Schuster, M. R., Rothenfluh, T., & Orth, A. (2014). Methanation of CO_2-storage of renewable energy in a gas distribution system. *Energy, Sustainability and Society*, *4*(1), 2. https://doi.org/10.1186/s13705-014-0029-1
319. Schlereth, D., & Hinrichsen, O. (2014). A fixed-bed reactor modeling study on the methanation of CO_2. *Chemical Engineering Research and Design*, *92*(4), 702–712. https://doi.org/10.1016/j.cherd.2013.11.014
320. Walspurger, S., Elzinga, G. D., Dijkstra, J. W., Sarić, M., & Haije, W. G. (2014). Sorption enhanced methanation for substitute natural gas production: Experimental results and thermodynamic considerations. *Chemical Engineering Journal*, *242*, 379–386. https://doi.org/10.1016/j.cej.2013.12.045
321. Giglio, E., Lanzini, A., Santarelli, M., & Leone, P. (2015). Synthetic natural gas via integrated high-temperature electrolysis and methanation: Part II—Economic analysis. *Journal of Energy Storage*, *2*, 64–79. https://doi.org/10.1016/j.est.2015.06.004
322. Giglio, E., Lanzini, A., Santarelli, M., & Leone, P. (2015). Synthetic natural gas via integrated high-temperature electrolysis and methanation: Part I—Energy performance. *Journal of Energy Storage*, *1*, 22–37. https://doi.org/10.1016/j.est.2015.04.002
323. Jürgensen, L., Ehimen, E. A., Born, J., & Holm-Nielsen, J. B. (2015). Dynamic biogas upgrading based on the Sabatier process: Thermodynamic and dynamic process simulation. *Bioresource Technology*, *178*, 323–329. https://doi.org/10.1016/j.biortech.2014.10.069
324. Jürgensen, L., Ehimen, E. A., Born, J., Holm-Nielsen, J. B., & Rooney, D. (2015). Influence of trace substances on methanation catalysts used in dynamic biogas upgrading. *Bioresource Technology*, *178*, 319–322. https://doi.org/10.1016/j.biortech.2014.09.080
325. Lefebvre, J., Götz, M., Bajohr, S., Reimert, R., & Kolb, T. (2015). Improvement of three-phase methanation reactor performance for steady-state and transient operation. *Fuel Processing Technology*, *132*, 83–90. https://doi.org/10.1016/j.fuproc.2014.10.040
326. Schiebahn, S., Grube, T., Robinius, M., Tietze, V., Kumar, B., & Stolten, D. (2015). Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany. *International Journal of Hydrogen Energy*, *40*(12), 4285–4294. https://doi.org/10.1016/j.ijhydene.2015.01.123
327. Abate, S., Mebrahtu, C., Giglio, E., Deorsola, F., Bensaid, S., Perathoner, S., et al. (2016). Catalytic performance of γ-Al_2O_3–ZrO_2–TiO_2–CeO_2 composite oxide supported Ni-based catalysts for CO_2 methanation. *Industrial & Engineering Chemistry Research*, *55*(16), 4451–4460. https://doi.org/10.1021/acs.iecr.6b00134
328. García-García, I., Izquierdo, U., Barrio, V. L., Arias, P. L., & Cambra, J. F. (2016). Power-to-Gas: Storing surplus electrical energy. Study of Al_2O_3 support modification. *International Journal of Hydrogen Energy*, *41*(43), 19587–19594. https://doi.org/10.1016/j.ijhydene.2016.04.010
329. Götz, M., Lefebvre, J., Mörs, F., Koch, A. M., Graf, F., Bajohr, S., et al. (2016). Renewable Power-to-Gas: A technological and economic review. *Renewable Energy*, *85*, 1371–1390. https://doi.org/10.1016/j.renene.2015.07.066
330. Lazdans, A., Dace, E., & Gusca, J. (2016). Development of the experimental scheme for methanation process. *Energy Procedia*, *95*, 540–545. https://doi.org/10.1016/j.egypro.2016.09.082
331. Bremer, J., Rätze, K. H., & Sundmacher, K. (2017). CO_2 methanation: Optimal start-up control of a fixed-bed reactor for power-to-gas applications. *AIChE Journal*, *63*(1), 23–31. https://doi.org/10.1002/aic.15496
332. Castellani, B., Morini, E., Bonamente, E., & Rossi, F. (2017). Experimental investigation and energy considerations on hydrate-based biogas upgrading with CO_2 valorization. *Biomass and Bioenergy*, *105*, 364–372. https://doi.org/10.1016/j.biombioe.2017.07.022
333. Díez-Ramírez, J., Sánchez, P., Kyriakou, V., Zafeiratos, S., Marnellos, G. E., Konsolakis, M., et al. (2017). Effect of support nature on the cobalt-catalyzed CO_2 hydrogenation. *Journal of CO2 Utilization*, *21*, 562–571. https://doi.org/10.1016/j.jcou.2017.08.019
334. Kezibri, N., & Bouallou, C. (2017). Conceptual design and modelling of an industrial scale power to gas-oxy-combustion power plant. *International Journal of Hydrogen Energy*, *42*(30), 19411–19419. https://doi.org/10.1016/j.ijhydene.2017.05.133
335. Leonzio, G. (2017). Design and feasibility analysis of a Power-to-Gas plant in Germany. *Journal of Cleaner Production*, *162*, 609–623. https://doi.org/10.1016/j.jclepro.2017.05.168
336. Meylan, F. D., Piguet, F. P., & Erkman, S. (2017). Power-to-gas through CO_2 methanation: Assessment of the carbon balance regarding EU directives. *Journal of Energy Storage*, *11*, 16–24. https://doi.org/10.1016/j.est.2016.12.005
337. Stangeland, K., Kalai, D., Li, H., & Yu, Z. (2017). CO_2 methanation: the effect of catalysts and reaction conditions. *Energy Procedia*, *105*, 2022–2027. https://doi.org/10.1016/j.egypro.2017.03.577
338. Sun, D., & Simakov, D. S. (2017). Thermal management of a Sabatier reactor for CO_2 conversion into CH_4: Simulation-based analysis. *Journal of CO2 Utilization*, *21*, 368–382. https://doi.org/10.1016/j.jcou.2017.07.015
339. Beierlein, D., Schirrmeister, S., Traa, Y., & Klemm, E. (2018). Experimental approach for identifying hotspots in lab-scale fixed-bed reactors exemplified by the Sabatier reaction. *Reaction Kinetics, Mechanisms and Catalysis*, *125*, 157–170. https://doi.org/10.1007/s11144-018-1402-4

340. Castellani, B., Rinaldi, S., Bonamente, E., Nicolini, A., Rossi, F., & Cotana, F. (2018). Carbon and energy footprint of the hydrate-based biogas upgrading process integrated with CO_2 valorization. *Science of the Total Environment*, *615*, 404–411. https://doi.org/10.1016/j.scitotenv.2017.09.254
341. Er-Rbib, H., Kezibri, N., & Bouallou, C. (2018). Performance assessment of a power-to-gas process based on reversible solid oxide cell. *Frontiers of Chemical Science and Engineering*, *12*, 697–707. https://doi.org/10.1007/s11705-018-1774-z
342. Falbo, L., Martinelli, M., Visconti, C. G., Lietti, L., Bassano, C., & Deiana, P. (2018). Kinetics of CO_2 methanation on a Ru-based catalyst at process conditions relevant for Power-to-Gas applications. *Applied Catalysis B: Environmental*, *225*, 354–363. https://doi.org/10.1016/j.apcatb.2017.11.066
343. García-García, I., Barrio, V. L., & Cambra, J. F. (2018). Power-to-Gas: Storing surplus electrical energy. Study of catalyst synthesis and operating conditions. *International Journal of Hydrogen Energy*, *43*(37), 17737–17747. https://doi.org/10.1016/j.ijhydene.2018.06.192
344. Giglio, E., Deorsola, F. A., Gruber, M., Harth, S. R., Morosanu, E. A., Trimis, D., et al. (2018). Power-to-gas through high temperature electrolysis and carbon dioxide methanation: reactor design and process modeling. *Industrial & Engineering Chemistry Research*, *57*(11), 4007–4018. https://doi.org/10.1021/acs.iecr.8b00477
345. Gruber, M., Weinbrecht, P., Biffar, L., Harth, S., Trimis, D., Brabandt, J., et al. (2018). Power-to-Gas through thermal integration of high-temperature steam electrolysis and carbon dioxide methanation-Experimental results. *Fuel Processing Technology*, *181*, 61–74. https://doi.org/10.1016/j.fuproc.2018.09.003
346. Iaquaniello, G., Setini, S., Salladini, A., & De Falco, M. (2018). CO_2 valorization through direct methanation of flue gas and renewable hydrogen: A technical and economic assessment. *International Journal of Hydrogen Energy*, *43*(36), 17069–17081. https://doi.org/10.1016/j.ijhydene.2018.07.099
347. Inkeri, E., Tynjälä, T., Laari, A., & Hyppänen, T. (2018). Dynamic one-dimensional model for biological methanation in a stirred tank reactor. *Applied Energy*, *209*, 95–107. https://doi.org/10.1016/j.apenergy.2017.10.073
348. Luo, Y., Shi, Y., Li, W., & Cai, N. (2018). Synchronous enhancement of H_2O/CO_2 co-electrolysis and methanation for efficient one-step power-to-methane. *Energy Conversion and Management*, *165*, 127–136. https://doi.org/10.1016/j.enconman.2018.03.028
349. Mebrahtu, C., Abate, S., Chen, S., Sierra Salazar, A. F., Perathoner, S., Krebs, F., et al. (2018). Enhanced catalytic activity of iron-promoted nickel on γ-Al_2O_3 nanosheets for carbon dioxide methanation. *Energy Technology*, *6*(6), 1196–1207. https://doi.org/10.1002/ente.201700835
350. Mebrahtu, C., Abate, S., Perathoner, S., Chen, S., & Centi, G. (2018). CO_2 methanation over Ni catalysts based on ternary and quaternary mixed oxide: A comparison and analysis of the structure-activity relationships. *Catalysis Today*, *304*, 181–189. https://doi.org/10.1016/j.cattod.2017.08.060
351. Schollenberger, D., Bajohr, S., Gruber, M., Reimert, R., & Kolb, T. (2018). Scale-Up of Innovative Honeycomb Reactors for Power-to-Gas Applications–The Project Store&Go. *Chemie Ingenieur Technik*, *90*(5), 696–702. https://doi.org/10.1002/cite.201700139
352. Toro, C., & Sciubba, E. (2018). Sabatier based power-to-gas system: Heat exchange network design and thermoeconomic analysis. *Applied Energy*, *229*, 1181–1190. https://doi.org/10.1016/j.apenergy.2018.08.036
353. Van Dael, M., Kreps, S., Virag, A., Kessels, K., Remans, K., Thomas, D., et al. (2018). Techno-economic assessment of a microbial power-to-gas plant–Case study in Belgium. *Applied Energy*, *215*, 416–425. https://doi.org/10.1016/j.apenergy.2018.01.092
354. Veselovskaya, J. V., Parunin, P. D., Netskina, O. V., Kibis, L. S., Lysikov, A. I., & Okunev, A. G. (2018). Catalytic methanation of carbon dioxide captured from ambient air. *Energy*, *159*, 766–773. https://doi.org/10.1016/j.energy.2018.06.180
355. Veselovskaya, J. V., Parunin, P. D., Netskina, O. V., & Okunev, A. G. (2018). A novel process for renewable methane production: combining direct air capture by K_2CO_3/alumina sorbent with CO_2 methanation over Ru/alumina catalyst. *Topics in Catalysis*, *61*, 1528–1536. https://doi.org/10.1007/s11244-018-0997-z
356. Vo, T. T., Wall, D. M., Ring, D., Rajendran, K., & Murphy, J. D. (2018). Techno-economic analysis of biogas upgrading via amine scrubber, carbon capture and ex-situ methanation. *Applied Energy*, *212*, 1191–1202. https://doi.org/10.1016/j.apenergy.2017.12.099
357. Witte, J., Kunz, A., Biollaz, S. M., & Schildhauer, T. J. (2018). Direct catalytic methanation of biogas–Part II: Techno-economic process assessment and feasibility reflections. *Energy Conversion and Management*, *178*, 26–43. https://doi.org/10.1016/j.enconman.2018.09.079
358. Witte, J., Settino, J., Biollaz, S. M., & Schildhauer, T. J. (2018). Direct catalytic methanation of biogas–Part I: new insights into biomethane production using rate-based modelling and detailed process analysis. *Energy Conversion and Management*, *171*, 750–768. https://doi.org/10.1016/j.enconman.2018.05.056
359. Bassano, C., Deiana, P., Lietti, L., & Visconti, C. G. (2019). P_2G movable modular plant operation on synthetic methane production from CO_2 and hydrogen from renewables sources. *Fuel*, *253*, 1071–1079. https://doi.org/10.1016/j.fuel.2019.05.074
360. Cao, X., Bao, H., & Peng, Y. (2019). A kinetic model for isotopologue signatures of methane generated by biotic and abiotic CO_2 methanation. *Geochimica et Cosmochimica Acta*, *249*, 59–75. https://doi.org/10.1016/j.gca.2019.01.021
361. Moioli, E., Gallandat, N., & Züttel, A. (2019). Model based determination of the optimal reactor concept for Sabatier reaction in small-scale applications over Ru/Al_2O_3. *Chemical Engineering Journal*, *375*, 121954. https://doi.org/10.1016/j.cej.2019.121954
362. Moioli, E., Gallandat, N., & Züttel, A. (2019). Parametric sensitivity in the Sabatier reaction over Ru/Al_2O_3–theoretical determination of the minimal requirements for reactor activation. *Reaction Chemistry & Engineering*, *4*(1), 100–111. https://doi.org/10.1039/c8re00133b
363. Neuberg, S., Pennemann, H., Shanmugam, V., Thiermann, R., Zapf, R., Gac, W., et al. (2019). CO_2 methanation in microstructured reactors–catalyst development and process design. *Chemical Engineering & Technology*, *42*(10), 2076–2084. https://doi.org/10.1002/ceat.201900132
364. Pérez, S., Aragón, J. J., Peciña, I., & Garcia-Suarez, E. J. (2019). Enhanced CO_2 methanation by new microstructured reactor concept and design. *Topics in Catalysis*, *62*(5), 518–523. https://doi.org/10.1007/s11244-019-01139-4
365. Pérez, S., Del Molino, E., & Barrio, V. L. (2019). Modeling and testing of a milli-structured reactor for carbon dioxide methanation. *International Journal of Chemical Reactor Engineering*, *17*(11), 20180238. https://doi.org/10.1515/ijcre-2018-0238

366. Thema, M., Bauer, F., & Sterner, M. (2019). Power-to-Gas: Electrolysis and methanation status review. *Renewable and Sustainable Energy Reviews*, *112*, 775–787. https://doi.org/10.1016/j.rser.2019.06.030
367. Uebbing, J., Rihko-Struckmann, L. K., & Sundmacher, K. (2019). Exergetic assessment of CO_2 methanation processes for the chemical storage of renewable energies. *Applied Energy*, *233*, 271–282. https://doi.org/10.1016/j.apenergy.2018.10.014
368. Vogt, C., Monai, M., Kramer, G. J., & Weckhuysen, B. M. (2019). The renaissance of the Sabatier reaction and its applications on Earth and in space. *Nature Catalysis*, *2*(3), 188–197. https://doi.org/10.1038/s41929-019-0244-4
369. Wang, W., Duong-Viet, C., Xu, Z., Ba, H., Tuci, G., Giambastiani, G., et al. (2020). CO_2 methanation under dynamic operational mode using nickel nanoparticles decorated carbon felt (Ni/OCF) combined with inductive heating. *Catalysis Today*, *357*, 214–220. https://doi.org/10.1016/j.cattod.2019.02.050
370. Hidalgo, D., & Martín-Marroquín, J. M. (2020). Power-to-methane, coupling CO_2 capture with fuel production: An overview. *Renewable and Sustainable Energy Reviews*, *132*, 110057. https://doi.org/10.1016/j.rser.2020.110057
371. Tripodi, A., Conte, F., & Rossetti, I. (2020). Carbon dioxide methanation: design of a fully integrated plant. *Energy & Fuels*, *34*(6), 7242–7256. https://doi.org/10.1021/acs.energyfuels.0c00580
372. Chubb, T. A. (1982). *Thermochemical energy transport process* (Patent No. US4347891). U.S. Patent and Trade Mark Office.
373. Chubb, T. A. (1984). *Thermochemical energy transport using a hydrogen rich working fluid* (Patent No. US4484618). U.S. Patent and Trade Mark Office.
374. Li, Y., Wang, Y., Zhang, Z., Hong, X., & Liu, Y. (2008). Oxidative reformings of methane to syngas with steam and CO_2 catalyzed by metallic Ni based monolithic catalysts. *Catalysis Communications*, *9*(6), 1040–1044. https://doi.org/10.1016/j.catcom.2007.10.003
375. Gao, J., Hou, Z., Liu, X., Zeng, Y., Luo, M., & Zheng, X. (2009). Methane autothermal reforming with CO_2 and O_2 to synthesis gas at the boundary between Ni and ZrO_2. *International Journal of Hydrogen Energy*, *34*(9), 3734–3742. https://doi.org/10.1016/j.ijhydene.2009.02.074
376. Múnera, J. F., Carrara, C., Cornaglia, L. M., & Lombardo, E. A. (2010). Combined oxidation and reforming of methane to produce pure H_2 in a membrane reactor. *Chemical Engineering Journal*, *161*(1–2), 204–211. https://doi.org/10.1016/j.cej.2010.04.022
377. Zhao, W., Ding, M., Yang, P., Wang, Q., Zhang, K., Zhan, X., et al. (2023). Pit-embellished low-valent metal active sites customize CO_2 photoreduction to methanol. *EES Catalysis*, *1*(1), 36–44. https://doi.org/10.1039/D2EY00029F
378. Sharma, I., Shah, V., & Shah, M. (2022). A comprehensive study on production of methanol from wind energy. *Environmental Technology & Innovation*, *28*, 102589. https://doi.org/10.1016/j.eti.2022.102589
379. Li, W., Zhang, J., Jiang, X., Mu, M., Zhang, A., Song, C., et al. (2022). Co-promoted In_2O_3/ZrO_2 integrated with ultrathin nanosheet HZSM-5 as efficient catalysts for CO_2 hydrogenation to gasoline. *Industrial & Engineering Chemistry Research*, *61*(19), 6322–6332. https://doi.org/10.1021/acs.iecr.2c00460
380. Zhang, X., Zhang, G., Song, C., & Guo, X. (2021). Catalytic conversion of carbon dioxide to methanol: Current status and future perspective. *Frontiers in Energy Research*, *8*, 621119. https://doi.org/10.3389/fenrg.2020.621119
381. Xaba, B. S., Mahomed, A. S., & Friedrich, H. B. (2021). The effect of CO_2 and H_2 adsorption strength and capacity on the performance of Ga and Zr modified Cu-Zn catalysts for CO_2 hydrogenation to methanol. *Journal of Environmental Chemical Engineering*, *9*(1), 104834. https://doi.org/10.1016/j.jece.2020.104834
382. Wang, J., Zhang, G., Zhu, J., Zhang, X., Ding, F., Zhang, A., et al. (2021). CO_2 hydrogenation to methanol over In_2O_3-based catalysts: from mechanism to catalyst development. *ACS Catalysis*, *11*(3), 1406–1423. https://doi.org/10.1021/acscatal.0c03665
383. Stolar, T., Prašnikar, A., Martinez, V., Karadeniz, B., Bjelic, A., Mali, G., et al. (2021). Scalable mechanochemical amorphization of bimetallic Cu-Zn MOF-74 catalyst for selective CO_2 reduction reaction to methanol. *ACS Applied Materials & Interfaces*, *13*(2), 3070–3077. https://doi.org/10.1021/acsami.0c21265
384. Qi, T., Zhao, Y., Chen, S., Li, W., Guo, X., Zhang, Y., et al. (2021). Bimetallic metal organic framework-templated synthesis of a Cu-ZnO/Al_2O_3 catalyst with superior methanol selectivity for CO_2 hydrogenation. *Molecular Catalysis*, *514*, 111870. https://doi.org/10.1016/j.mcat.2021.111870
385. Pratschner, S., Skopec, P., Hrdlicka, J., & Winter, F. (2021). Power-to-Green Methanol via CO_2 Hydrogenation—A Concept Study including Oxyfuel Fluidized Bed Combustion of Biomass. *Energies*, *14*(15), 4638. https://doi.org/10.3390/en14154638
386. Nguyen, T. T., Yamaki, T., Taniguchi, S., Endo, A., & Kataoka, S. (2021). Integrating life cycle assessment for design and optimization of methanol production from combining methane dry reforming and partial oxidation. *Journal of Cleaner Production*, *292*, 125970. https://doi.org/10.1016/j.jclepro.2021.125970
387. Nezam, I., Zhou, W., Gusmão, G. S., Realff, M. J., Wang, Y., Medford, A. J., et al. (2021). Direct aromatization of CO_2 via combined CO_2 hydrogenation and zeolite-based acid catalysis. *Journal of CO2 Utilization*, *45*, 101405. https://doi.org/10.1016/j.jcou.2020.101405
388. Mansoor, R., & Tahir, M. (2021). Recent developments in natural gas flaring reduction and reformation to energy-efficient fuels: a review. *Energy & Fuels*, *35*(5), 3675–3714. https://doi.org/10.1021/acs.energyfuels.0c04269
389. Liu, T., Xu, D., Wu, D., Liu, G., & Hong, X. (2021). Spinel $ZnFe_2O_4$ regulates copper sites for CO_2 hydrogenation to methanol. *ACS Sustainable Chemistry & Engineering*, *9*(11), 4033–4041. https://doi.org/10.1021/acssuschemeng.0c07682
390. Lin, F., Jiang, X., Boreriboon, N., Song, C., Wang, Z., & Cen, K. (2021). CO_2 hydrogenation to methanol over bimetallic Pd-Cu catalysts supported on TiO_2-CeO_2 and TiO_2-ZrO_2. *Catalysis Today*, *371*, 150–161. https://doi.org/10.1016/j.cattod.2020.05.049
391. Kanega, R., Onishi, N., Tanaka, S., Kishimoto, H., & Himeda, Y. (2021). Catalytic hydrogenation of CO_2 to methanol using multinuclear iridium complexes in a gas–solid phase reaction. *Journal of the American Chemical Society*, *143*(3), 1570–1576. https://doi.org/10.1021/jacs.0c11927
392. Francis, A., Kumar, H., Sudhakar, K., & Tahir, M. (2021). A review on recent developments in solar photoreactors for carbon dioxide conversion to fuels. *Journal of CO2 Utilization*, *47*, 101515. https://doi.org/10.1016/j.jcou.2021.101515
393. Din, I. U., Usman, M., Khan, S., Helal, A., Alotaibi, M. A., Alharthi, A. I., et al. (2021). Prospects for a green methanol thermo-catalytic process from CO_2 by using MOFs based materials: A mini-review. *Journal of CO2 Utilization*, *43*, 101361. https://doi.org/10.1016/j.jcou.2020.101361
394. Bisotti, F., Fedeli, M., Prifti, K., Galeazzi, A., Dell'Angelo, A., Barbieri, M., et al. (2021). Century of technology trends in methanol synthesis: any need for kinetics refitting? *Industrial & Engineering Chemistry Research*, *60*(44), 16032–16053. https://doi.org/10.1021/acs.iecr.1c02877

395. Atsbha, T. A., Yoon, T., Seongho, P., & Lee, C. J. (2021). A review on the catalytic conversion of CO_2 using H_2 for synthesis of CO, methanol, and hydrocarbons. *Journal of CO2 Utilization*, *44*, 101413. https://doi.org/10.1016/j.jcou.2020.101413
396. Albo, J., & García, G. (2021). Enhanced visible-light photoreduction of CO_2 to methanol over Mo_2C/TiO_2 surfaces in an optofluidic microreactor. *Reaction Chemistry & Engineering*, *6*(2), 304–312. https://doi.org/10.1039/d0re00376j
397. Wang, L., Guan, E., Wang, Y., Wang, L., Gong, Z., Cui, Y., et al. (2020). Silica accelerates the selective hydrogenation of CO_2 to methanol on cobalt catalysts. *Nature Communications*, *11*(1), 1033. https://doi.org/10.1038/s41467-020-14817-9
398. Meunier, N., Chauvy, R., Mouhoubi, S., Thomas, D., & De Weireld, G. (2020). Alternative production of methanol from industrial CO_2. *Renewable Energy*, *146*, 1192–1203. https://doi.org/10.1016/j.renene.2019.07.010
399. Jiang, X., Nie, X., Guo, X., Song, C., & Chen, J. G. (2020). Recent advances in carbon dioxide hydrogenation to methanol via heterogeneous catalysis. *Chemical Reviews*, *120*(15), 7984–8034. https://doi.org/10.1021/acs.chemrev.9b00723
400. Moioli, E., Mutschler, R., & Züttel, A. (2019). Renewable energy storage via CO_2 and H_2 conversion to methane and methanol: Assessment for small scale applications. *Renewable and Sustainable Energy Reviews*, *107*, 497–506. https://doi.org/10.1016/j.rser.2019.03.022
401. Lin, F., Jiang, X., Boreriboon, N., Wang, Z., Song, C., & Cen, K. (2019). Effects of supports on bimetallic Pd-Cu catalysts for CO_2 hydrogenation to methanol. *Applied Catalysis A: General*, *585*, 117210. https://doi.org/10.1016/j.apcata.2019.117210
402. Hou, X. X., Xu, C. H., Liu, Y. L., Li, J. J., Hu, X. D., Liu, J., et al. (2019). Improved methanol synthesis from CO_2 hydrogenation over CuZnAlZr catalysts with precursor pre-activation by formaldehyde. *Journal of Catalysis*, *379*, 147–153. https://doi.org/10.1016/j.jcat.2019.09.025
403. Zhan, H., Wu, Z., Zhao, N., Liu, W., & Wei, W. (2018). Structural properties and catalytic performance of the LaCuZn mixed oxides for CO_2 hydrogenation to methanol. *Journal of Rare Earths*, *36*(3), 273–280. https://doi.org/10.1016/j.jre.2017.07.017
404. Yuan, J., Yang, M. P., Hu, Q. L., Li, S. M., Wang, H., & Lu, J. X. (2018). Cu/TiO_2 nanoparticles modified nitrogen-doped graphene as a highly efficient catalyst for the selective electroreduction of CO_2 to different alcohols. *Journal of CO2 Utilization*, *24*, 334–340. https://doi.org/10.1016/j.jcou.2018.01.021
405. Xu, D., Cheng, B., Wang, W., Jiang, C., & Yu, J. (2018). $Ag_2CrO_4/g\text{-}C_3N_4$/graphene oxide ternary nanocomposite Z-scheme photocatalyst with enhanced CO_2 reduction activity. *Applied Catalysis B: Environmental*, *231*, 368–380. https://doi.org/10.1016/j.apcatb.2018.03.036
406. Witoon, T., Numpilai, T., Phongamwong, T., Donphai, W., Boonyuen, C., Warakulwit, C., et al. (2018). Enhanced activity, selectivity and stability of a CuO-ZnO-ZrO_2 catalyst by adding graphene oxide for CO_2 hydrogenation to methanol. *Chemical Engineering Journal*, *334*, 1781–1791. https://doi.org/10.1016/j.cej.2017.11.117
407. Wang, L., Ghoussoub, M., Wang, H., Shao, Y., Sun, W., Tountas, A. A., et al. (2018). Photocatalytic hydrogenation of carbon dioxide with high selectivity to methanol at atmospheric pressure. *Joule*, *2*(7), 1369–1381. https://doi.org/10.1016/j.joule.2018.03.007
408. Tisseraud, C., Comminges, C., Habrioux, A., Pronier, S., Pouilloux, Y., & Le Valant, A. (2018). Cu-ZnO catalysts for CO_2 hydrogenation to methanol: Morphology change induced by ZnO lixiviation and its impact on the active phase formation. *Molecular Catalysis*, *446*, 98–105. https://doi.org/10.1016/j.mcat.2017.12.036
409. Tang, Q., Shen, Z., Russell, C. K., & Fan, M. (2018). Thermodynamic and kinetic study on carbon dioxide hydrogenation to methanol over a Ga_3Ni_5 (111) surface: The effects of step edge. *The Journal of Physical Chemistry C*, *122*(1), 315–330. https://doi.org/10.1021/acs.jpcc.7b08232
410. Szima, S., & Cormos, C. C. (2018). Improving methanol synthesis from carbon-free H_2 and captured CO_2: A techno-economic and environmental evaluation. *Journal of CO2 Utilization*, *24*, 555–563. https://doi.org/10.1016/j.jcou.2018.02.007
411. Nieminen, H., Givirovskiy, G., Laari, A., & Koiranen, T. (2018). Alcohol promoted methanol synthesis enhanced by adsorption of water and dual catalysts. *Journal of CO2 Utilization*, *24*, 180–189. https://doi.org/10.1016/j.jcou.2018.01.002
412. Maru, M. S., Ram, S., Shukla, R. S., & Noor-ul, H. K. (2018). Ruthenium-hydrotalcite (Ru-HT) as an effective heterogeneous catalyst for the selective hydrogenation of CO_2 to formic acid. *Molecular Catalysis*, *446*, 23–30. https://doi.org/10.1016/j.mcat.2017.12.005
413. Marlin, D. S., Sarron, E., & Sigurbjörnsson, Ó. (2018). Process advantages of direct CO_2 to methanol synthesis. *Frontiers in Chemistry*, *6*, 446. https://doi.org/10.3389/fchem.2018.00446
414. Liu, W. C., Baek, J., & Somorjai, G. A. (2018). The methanol economy: methane and carbon dioxide conversion. *Topics in Catalysis*, *61*, 530–541. https://doi.org/10.1007/s11244-018-0907-4
415. Li, M. M. J., & Tsang, S. C. E. (2018). Bimetallic catalysts for green methanol production via CO_2 and renewable hydrogen: a mini-review and prospects. *Catalysis Science & Technology*, *8*(14), 3450–3464. https://doi.org/10.1039/C8CY00304A
416. Lais, A., Gondal, M. A., Dastageer, M. A., & Al-Adel, F. F. (2018). Experimental parameters affecting the photocatalytic reduction performance of CO_2 to methanol: a review. *International Journal of Energy Research*, *42*(6), 2031–2049. https://doi.org/10.1002/er.3965
417. Lais, A., Gondal, M. A., & Dastageer, M. A. (2018). Semiconducting oxide photocatalysts for reduction of CO_2 to methanol. *Environmental Chemistry Letters*, *16*, 183–210. https://doi.org/10.1007/s10311-017-0673-8
418. Koh, M. K., Wong, Y. J., Chai, S. P., & Mohamed, A. R. (2018). Carbon dioxide hydrogenation to methanol over multi-functional catalyst: Effects of reactants adsorption and metal-oxide(s) interfacial area. *Journal of Industrial and Engineering Chemistry*, *62*, 156–165. https://doi.org/10.1016/j.jiec.2017.12.053
419. Koh, M. K., Khavarian, M., Chai, S. P., & Mohamed, A. R. (2018). The morphological impact of siliceous porous carriers on copper-catalysts for selective direct CO_2 hydrogenation to methanol. *International Journal of Hydrogen Energy*, *43*(19), 9334–9342. https://doi.org/10.1016/j.ijhydene.2018.03.202
420. Kar, S., Sen, R., Goeppert, A., & Prakash, G. S. (2018). Integrative CO_2 capture and hydrogenation to methanol with reusable catalyst and amine: toward a carbon neutral methanol economy. *Journal of the American Chemical Society*, *140*(5), 1580–1583. https://doi.org/10.1021/jacs.7b12183
421. Kar, S., Kothandaraman, J., Goeppert, A., & Prakash, G. S. (2018). Advances in catalytic homogeneous hydrogenation of carbon dioxide to methanol. *Journal of CO2 Utilization*, *23*, 212–218. https://doi.org/10.1016/j.jcou.2017.10.023

422. Jiang, X., Wang, X., Nie, X., Koizumi, N., Guo, X., & Song, C. (2018). CO_2 hydrogenation to methanol on Pd-Cu bimetallic catalysts: H_2/CO_2 ratio dependence and surface species. *Catalysis Today*, *316*, 62–70. https://doi.org/10.1016/j.cattod.2018.02.055
423. Bayomie, O. S., & Bouallou, C. (2018). Energy and conversion investigations of different process configurations for hydrogenation of CO_2 into methanol from industrial flue gases. *Chemical Engineering Transactions*, *70*, 1345–1350. https://doi.org/10.3303/CET1870225
424. Bahruji, H., Esquius, J. R., Bowker, M., Hutchings, G., Armstrong, R. D., & Jones, W. (2018). Solvent free synthesis of PdZn/TiO_2 catalysts for the hydrogenation of CO_2 to methanol. *Topics in Catalysis*, *61*, 144–153. https://doi.org/10.1007/s11244-018-0885-6
425. Al-Saydeh, S. A., & Zaidi, S. J. (2018). Carbon dioxide conversion to methanol: Opportunities and fundamental challenges. In I. Karamé, J. Shaya, & H. Srour (Eds.), *Carbon Dioxide Chemistry, Capture and Oil Recovery* (pp. 42–64). InTechOpen. https://doi.org/10.5772/intechopen.74779
426. Zhao, F., Gong, M., Cao, K., Zhang, Y., Li, J., & Chen, R. (2017). Atomic layer deposition of Ni on Cu nanoparticles for methanol synthesis from CO_2 hydrogenation. *ChemCatChem*, *9*(19), 3772–3778. https://doi.org/10.1002/cctc.201700622
427. Zachopoulos, A., & Heracleous, E. (2017). Overcoming the equilibrium barriers of CO_2 hydrogenation to methanol via water sorption: A thermodynamic analysis. *Journal of CO2 Utilization*, *21*, 360–367. https://doi.org/10.1016/j.jcou.2017.06.007
428. Wang, J., Li, G., Li, Z., Tang, C., Feng, Z., An, H., et al. (2017). A highly selective and stable ZnO-ZrO_2 solid solution catalyst for CO_2 hydrogenation to methanol. *Science Advances*, *3*(10), e1701290. https://doi.org/10.1126/sciadv.1701290
429. Sempuga, B. C., & Yao, Y. (2017). CO_2 hydrogenation from a process synthesis perspective: Setting up process targets. *Journal of CO2 Utilization*, *20*, 34–42. https://doi.org/10.1016/j.jcou.2017.05.004
430. Rui, N., Wang, Z., Sun, K., Ye, J., Ge, Q., & Liu, C. J. (2017). CO_2 hydrogenation to methanol over Pd/In_2O_3: effects of Pd and oxygen vacancy. *Applied Catalysis B: Environmental*, *218*, 488–497. https://doi.org/10.1016/j.apcatb.2017.06.069
431. Makertiharta, I. G. B. N., Dharmawijaya, P. T., & Wenten, I. G. (2017, January). Current progress on zeolite membrane reactor for CO_2 hydrogenation. In *AIP Conference Proceedings* (Vol. 1788, No. 1). AIP Publishing. https://doi.org/10.1063/1.4968389
432. Li, F., Zhan, H., Zhao, N., & Xiao, F. (2017). CO_2 hydrogenation to methanol over La-Mn-Cu-Zn-O based catalysts derived from perovskite precursors. *International Journal of Hydrogen Energy*, *42*(32), 20649–20657. https://doi.org/10.1016/j.ijhydene.2017.06.200
433. Le-Phuc, N., Van Tran, T., Thuy, P. N., Nguyen, L. H., & Trinh, T. T. (2018). Correlation between the porosity of γ-Al_2O_3 and the performance of CuO-ZnO-Al_2O_3 catalysts for CO_2 hydrogenation into methanol. *Reaction Kinetics, Mechanisms and Catalysis*, *124*(1), 171–185. https://doi.org/10.1007/s11144-017-1323-7
434. Kommoß, B., Klemenz, S., Schmitt, F., Hocke, E., Vogel, K., Drochner, A., et al. (2017). Heterogeneously catalyzed hydrogenation of supercritical CO_2 to methanol. *Chemical Engineering & Technology*, *40*(10), 1907–1915. https://doi.org/10.1002/ceat.201600400
435. Huš, M., Kopač, D., Štefančič, N. S., Jurković, D. L., Dasireddy, V. D., & Likozar, B. (2017). Unravelling the mechanisms of CO_2 hydrogenation to methanol on Cu-based catalysts using first-principles multiscale modelling and experiments. *Catalysis Science & Technology*, *7*(24), 5900–5913. https://doi.org/10.1039/c7cy01659j
436. Huš, M., Dasireddy, V. D., Štefančič, N. S., & Likozar, B. (2017). Mechanism, kinetics and thermodynamics of carbon dioxide hydrogenation to methanol on Cu/$ZnAl_2O_4$ spinel-type heterogeneous catalysts. *Applied Catalysis B: Environmental*, *207*, 267–278. https://doi.org/10.1016/j.apcatb.2017.01.077
437. Huang, C., Mao, D., Guo, X., & Yu, J. (2017). Microwave-Assisted Hydrothermal Synthesis of CuO-ZnO-ZrO_2 as Catalyst for Direct Synthesis of Methanol by Carbon Dioxide Hydrogenation. *Energy Technology*, *5*(11), 2100–2107. https://doi.org/10.1002/ente.201700190
438. Gesmanee, S., & Koo-Amornpattana, W. (2017). Catalytic hydrogenation of CO_2 for methanol production in fixed-bed reactor using Cu-Zn supported on gamma-Al_2O_3. *Energy Procedia*, *138*, 739–744. https://doi.org/10.1016/j.egypro.2017.10.211
439. Everett, M., & Wass, D. F. (2017). Highly productive CO_2 hydrogenation to methanol–a tandem catalytic approach via amide intermediates. *Chemical Communications*, *53*(68), 9502–9504. https://doi.org/10.1039/C7CC04613H
440. Díez-Ramírez, J., Díaz, J. A., Sánchez, P., & Dorado, F. (2017). Optimization of the Pd/Cu ratio in Pd-Cu-Zn/SiC catalysts for the CO_2 hydrogenation to methanol at atmospheric pressure. *Journal of CO2 Utilization*, *22*, 71–80. https://doi.org/10.1016/j.jcou.2017.09.012
441. Deerattrakul, V., Puengampholsrisook, P., Limphirat, W., & Kongkachuichay, P. (2018). Characterization of supported Cu-Zn/graphene aerogel catalyst for direct CO_2 hydrogenation to methanol: Effect of hydrothermal temperature on graphene aerogel synthesis. *Catalysis Today*, *314*, 154–163. https://doi.org/10.1016/j.cattod.2017.12.010
442. Collodi, G., Azzaro, G., Ferrari, N., & Santos, S. (2017). Demonstrating large scale industrial CCS through CCU–a case study for methanol production. *Energy Procedia*, *114*, 122–138. https://doi.org/10.1016/j.egypro.2017.03.1155
443. Choi, E. J., Lee, Y. H., Lee, D. W., Moon, D. J., & Lee, K. Y. (2017). Hydrogenation of CO_2 to methanol over Pd-Cu/CeO_2 catalysts. *Molecular Catalysis*, *434*, 146–153. https://doi.org/10.1016/j.mcat.2017.02.005
444. Bellotti, D., Rivarolo, M., Magistri, L., & Massardo, A. F. (2017). Feasibility study of methanol production plant from hydrogen and captured carbon dioxide. *Journal of CO2 Utilization*, *21*, 132–138. https://doi.org/10.1016/j.jcou.2017.07.001
445. Abdelaziz, O. Y., Hosny, W. M., Gadalla, M. A., Ashour, F. H., Ashour, I. A., & Hulteberg, C. P. (2017). Novel process technologies for conversion of carbon dioxide from industrial flue gas streams into methanol. *Journal of CO2 Utilization*, *21*, 52–63. https://doi.org/10.1016/j.jcou.2017.06.018
446. Yu, Y. (2016). Cu-ZnO-Al_2O_3 catalyst modify with light rare earth elements for CO_2 hydrogenation to methanol. *Shiyou Huagong/Petrochemical Technology*, *45*(1), 24–30. https://doi.org/10.3969/j.issn.1000-8144.2016.01.004
447. Ye, J., & Johnson, J. K. (2016). Catalytic hydrogenation of CO_2 to methanol in a Lewis pair functionalized MOF. *Catalysis Science & Technology*, *6*(24), 8392–8405. https://doi.org/10.1039/c6cy01245k

448. Wiesberg, I. L., de Medeiros, J. L., Alves, R. M., Coutinho, P. L., & Araújo, O. Q. (2016). Carbon dioxide management by chemical conversion to methanol: HYDROGENATION and BI-REFORMING. *Energy Conversion and Management*, *125*, 320–335. https://doi.org/10.1016/j.enconman.2016.04.041
449. Spire. (2016). *MefCO2, methanol fuel from CO2*. http://www.mefco2.eu/project_progress.php (accessed 17 August 2019).
450. Rungtaweevoranit, B., Baek, J., Araujo, J. R., Archanjo, B. S., Choi, K. M., Yaghi, O. M., et al. (2016). Copper nanocrystals encapsulated in Zr-based metal–organic frameworks for highly selective CO_2 hydrogenation to methanol. *Nano Letters*, *16*(12), 7645–7649. https://doi.org/10.1021/acs.nanolett.6b03637
451. Rivera-Tinoco, R., Farran, M., Bouallou, C., Auprêtre, F., Valentin, S., Millet, P., et al. (2016). Investigation of power-to-methanol processes coupling electrolytic hydrogen production and catalytic CO_2 reduction. *International Journal of Hydrogen Energy*, *41*(8), 4546–4559. https://doi.org/10.1016/j.ijhydene.2016.01.059
452. Rivarolo, M., Bellotti, D., Magistri, L., & Massardo, A. F. (2016). Feasibility study of methanol production from different renewable sources and thermo-economic analysis. *International Journal of Hydrogen Energy*, *41*(4), 2105–2116. https://doi.org/10.1016/j.ijhydene.2015.12.128
453. Pérez-Fortes, M., Schöneberger, J. C., Boulamanti, A., & Tzimas, E. (2016). Methanol synthesis using captured CO_2 as raw material: Techno-economic and environmental assessment. *Applied Energy*, *161*, 718–732. https://doi.org/10.1016/j.apenergy.2015.07.067
454. Martin, O., Martín, A. J., Mondelli, C., Mitchell, S., Segawa, T. F., Hauert, R., et al. (2016). Indium oxide as a superior catalyst for methanol synthesis by CO_2 hydrogenation. *Angewandte Chemie*, *128*(21), 6369–6373. https://doi.org/10.1002/anie.201600943
455. Marcellin, E., Behrendorff, J. B., Nagaraju, S., DeTissera, S., Segovia, S., & Palfreyman, R. W. (2016). Low carbon fuels and commodity chemicals from waste gases–systematic approach to understand energy metabolism in a model acetogen. *Green Chemistry*, *18*(10), 3020–3028. https://doi.org/10.1039/c5gc02708j
456. Kiss, A. A., Pragt, J. J., Vos, H. J., Bargeman, G., & De Groot, M. T. (2016). Novel efficient process for methanol synthesis by CO_2 hydrogenation. *Chemical Engineering Journal*, *284*, 260–269. https://doi.org/10.1016/j.cej.2015.08.101
457. Hartadi, Y., Widmann, D., & Behm, R. J. (2016). Methanol synthesis via CO_2 hydrogenation over a Au/ZnO catalyst: an isotope labelling study on the role of CO in the reaction process. *Physical Chemistry Chemical Physics*, *18*(16), 10781–10791. https://doi.org/10.1039/c5cp06888f
458. Díez-Ramírez, J., Valverde, J. L., Sánchez, P., & Dorado, F. (2016). CO_2 hydrogenation to methanol at atmospheric pressure: influence of the preparation method of Pd/ZnO catalysts. *Catalysis Letters*, *146*, 373–382. https://doi.org/10.1007/s10562-015-1627-z
459. Ben, S., Yuan, F., & Zhu, Y. (2016). Effect of Zr addition on catalytic performance of Cu-Zn-Al oxides for CO_2 hydrogenation to methanol. *Chemical Research in Chinese Universities*, *32*(6), 1005–1009. https://doi.org/10.1007/s40242-016-6130-6
460. Olah, G. A., & Prakash, G. K. S. (2009). *Efficient and selective conversion of carbon dioxide to methanol, dimethyl ether and derived products* (Patent No. US7605293). U.S. Patent and Trade Mark Office.
461. Shulenberger, A. M., Jonsson, F. R., Ingolfsson, O., & Tran, K.-C. (2012). *Process for producing liquid fuel from carbon dioxide and water* (Patent No. US8198338). U.S. Patent and Trade Mark Office.
462. Singh, S., Sigurbjornsson, O. F., & Tran, K.-C. (2013) *Process and system for producing liquid fuel from carbon dioxide and water* (Patent No. US8506910). U.S. Patent and Trade Mark Office.
463. Zaromb, S. (2013). *Apparatus and methods for carbon dioxide capture and conversion* (Patent No. US8413420). U.S. Patent and Trade Mark Office.
464. Sigurbjornsson, O. F., Singh, S., & Eythorsson, D. (2014). *System and process to capture industrial emissions and recycle for the production of chemicals* (Patent No. WO2014087433). WIPO.
465. Simmons, W. W., White, S. P., & Perkins, C. (2017). *Various methods and apparatuses for multi-stage synthesis gas generation* (Patent No. US9663363). U.S. Patent and Trade Mark Office.
466. Bowker, M., & Hayward, J. (2018). *Catalyst suitable for methanol synthesis* (Patent No. WO2018138512). WIPO.
467. Li, X., Xu, Y., Ru, J., Yang, K., & Zhang, T. (2022). *Comprehensive treatment device for carbon dioxide generated by waste incineration* (Patent No. CN218154221). China National Intellectual Property Administration.
468. Wix, C., & Stummann, T. D. (2022). *Conversion of carbon dioxide and water to synthesis gas for producing methanol and hydrocarbon products* (Patent Application No. CA3203055). Canadian Intellectual Property Office.
469. Rohendi, D., Sya'baniah, N. F., Majlan, E. H., Syarif, N., Rachmat, A., Yulianti, D. H., et al. (2023). The electrochemical conversion of CO2 into methanol with khco3 electrolyte using membrane electrode assembly (mea). *Science and Technology Indonesia*, *8*(4), 632–639. https://doi.org/10.26554/sti.2023.8.4.632-639
470. Xu, D., Sullivan, I., Xiang, C., & Lin, M. (2022). Comparative Study on Electrochemical and Thermochemical Pathways for Carbonaceous Fuel Generation Using Sunlight and Air. *ACS Sustainable Chemistry & Engineering*, *10*(42), 13945–13954. https://doi.org/10.1021/acssuschemeng.2c03230
471. Wang, Y., Zheng, M., Wang, X., & Zhou, X. (2022). Electrocatalytic Reduction of CO_2 to C_1 Compounds by Zn-Based Monatomic Alloys: A DFT Calculation. *Catalysts*, *12*(12), 1617. https://doi.org/10.3390/catal12121617
472. Li, P., Gong, S., Li, C., & Liu, Z. (2022). Analysis of routes for electrochemical conversion of CO_2 to methanol. *Clean Energy*, *6*(1), 202–210. https://doi.org/10.1093/ce/zkac007
473. Liu, H., Syama, L., Zhang, L., Lee, C., Liu, C., Dai, Z., et al. (2021). High-entropy alloys and compounds for electrocatalytic energy conversion applications. *SusMat*, *1*(4), 482–505. https://doi.org/10.1002/sus2.32
474. de Brito, J. F., Irikura, K., Terzi, C. M., Nakagaki, S., & Zanoni, M. V. B. (2020). The great performance of TiO_2 nanotubes electrodes modified by copper (II) porphyrin in the reduction of carbon dioxide to alcohol. *Journal of CO2 Utilization*, *41*, 101261. https://doi.org/10.1016/j.jcou.2020.101261
475. Zhang, Q., Du, J., He, A., Liu, Z., & Tao, C. (2019). High-selectivity electrochemical conversion of CO_2 to lower alcohols using a multi-active sites catalyst of transition-metal oxides. *Journal of CO2 Utilization*, *34*, 635–645. https://doi.org/10.1016/j.jcou.2019.08.005
476. Wu, J., Shi, Q., & Mu, S. (2019). Synthesis of aniline copolymer and as an active catalyst layer for electrochemical reduction of carbon dioxide in water free of supporting electrolytes. *Synthetic Metals*, *255*, 116109. https://doi.org/10.1016/j.synthmet.2019.116109
477. Smith, W. A., Burdyny, T., Vermaas, D. A., & Geerlings, H. (2019). Pathways to industrial-scale fuel out of thin air from CO_2 electrolysis. *Joule*, *3*(8), 1822–1834. https://doi.org/10.1016/j.joule.2019.07.009

478. Bargiacchi, E., Antonelli, M., & Desideri, U. (2019). A comparative assessment of Power-to-Fuel production pathways. *Energy*, *183*, 1253–1265. https://doi.org/10.1016/j.energy.2019.06.149
479. Zhang, W., Hu, Y., Ma, L., Zhu, G., Wang, Y., Xue, X., et al. (2018). Progress and perspective of electrocatalytic CO_2 reduction for renewable carbonaceous fuels and chemicals. *Advanced Science*, *5*(1), 1700275. https://doi.org/10.1002/advs.201700275
480. Weekes, D. M., Salvatore, D. A., Reyes, A., Huang, A., & Berlinguette, C. P. (2018). Electrolytic CO_2 reduction in a flow cell. *Accounts of Chemical Research*, *51*(4), 910–918. https://doi.org/10.1021/acs.accounts.8b00010
481. Tayyebi, E., Hussain, J., Abghoui, Y., & Skúlason, E. (2018). Trends of electrochemical CO_2 reduction reaction on transition metal oxide catalysts. *The Journal of Physical Chemistry C*, *122*(18), 10078–10087. https://doi.org/10.1021/acs.jpcc.8b02224
482. Li, Y. C., Yan, Z., Hitt, J., Wycisk, R., Pintauro, P. N., & Mallouk, T. E. (2018). Bipolar membranes inhibit product crossover in CO2 electrolysis cells. *Advanced Sustainable Systems*, *2*(4), 1700187. https://doi.org/10.1002/adsu.201700187
483. Gutiérrez-Guerra, N., González, J. A., Serrano-Ruiz, J. C., López-Fernández, E., Valverde, J. L., & de Lucas-Consuegra, A. (2019). Gas-phase electrocatalytic conversion of CO_2 to chemicals on sputtered Cu and Cu-C catalysts electrodes. *Journal of Energy Chemistry*, *31*, 46–53. https://doi.org/10.1016/j.jechem.2018.05.005
484. de Lucas-Consuegra, A., Serrano-Ruiz, J. C., Gutiérrez-Guerra, N., & Valverde, J. L. (2018). Low-temperature electrocatalytic conversion of CO_2 to liquid fuels: effect of the Cu particle size. *Catalysts*, *8*(8), 340. https://doi.org/10.3390/catal8080340
485. Chen, C., Kotyk, J. F. K., & Sheehan, S. W. (2018). Progress toward commercial application of electrochemical carbon dioxide reduction. *Chem*, *4*(11), 2571–2586. https://doi.org/10.1016/j.chempr.2018.08.019
486. Zhu, G., Li, Y., Zhu, H., Su, H., Chan, S. H., & Sun, Q. (2017). Enhanced CO_2 electroreduction on armchair graphene nanoribbons edge-decorated with copper. *Nano Research*, *10*, 1641–1650. https://doi.org/10.1007/s12274-016-1362-9
487. Ngo, K. T., McKinnon, M., Mahanti, B., Narayanan, R., Grills, D. C., Ertem, M. Z., et al. (2017). Turning on the protonation-first pathway for electrocatalytic CO_2 reduction by manganese bipyridyl tricarbonyl complexes. *Journal of the American Chemical Society*, *139*(7), 2604–2618. https://doi.org/10.1021/jacs.6b08776
488. Marepally, B. C., Ampelli, C., Genovese, C., Tavella, F., Veyre, L., Quadrelli, E. A., et al. (2017). Role of small Cu nanoparticles in the behaviour of nanocarbon-based electrodes for the electrocatalytic reduction of CO_2. *Journal of CO2 Utilization*, *21*, 534–542. https://doi.org/10.1016/j.jcou.2017.08.008
489. Li, X., Zeng, Z., Hu, B., Qian, L., & Hong, X. (2017). Surface-Atom Dependence of ZnO-Supported Ag@Pd Core@Shell Nanocatalysts in CO_2 Hydrogenation to CH_3OH. *ChemCatChem*, *9*(6), 924–928. https://doi.org/10.1002/cctc.201601119
490. Hatsukade, T., Kuhl, K. P., Cave, E. R., Abram, D. N., Feaster, J. T., Jongerius, A. L., et al. (2017). Carbon dioxide electroreduction using a silver–zinc alloy. *Energy Technology*, *5*(6), 955–961. https://doi.org/10.1002/ente.201700087
491. Cave, E. R., Montoya, J. H., Kuhl, K. P., Abram, D. N., Hatsukade, T., Shi, C., et al. (2017). Electrochemical CO2 reduction on Au surfaces: mechanistic aspects regarding the formation of major and minor products. *Physical Chemistry Chemical Physics*, *19*(24), 15856–15863. https://doi.org/10.1039/c7cp02855e
492. Schlager, S., Dumitru, L. M., Haberbauer, M., Fuchsbauer, A., Neugebauer, H., Hiemetsberger, D., et al. (2016). Electrochemical reduction of carbon dioxide to methanol by direct injection of electrons into immobilized enzymes on a modified electrode. *ChemSusChem*, *9*(6), 631–635. https://doi.org/10.1002/cssc.201501496
493. Jovanov, Z. P., Hansen, H. A., Varela, A. S., Malacrida, P., Peterson, A. A., Nørskov, J. K., et al. (2016). Opportunities and challenges in the electrocatalysis of CO_2 and CO reduction using bifunctional surfaces: A theoretical and experimental study of Au-Cd alloys. *Journal of Catalysis*, *343*, 215–231. https://doi.org/10.1016/j.jcat.2016.04.008
494. Gutiérrez-Guerra, N., Moreno-López, L., Serrano-Ruiz, J. C., Valverde, J. L., & de Lucas-Consuegra, A. (2016). Gas phase electrocatalytic conversion of CO_2 to syn-fuels on Cu based catalysts-electrodes. *Applied Catalysis B: Environmental*, *188*, 272–282. https://doi.org/10.1016/j.apcatb.2016.02.010
495. Díez-Ramírez, J., Sánchez, P., Valverde, J. L., & Dorado, F. (2016). Electrochemical promotion and characterization of PdZn alloy catalysts with K and Na ionic conductors for pure gaseous CO_2 hydrogenation. *Journal of CO2 Utilization*, *16*, 375–383. https://doi.org/10.1016/j.jcou.2016.09.007
496. Albo, J., & Irabien, A. (2016). Cu2O-loaded gas diffusion electrodes for the continuous electrochemical reduction of CO2 to methanol. *Journal of Catalysis*, *343*, 232–239. https://doi.org/10.1016/j.jcat.2015.11.014
497. Karamad, M., Hansen, H. A., Rossmeisl, J., & Nørskov, J. K. (2015). Mechanistic pathway in the electrochemical reduction of CO_2 on RuO_2. *ACS Catalysis*, *5*(7), 4075–4081. https://doi.org/10.1021/cs501542n
498. Kuhl, K. P., Hatsukade, T., Cave, E. R., Abram, D. N., Kibsgaard, J., & Jaramillo, T. F. (2014). Electrocatalytic conversion of carbon dioxide to methane and methanol on transition metal surfaces. *Journal of the American Chemical Society*, *136*(40), 14107–14113. https://doi.org/10.1021/ja505791r
499. Hatsukade, T., Kuhl, K. P., Cave, E. R., Abram, D. N., & Jaramillo, T. F. (2014). Insights into the electrocatalytic reduction of CO_2 on metallic silver surfaces. *Physical Chemistry Chemical Physics*, *16*(27), 13814–13819. https://doi.org/10.1039/c4cp00692e
500. Ampelli, C., Genovesea, C., Perathonera, S., Centia, G., Errahalib, M., Gattib, G., et al. (2014). An electrochemical reactor for the CO_2 reduction in gas phase by using conductive polymer based electrocatalysts. *Chemical Engineering*, *41*, 13–18. https://doi.org/10.3303/CET1441003
501. Al-Rowaili, F. N., Khaled, M., Jamal, A., Onaizi, S. A., & Zahid, U. (2022). *Electrochemical reduction of carbon dioxide* (Patent No. US11512400). U.S. Patent and Trade Mark Office.
502. Hou, C., Lv, H., Ding, L. A., Zhang, K., & Zhang, X. (2022). *Peak regulation power generation system and method coupled with carbon dioxide capture and utilization* (Patent No. CN114899884). China National Intellectual Property Administration.
503. Roustaei, A. H., & Djemai, A. (2010). *System for production, conversion and reproduction of gas-liquid-gas hydrogen cycle with absorption of carbon dioxide, comprises water electrolyzer device with electrolysis chamber, electrodes and electrolyte, and gas transformation device* (Patent No. FR2939450). French Patent and Trademark Office (INPI).
504. Kumar, P., Srivastava, V. C., Gläser, R., With, P., & Mishra, I. M. (2017). Active ceria-calcium oxide catalysts for dimethyl carbonate synthesis by conversion of CO_2. *Powder Technology*, *309*, 13–21. https://doi.org/10.1016/j.powtec.2016.12.016

505. Zhao, S. Y., Wang, S. P., Zhao, Y. J., & Ma, X. B. (2017). An in situ infrared study of dimethyl carbonate synthesis from carbon dioxide and methanol over well-shaped CeO_2. *Chinese Chemical Letters*, *28*(1), 65–69. https://doi.org/10.1016/j.cclet.2016.06.003
506. Jung, K. T., & Bell, A. T. (2001). An in situ infrared study of dimethyl carbonate synthesis from carbon dioxide and methanol over zirconia. *Journal of Catalysis*, *204*(2), 339–347. https://doi.org/10.1006/jcat.2001.3411
507. Marciniak, A. A., Henrique, F. J., de Lima, A. F., Alves, O. C., Moreira, C. R., Appel, L. G., et al. (2020). What are the preferred CeO_2 exposed planes for the synthesis of dimethyl carbonate? Answers from theory and experiments. *Molecular Catalysis*, *493*, 111053. https://doi.org/10.1016/j.mcat.2020.111053
508. Tamboli, A. H., Chaugule, A. A., Gosavi, S. W., & Kim, H. (2018). $Ce_xZr1\text{-}_xO_2$ solid solutions for catalytic synthesis of dimethyl carbonate from CO_2: Reaction mechanism and the effect of catalyst morphology on catalytic activity. *Fuel*, *216*, 245–254. https://doi.org/10.1016/j.fuel.2017.12.008
509. Wang, X., Zhao, J., Li, Y., Huang, S., An, J., Shi, R., et al. (2021). Effects of surface acid-base properties of ZrO_2 on the direct synthesis of DMC from CO_2 and methanol: A combined DFT and experimental study. *Chemical Engineering Science*, *229*, 116018. https://doi.org/10.1016/j.ces.2020.116018
510. Yang, G., Jia, A., Li, J., Li, F., & Wang, Y. (2022). Investigation of synthesis parameters to fabricate CeO_2 with a large surface and high oxygen vacancies for dramatically enhanced performance of direct DMC synthesis from CO_2 and methanol. *Molecular Catalysis*, *528*, 112471. https://doi.org/10.1016/j.mcat.2022.112471
511. Tamboli, A. H., Chaugule, A. A., & Kim, H. (2017). Catalytic developments in the direct dimethyl carbonate synthesis from carbon dioxide and methanol. *Chemical Engineering Journal*, *323*, 530–544. https://doi.org/10.1016/j.cej.2017.04.112
512. Daniel, C., Schuurman, Y., & Farrusseng, D. (2021). Surface effect of nano-sized cerium-zirconium oxides for the catalytic conversion of methanol and CO_2 into dimethyl carbonate. *Journal of Catalysis*, *394*, 486–494. https://doi.org/10.1016/j.jcat.2020.09.023
513. Santos, B. A., Silva, V. M., Loureiro, J. M., & Rodrigues, A. E. (2014). Review for the direct synthesis of dimethyl carbonate. *ChemBioEng Reviews*, *1*(5), 214–229. https://doi.org/10.1002/cben.201400020
514. Stoian, D. C., Taboada, E., Llorca, J., Molins, E., Medina, F., & Segarra, A. M. (2013). Boosted CO_2 reaction with methanol to yield dimethyl carbonate over Mg–Al hydrotalcite-silica lyogels. *Chemical Communications*, *49*(48), 5489–5491. https://doi.org/10.1039/c3cc41298a
515. Sakakura, T., Choi, J. C., Saito, Y., Masuda, T., Sako, T., & Oriyama, T. (1999). Metal-catalyzed dimethyl carbonate synthesis from carbon dioxide and acetals. *The Journal of Organic Chemistry*, *64*(12), 4506–4508. https://doi.org/10.1021/jo990155t
516. Li, X., Han, S. G., Wu, W., Zhang, K., Chen, B., Zhou, S., et al. (2023). Convergent paired electrosynthesis of dimethyl carbonate from carbon dioxide enabled by designing the superstructure of axial oxygen coordinated nickel single-atom catalysts. *Energy & Environmental Science*, *16*(2), 502–512. https://doi.org/10.1039/D2EE03022E
517. Lui, Y. W., Chan, B., & Lui, M. Y. (2022). Methylation with dimethyl carbonate/dimethyl sulfide mixtures: An integrated process without addition of acid/base and formation of residual salts. *ChemSusChem*, *15*(3), e202102538. https://doi.org/10.1002/cssc.202102538
518. Zhang, L., Niu, D., Zhang, K., Zhang, G., Luo, Y., & Lu, J. (2008). Electrochemical activation of CO_2 in ionic liquid (BMIMBF 4): synthesis of organic carbonates under mild conditions. *Green Chemistry*, *10*(2), 202–206. https://doi.org/10.1039/b711981j
519. Tundo, P., & Perosa, A. (2002). Green organic syntheses: organic carbonates as methylating agents. *The Chemical Record*, *2*(1), 13–23. https://doi.org/10.1002/tcr.10007
520. Aresta, M., & Quaranta, E. (1997). Carbon dioxide: a substitute for phosgene. *Chemtech*, *27*(3).
521. Darensbourg, D. J., & Holtcamp, M. W. (1996). Catalysts for the reactions of epoxides and carbon dioxide. *Coordination Chemistry Reviews*, *153*, 155–174. https://doi.org/10.1016/0010-8545(95)01232-X
522. Delledonne, D., Rivetti, F., & Romano, U. (2001). Developments in the production and application of dimethylcarbonate. *Applied Catalysis A: General*, *221*(1–2), 241–251. https://doi.org/10.1016/S0926-860X(01)00796-7
523. Elmas, S., Subhani, M. A., Leitner, W., & Müller, T. E. (2015). Anion effect controlling the selectivity in the zinc-catalysed copolymerisation of CO2 and cyclohexene oxide. *Beilstein Journal of Organic Chemistry*, *11*(1), 42–49. https://doi.org/10.3762/bjoc.11.7
524. Fukuoka, S., Kawamura, M., Komiya, K., Tojo, M., Hachiya, H., Hasegawa, K., et al. (2003). A novel non-phosgene polycarbonate production process using by-product CO_2 as starting material. *Green Chemistry*, *5*(5), 497–507. https://doi.org/10.1039/b304963a
525. Pedersen, T. H., & Conti, F. (2017). Improving the circular economy via hydrothermal processing of high-density waste plastics. *Waste Management*, *68*, 24–31. https://doi.org/10.1016/j.wasman.2017.06.002
526. Liu, T., Wang, G., & Yang, X. (2022). Controlled synthesis of aliphatic polycarbonate diols using dimethyl carbonate and various diols. *Journal of the Chinese Chemical Society*, *69*(6), 995–1001. https://doi.org/10.1002/jccs.202200155
527. Fang, W., Zhang, Y., Yang, Z., Zhang, Z., Xu, F., Wang, W., et al. (2021). Efficient activation of dimethyl carbonate to synthesize bio-based polycarbonate by eco-friendly amino acid ionic liquid catalyst. *Applied Catalysis A: General*, *617*, 118111. https://doi.org/10.1016/j.apcata.2021.118111
528. Gómez-de-Miranda-Jiménez-de-Aberasturi, O., Centeno-Pedrazo, A., Prieto Fernández, S., Rodriguez Alonso, R., Medel, S., María Cuevas, J., et al. (2021). The future of isosorbide as a fundamental constituent for polycarbonates and polyurethanes. *Green Chemistry Letters and Reviews*, *14*(3), 534–544. https://doi.org/10.1080/17518253.2021.1965223
529. Yang, Z., Liu, L., An, H., Li, C., Zhang, Z., Fang, W., et al. (2020). Cost-effective synthesis of high molecular weight biobased polycarbonate via melt polymerization of isosorbide and dimethyl carbonate. *ACS Sustainable Chemistry & Engineering*, *8*(27), 9968–9979. https://doi.org/10.1021/acssuschemeng.0c00430
530. Fukuoka, S., Fukawa, I., Adachi, T., Fujita, H., Sugiyama, N., & Sawa, T. (2019). Industrialization and expansion of green sustainable chemical process: a review of non-phosgene polycarbonate from CO_2. *Organic Process Research & Development*, *23*(2), 145–169. https://doi.org/10.1021/acs.oprd.8b00391
531. Sun, J., Aly, K. I., & Kuckling, D. (2017). A novel one-pot process for the preparation of linear and hyperbranched polycarbonates of various diols and triols using dimethyl carbonate. *RSC Advances*, *7*(21), 12550–12560. https://doi.org/10.1039/c7ra01317e
532. Sun, J., & Kuckling, D. (2016). Synthesis of high-molecular-weight aliphatic polycarbonates by organo-catalysis. *Polymer Chemistry*, *7*(8), 1642–1649. https://doi.org/10.1039/c5py01843a

533. Bigot, S., Kebir, N., Plasseraud, L., & Burel, F. (2015). Organocatalytic synthesis of new telechelic polycarbonates and study of their chemical reactivity. *Polymer*, *66*, 127–134. https://doi.org/10.1016/j.polymer.2015.04.046
534. Park, J. H., Jeon, J. Y., Lee, J. J., Jang, Y., Varghese, J. K., & Lee, B. Y. (2013). Preparation of high-molecular-weight aliphatic polycarbonates by condensation polymerization of diols and dimethyl carbonate. *Macromolecules*, *46*(9), 3301–3308. https://doi.org/10.1021/ma400360w
535. Naik, P. U., Refes, K., Sadaka, F., Brachais, C. H., Boni, G., Couvercelle, J. P., et al. (2012). Organo-catalyzed synthesis of aliphatic polycarbonates in solvent-free conditions. *Polymer Chemistry*, *3*(6), 1475–1480. https://doi.org/10.1039/c2py20056b
536. Fukuoka, S., Fukawa, I., Tojo, M., Oonishi, K., Hachiya, H., Aminaka, M., et al. (2010). A novel non-phosgene process for polycarbonate production from CO_2: green and sustainable chemistry in practice. *Catalysis Surveys from Asia*, *14*, 146–163. https://doi.org/10.1007/s10563-010-9093-5
537. Kim, W. B., Joshi, U. A., & Lee, J. S. (2004). Making polycarbonates without employing phosgene: An overview on catalytic chemistry of intermediate and precursor syntheses for polycarbonate. *Industrial & Engineering Chemistry Research*, *43*(9), 1897–1914. https://doi.org/10.1021/ie034004z
538. Rodney, R. L., Stagno, J. L., Beckman, E. J., & Russell, A. J. (1999). Enzymatic synthesis of carbonate monomers and polycarbonates. *Biotechnology and Bioengineering*, *62*(3), 259–266. https://doi.org/10.1002/(SICI)1097-0290(19990205)62:3<259::AID-BIT2>3.0.CO;2-I
539. Riduan, S. N., & Zhang, Y. (2010). Recent developments in carbon dioxide utilization under mild conditions. *Dalton Transactions*, *39*(14), 3347–3357. https://doi.org/10.1039/b920163g
540. Aresta, M., Quaranta, E., Dibenedetto, A., Tommasi, I., & Marciniec, B. (2000). CO_2-catalysed carbamation of aminofunctional silanes. *Applied Organometallic Chemistry*, *14*(12), 871–873. https://doi.org/10.1002/1099-0739(200012)14:12<871::AID-AOC93>3.0.CO;2-H
541. Castillo, A. C., & Angelis-Dimakis, A. (2019). Analysis and recommendations for European carbon dioxide utilization policies. *Journal of Environmental Management*, *247*, 439–448. https://doi.org/10.1016/j.jenvman.2019.06.092
542. Langanke, J., Wolf, A., Hofmann, J., Böhm, K., Subhani, M. A., Müller, T. E., et al. (2014). Carbon dioxide (CO_2) as sustainable feedstock for polyurethane production. *Green Chemistry*, *16*(4), 1865–1870. https://doi.org/10.1039/c3gc41788c
543. Tundo, P., Aricò, F., & McElroy, C. R. (2011). The greening of chemistry. In *The Chemical Element* (pp. 189–234). John Wiley & Sons. https://doi.org/10.1002/9783527635641.ch6
544. Tundo, P., McElroy, C. R., & Aricò, F. (2010). Synthesis of carbamates from amines and dialkyl carbonates: influence of leaving and entering groups. *Synlett*, *2010*(10), 1567–1571. https://doi.org/10.1055/s-0029-1219927
545. Yadav, N., Seidi, F., Crespy, D., & D'Elia, V. (2019). Polymers based on cyclic carbonates as trait d'union between polymer chemistry and sustainable CO_2 utilization. *ChemSusChem*, *12*(4), 724–754. https://doi.org/10.1002/cssc.201802770
546. Ostapowicz, T. G., Schmitz, M., Krystof, M., Klankermayer, J., & Leitner, W. (2013). Carbon dioxide as a C1 building block for the formation of carboxylic acids by formal catalytic hydrocarboxylation. *Angewandte Chemie*, *125*(46), 12341–12345. https://doi.org/10.1002/anie.201304529
547. Leitner, W., Franciò, G., Scott, M., Westhues, C., Langanke, J., Lansing, M., et al. (2018). Carbon2Polymer–Chemical Utilization of CO_2 in the Production of Isocyanates. *Chemie Ingenieur Technik*, *90*(10), 1504–1512. https://doi.org/10.1002/cite.201800040
548. Suh, H. S., Ha, J. Y., Yoon, J. H., Ha, C. S., Suh, H., & Kim, I. (2010). Polyester polyol synthesis by alternating copolymerization of propylene oxide with cyclic acid anhydrides by using double metal cyanide catalyst. *Reactive and Functional Polymers*, *70*(5), 288–293. https://doi.org/10.1016/j.reactfunctpolym.2010.02.001
549. Lackner, K. S., Wendt, C. H., Butt, D. P., Joyce, E. L., Jr, & Sharp, D. H. (1995). Carbon dioxide disposal in carbonate minerals. *Energy*, *20*(11), 1153–1170. https://doi.org/10.1016/0360-5442(95)00071-N
550. Doucet, F. J. (2001). *Scoping study on CO2 mineralization technologies* (CGS-2011-007 Report). CGS. https://www.academia.edu/4061042/Scoping_study_on_CO2_mineralization_technologies (accessed 11 January 2020).
551. Chen, Z. Y., O'Connor, W. K., & Gerdemann, S. J. (2006). Chemistry of aqueous mineral carbonation for carbon sequestration and explanation of experimental results. *Environmental Progress*, *25*(2), 161–166. https://doi.org/10.1002/ep.10127
552. Gerdemann, S. J., O'Connor, W. K., Dahlin, D. C., Penner, L. R., & Rush, H. (2007). Ex situ aqueous mineral carbonation. *Environmental Science & Technology*, *41*(7), 2587–2593. https://doi.org/10.1021/es0619253
553. Bao, W., Li, H., & Zhang, Y. (2007). Progress in carbon dioxide sequestration by mineral carbonation. *CIESC Journal*, *58*(1), 1–9.
554. Delgado Torróntegui, M. (2010). *Assessing the mineral carbonation science and technology* [Master's Thesis]. ETH Zurich.
555. Priestnall, M. (2010). CO_2 mineralisation via fuel cells. How to make CCS profitable. In *Proceedings of Finding Petroleum CCS Forum*. Geological Society. http://www.findingpetroleum.com/files/event15/ccc.pdf (accessed 27 February 2020).
556. Zimmermann, A., Styles, M. T., Lacinska, A. M., Zemskova, S., Sanna, A., Hall, M., et al. (2011). *Carbon Capture and Storage by Mineralisation Stage Gate 1 Report*. Energy Technologies Institute.
557. Priestnall, M. (28 November 2012). *Silica, metals, Mg/ca oxides, CCS (& electricity) from minerals & wastes*. The Mineralisation Cluster Workshop, London, UK.
558. Zevenhoven, R., Fagerlund, J., Björklöf, T., Mäkelä, M., & Eklund, O. (26–29 June 2012). *Carbon dioxide mineralisation and integration with flue gas desulphurisation applied to a modern coal-fired power plant*. ECOS2012, Perugia, Italy.
559. Priestnall, M. (3 February 2013). Making money from mineralisation of CO_2. *Carbon Capture Journal*. https://www.carboncapturejournal.com/news/making-money-from-mineralisation-of-co2/3251.aspx?Category=featured (accessed 27 February 2020).
560. Santos, R. M., François, D., Mertens, G., Elsen, J., & Van Gerven, T. (2013). Ultrasound-intensified mineral carbonation. *Applied Thermal Engineering*, *57*(1–2), 154–163. https://doi.org/10.1016/j.applthermaleng.2012.03.035
561. Santos, R. M., Verbeeck, W., Knops, P., Rijnsburger, K., Pontikes, Y., & Van Gerven, T. (2013). Integrated mineral carbonation reactor technology for sustainable carbon dioxide sequestration:'CO_2 Energy Reactor'. *Energy Procedia*, *37*, 5884–5891. https://doi.org/10.1016/j.egypro.2013.06.513

562. Zevenhoven, R., Romão, I., & Slotte, M. (5–7 November 2013). *Mineralisation of CO$_2$ using serpentinite rock - towards industrial application*. IEAGHG/IETS Iron & Steel Industry CCUS & Process Integration Workshop, Tokyo, Japan. https://ieaghg.org/docs/General_Docs/Iron%20and%20Steel%202%20Secured%20presentations/3_1520%20Mikko%20Helle.pdf (accessed 27 February 2020).
563. Zevenhoven, R., Fagerlund, J., Nduagu, E., Romão, I., Jie, B., & Highfield, J. (2013). Carbon storage by mineralisation (CSM): Serpentinite rock carbonation via Mg(OH)$_2$ reaction intermediate without CO$_2$ pre-separation. *Energy Procedia*, *37*, 5945–5954. https://doi.org/10.1016/j.egypro.2013.06.521
564. Hemmati, A., Shayegan, J., Bu, J., Yeo, T. Y., & Sharratt, P. (2014). Process optimization for mineral carbonation in aqueous phase. *International Journal of Mineral Processing*, *130*, 20–27. https://doi.org/10.1016/j.minpro.2014.05.007
565. Priestnall, M. (2014). *Decarbonising flue gas using CO$_2$ mineralisation – project experience on ships.* Keeping the Momentum, Geological Society, London, UK.
566. Sanna, A., Uibu, M., Caramanna, G., Kuusik, R., & Maroto-Valer, M. M. (2014). A review of mineral carbonation technologies to sequester CO$_2$. *Chemical Society Reviews*, *43*(23), 8049–8080. https://doi.org/10.1039/c4cs00035h
567. Priestnall, M. (2014). *Can mineral carbonation be used for industrial carbon dioxide sequestration?* Environmental Chemistry Group Buletin. https://www.envchemgroup.com/can-mineral-carbonation-be-used-for-industrial-co2-sequestration.html (accessed 27 Februaty 2020).
568. Priestnall, M. (2015). *Method and system of sequestrating carbon dioxide* (Patent No. GB2515995). UK Patent and Trademark Office.
569. Romanov, V., Soong, Y., Carney, C., Rush, G. E., Nielsen, B., & O'Connor, W. (2015). Mineralization of carbon dioxide: a literature review. *ChemBioEng Reviews*, *2*(4), 231–256. https://doi.org/10.1002/cben.201500002
570. Romão, I. S. S. (2015). *Production of magnesium carbonates from serpentinites for CO$_2$ mineral sequestration- optimisation towards industrial application* [Doctoral Dissertation]. Universidade de Coimbra.
571. Zevenhoven, R., Romão, I., & Slotte, M. (2015). Mineralization of CO$_2$ using serpentinite rock - towards industrial application. In C. Ludwig, C. Matasci, & X. Edelmann (Eds.), *Natural resources: Sustainable targets, technologies, lifestyles and governance* (pp. 125–129). World Resources Forum. http://infoscience.epfl.ch/record/213010/files/Ludwig_Natural_Resources_2015.pdf (accessed 27 February 2020).
572. Zevenhoven, R., Slotte, M., Åbacka, J., & Highfield, J. (2016). A comparison of CO$_2$ mineral sequestration processes involving a dry or wet carbonation step. *Energy*, *117*, 604–611. https://doi.org/10.1016/j.energy.2016.05.066
573. Benhelal, E., Rashid, M. I., Rayson, M. S., Brent, G. F., Oliver, T., Stockenhuber, M., et al. (2019). Direct aqueous carbonation of heat activated serpentine: discovery of undesirable side reactions reducing process efficiency. *Applied Energy*, *242*, 1369–1382. https://doi.org/10.1016/j.apenergy.2019.03.170
574. Zevenhoven, R. (2020). Metals production, CO$_2$ mineralization and LCA. *Metals*, *10*(3), 342. https://doi.org/10.3390/met10030342
575. Wang, B., Pan, Z., Cheng, H., Zhang, Z., & Cheng, F. (2021). A review of carbon dioxide sequestration by mineral carbonation of industrial byproduct gypsum. *Journal of Cleaner Production*, *302*, 126930. https://doi.org/10.1016/j.jclepro.2021.126930
576. Britten, R. (2011). *System for halting the increase in atmospheric carbon dioxide and method of operation thereof* (Patent No. US2011171107). U.S. Patent and Trademark Office.
577. Jones, J. D., & St Angelo, D. (2015). *Removing carbon dioxide from waste streams through co-generation of carbonate and/or bicarbonate minerals* (Patent No. US9205375). U.S. Patent and Trademark Office.
578. Priestnall, M. (2018). *Method and system of activation of mineral silicate minerals* (Patent No. US9963351). U.S. Patent and Trademark Office.
579. Sano, K., Saito, H., Miyamoto, H., & Imada, T. (2022). *Carbon dioxide fixation method and carbon dioxide fixation system* (Patent Application No. US2022297058). U.S. Patent and Trademark Office.
580. Sano, K., Saito, H., Miyamoto, H., & Suzuki, A. (2023). *Carbon dioxide fixation system and method using seawater electrolysis* (Patent Application No. US2023051291). U.S. Patent and Trademark Office.
581. Manaka, Y., Nagatsuka, Y., & Motokura, K. (2020). Organic bases catalyze the synthesis of urea from ammonium salts derived from recovered environmental ammonia. *Scientific Reports*, *10*(1), 2834. https://doi.org/10.1038/s41598-020-59795-6
582. Meessen, J. (2014). Urea synthesis. *Chemie Ingenieur Technik*, *86*(12), 2180–2189. https://doi.org/10.1002/cite.201400064
583. Nguyen, D. S., Cho, J. K., Shin, S. H., Mishra, D. K., & Kim, Y. J. (2016). Reusable polystyrene-functionalized basic ionic liquids as catalysts for carboxylation of amines to disubstituted ureas. *ACS Sustainable Chemistry & Engineering*, *4*(2), 451–460. https://doi.org/10.1021/acssuschemeng.5b01369
584. Pérez-Fortes, M., Bocin-Dumitriu, A., & Tzimas, E. (2014). CO$_2$ utilization pathways: techno-economic assessment and market opportunities. *Energy Procedia*, *63*, 7968–7975. https://doi.org/10.1016/j.egypro.2014.11.834
585. Quaranta, E., & Aresta, M. (2010). The chemistry of N-CO$_2$ bonds: synthesis of carbamic acids and their derivatives, isocyanates, and ureas. In *Carbon dioxide as chemical feedstock* (pp. 121–167). Wiley-VCH. https://doi.org/10.1002/9783527629916.ch6
586. Shi, H., Du, J., Hou, J., Ni, W., Song, C., Li, K., et al. (2020). Solar-driven CO$_2$ conversion over Co^{2+} doped 0D/2D TiO$_2$/g-C$_3$N$_4$ heterostructure: Insights into the role of Co^{2+} and cocatalyst. *Journal of CO2 Utilization*, *38*, 16–23. https://doi.org/10.1016/j.jcou.2020.01.005
587. Cheng, K., & Cheng, W. (2018). *Tripolycyanamide whole circulation production process and device* (Patent No. CN108558783). China National Intellectual Property Administration.
588. Lee, J. M. (1995). *Process for manufacturing melamine from urea* (Patent No. US5384404). U.S. Patent and Trademark Office.
589. Li, D. (2014). *One-step method used for production of melamine by circulating ammonia gas as carrying gas* (Patent No. CN103601693). China National Intellectual Property Administration.
590. Mennen, J. H. (2018). *Integrated production of urea and melamine* (Patent No. US9981924). U.S. Patent and Trademark Office.
591. Sioli, G. (2012). *Process for the production of high purity melamine from urea* (Patent No. US9045439). U.S. Patent and Trademark Office.
592. Xiao, J., Zuo, Y., Liu, W., Wu, Y., & Zhao, X. (2016). Research progress of adhesives for strawboard (in Chinese). *Cailiao Daobao/Materials Review*, *30*(9), 78–83.
593. Zhao, L. F., Liu, Y., Xu, Z. D., Zhang, Y. Z., Zhao, F., & Zhang, S. B. (2011). State of research and trends in development of wood adhesives. *Forestry Studies in China*, *13*, 321–326. https://doi.org/10.1007/s11632-013-0401-9

594. Urea-formaldehyde resins theories challenged. (1984). *Chemical and Engineering News*, *62*(10), 25–28. https://doi.org/10.1021/cen-v062n010.p025
595. Yan, S., Li, Z., Zhou, Y., Ding, T., & Han, S. (2016). Research progress in high technologies of urea-formaldehyde resin (in Chinese). *Cailiao Daobao/Materials Review*, *30*(2), 70–75.
596. Wibowo, E. S., Park, B. D., & Causin, V. (2022). Recent advances in urea–formaldehyde resins: converting crystalline thermosetting polymers back to amorphous ones. *Polymer Reviews*, *62*(4), 722–756. https://doi.org/10.1080/15583724.2021.2014520
597. Maskew, R. (1941). Applications of Urea-Formaldehyde Resin Glues. *Aircraft Engineering and Aerospace Technology*, *13*(6), 171–172. https://doi.org/10.1108/eb030790
598. Meyer, B. (1979). *Urea-formaldehyde resins*. Addison-Wesley Publishing.
599. Marvel, C. S., Elliott, J. R., Boettner, F. E., & Yuska, H. (1946). The structure of urea-formaldehyde resins1. *Journal of the American Chemical Society*, *68*(9), 1681–1686. https://doi.org/10.1021/ja01213a001
600. Pizzi, A., & Mittal, K. L. (2003). Urea-formaldehyde adhesives. *Handbook of adhesive technology* (2nd ed.). Taylor & Francis.
601. Rammon, R. M., Johns, W. E., Magnuson, J., & Dunker, A. K. (1986). The chemical structure of UF resins. *The Journal of Adhesion*, *19*(2), 115–135. https://doi.org/10.1080/00218468608071217
602. Antov, P., Savov, V., Krišťák, Ľ., Réh, R., & Mantanis, G. I. (2021). Eco-friendly, high-density fiberboards bonded with urea-formaldehyde and ammonium lignosulfonate. *Polymers*, *13*(2), 220. https://doi.org/10.3390/polym13020220
603. River, B. H., Ebewele, R. O., & Myers, G. E. (1994). Failure mechanisms in wood joints bonded with urea-formaldehyde adhesives (in German). *Holz als Roh-und Werkstoff*, *52*(3), 179–184. https://doi.org/10.1007/BF02615219
604. Myers, G. E., & Koutsky, J. A. (1990). Formaldehyde liberation and cure behavior of urea-formaldehyde resins. https://doi.org/10.1515/hfsg.1990.44.2.117
605. Myers, G. E. (1984). How mole ratio of UF resin affects formaldehyde emission and other properties: a literature critique. *Forest Products Journal*, *34*(5), 35–41.
606. Lee, S. M., Park, J. Y., Park, S. B., Han, S. T., & Kang, E. C. (2012). Comparative study of the storage stability between a melamine-urea-formaldehyde and a urea-formaldehyde resin. *Forest Products Journal*, *62*(2), 146–149. https://doi.org/10.13073/0015-7473-62.2.146
607. Ebewele, R. O., Myers, G. E., River, B. H., & Koutsky, J. A. (1991). Polyamine-modified urea-formaldehyde resins. I. Synthesis, structure, and properties. *Journal of Applied Polymer Science*, *42*(11), 2997–3012. https://doi.org/10.1002/app.1991.070421118
608. Jeong, B., Park, B. D., & Causin, V. (2019). Influence of synthesis method and melamine content of urea-melamine-formaldehyde resins to their features in cohesion, interphase, and adhesion performance. *Journal of Industrial and Engineering Chemistry*, *79*, 87–96. https://doi.org/10.1016/j.jiec.2019.05.017
609. Braun, D., & Ritzert, H. J. (1987). Properties and processing behaviour of urea-melamine-formaldehyde resins. *Kunststoffe. German Plastics, 77*(12), 29–31.
610. Sokolova, E. G., Varankina, G. S., & Rusakov, D. S. (2022). Urea–Melamine Formaldehyde Resin for the Manufacture of Water-Resistant Plywood. *Polymer Science, Series D*, *15*(4), 557–561. https://doi.org/10.1134/S1995421222040281
611. Park, B. D., & Lee, S. M. (2015). Hydrolytic Stability of Cured Urea-Melamine-Formaldehyde Resins Depending on Hydrolysis Conditions and Hardener Types. *Journal of the Korean Wood Science and Technology*, *43*(5), 672–681. https://doi.org/10.5658/WOOD.2015.43.5.672
612. Mao, A., & Kim, M. G. (2013). Low mole ratio urea–melamine–formaldehyde resins entailing increased methylene-ether group contents and their formaldehyde emission potentials of wood composite boards. *BioResources*, *8*(3), 4659–4675. https://doi.org/10.15376/biores.8.3.4659-4675
613. Park, B. D., Lee, S. M., & Roh, J. K. (2009). Effects of formaldehyde/urea mole ratio and melamine content on the hydrolytic stability of cured urea-melamine-formaldehyde resin. *European Journal of Wood and Wood Products*, *67*, 121–123. https://doi.org/10.1007/s00107-008-0277-x
614. Shi, J. Y., & Ye, S. Y. (2010). Effects of addition ammonia modified urea-melamine-formaldehyde resin on the adhesions and formaldehyde emission in plywood. *Advanced Materials Research*, *113*, 1226–1229. https://doi.org/10.4028/www.scientific.net/AMR.113-116.1226
615. Young No, B., & Kim, M. G. (2007). Evaluation of melamine-modified urea-formaldehyde resins as particleboard binders. *Journal of Applied Polymer Science*, *106*(6), 4148–4156. https://doi.org/10.1002/app.26770
616. Alcasabas, A., Ellis, P. R., Malone, I., Williams, G., & Zalitis, C. (2021). A Comparison of Different Approaches to the Conversion of Carbon Dioxide into Useful Products: Part I: CO_2 reduction by electrocatalytic, thermocatalytic and biological routes. *Johnson Matthey Technology Review*, *65*(2), 180–196. https://doi.org/10.1595/205651321x16081175586719
617. Klankermayer, J., Wesselbaum, S., Beydoun, K., & Leitner, W. (2016). Selective catalytic synthesis using the combination of carbon dioxide and hydrogen: catalytic chess at the interface of energy and chemistry. *Angewandte Chemie International Edition*, *55*(26), 7296–7343. https://doi.org/10.1002/anie.201507458
618. Chung, W., Jeong, W., Lee, J., Kim, J., Roh, K., & Lee, J. H. (2023). Electrification of CO_2 conversion into chemicals and fuels: Gaps and opportunities in process systems engineering. *Computers & Chemical Engineering*, *170*, 108106. https://doi.org/10.1016/j.compchemeng.2022.108106
619. Ramirez-Corredores, M. M., Goldwasser, M. R., & Falabella de Sousa Aguiar, E. (2023). Perspectives and Future Views. In *Decarbonization as a Route Towards Sustainable Circularity* (pp. 127–153). Springer, Cham. https://doi.org/10.1007/978-3-031-19999-8_4
620. Carbon Recycling International (CRI). (2016). *Emission to liquid (ETL) technology*. https://www.carbonrecycling.is/george-olah (accessed 13 March 2021).
621. Carbon Recycling International (CRI) and HS Orka. (2011). *George Olah CO2 to renewable methanol plant*. https://www.chemicals-technology.com/projects/george-olah-renewable-methanol-plant-iceland (accessed 13 March 2021).
622. Alper, E., & Orhan, O. Y. (2017). CO_2 utilization: Developments in conversion processes. *Petroleum*, *3*(1), 109–126. https://doi.org/10.1016/j.petlm.2016.11.003
623. Chiang, P. C., & Pan, S. Y. (2017). *Carbon dioxide mineralization and utilization* (pp. 1–452). Springer Singapore.

624. Quadrelli, E. A., Armstrong, K., & Styring, P. (2015). Potential CO_2 utilisation contributions to a more carbon-sober future: a 2050 vision. In *Carbon Dioxide Utilisation* (pp. 285–302). Elsevier. https://doi.org/10.1016/B978-0-444-62746-9.00016-5
625. Cheah, W. Y., Ling, T. C., Juan, J. C., Lee, D. J., Chang, J. S., & Show, P. L. (2016). Biorefineries of carbon dioxide: From carbon capture and storage (CCS) to bioenergies production. *Bioresource Technology*, *215*, 346–356. https://doi.org/10.1016/j.biortech.2016.04.019
626. North, M. (2019). Across the board: Michael North on carbon dioxide biorefinery. *ChemSusChem*, *12*(8), 1763–1765. https://doi.org/10.1002/cssc.201900676
627. Bakonyi, P., Koók, L., Rózsenberszki, T., Kalauz-Simon, V., Bélafi-Bakó, K., & Nemestóthy, N. (2023). CO_2-refinery through microbial electrosynthesis (MES): A concise review on design, operation, biocatalysts and perspectives. *Journal of CO2 Utilization*, *67*, 102348. https://doi.org/10.1016/j.jcou.2022.102348
628. Ramirez-Corredores, M. M. (2017). Chapter 4 - Acidity in crude oils: naphthenic acids and naphthenates. *The Science and Technology of Unconventional Oils*, 295–385. https://doi.org/10.1016/B978-0-12-801225-3.00004-8
629. de Jong, E., & Jungmeier, G. (2015). Biorefinery concepts in comparison to petrochemical refineries. In *Industrial biorefineries & white biotechnology* (pp. 3–33). Elsevier. https://doi.org/10.1016/B978-0-444-63453-5.00001-X
630. Menegaki, A. (2008). Valuation for renewable energy: A comparative review. *Renewable and Sustainable Energy Reviews*, *12*(9), 2422–2437. https://doi.org/10.1016/j.rser.2007.06.003
631. Murphy, F., & Ronn, E. I. (2015). The valuation and information content of options on crude-oil futures contracts. *Review of Derivatives Research*, *18*, 95–106. https://doi.org/10.1007/s11147-014-9107-y
632. IEA. (2022). *CO_2 emissions in 2022*. https://www.iea.org/reports/co2-emissions-in-2022 (accessed 23 June 2023).
633. IEA. (2021). *Net zero by 2050: A roadmap for the global energy sector*. https://www.iea.org/reports/net-zero-by-2050 (accessed 23 June 2023).
634. Edwards, R. W., & Celia, M. A. (2018). Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States. *Proceedings of the National Academy of Sciences*, *115*(38), E8815–E8824. https://doi.org/10.1073/pnas.1806504115
635. Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., et al. (2021). *Net-zero America: Potential pathways, infrastructure, and impacts* (Final Report). Princeton University. https://netzeroamerica.princeton.edu/the-report (accessed 23 June 2023).
636. Rueda, O., Mogollón, J. M., Tukker, A., & Scherer, L. (2021). Negative-emissions technology portfolios to meet the 1.5 °C target. *Global Environmental Change*, *67*, 102238. https://doi.org/10.1016/j.gloenvcha.2021.102238
637. Brander, M., Ascui, F., Scott, V., & Tett, S. (2021). Carbon accounting for negative emissions technologies. *Climate Policy*, *21*(5), 699–717. https://doi.org/10.1080/14693062.2021.1878009
638. Pacala, S., & Socolow, R. (2004). Stabilization wedges: solving the climate problem for the next 50 years with current technologies. *Science*, *305*(5686), 968–972. https://doi.org/10.1126/science.1100103
639. Brown, M. A., Chandler, J., Lapsa, M. V., & Sovacool, B. K. (2008). *Carbon lock-in: barriers to deploying climate change mitigation technologies* (Report No. ORNL/TM-2007/124). Oak Ridge National Lab (ORNL).
640. Ioannou, I., Javaloyes-Antón, J., Caballero, J. A., & Guillén-Gosálbez, G. (2023). Economic and Environmental Performance of an Integrated CO_2 Refinery. *ACS Sustainable Chemistry & Engineering*, *11*(5), 1949–1961. https://doi.org/10.1021/acssuschemeng.2c06724