Carbon Capture, Utilisation and Storage, (CCUS): Decarbonisation Pathways for Singapore’s Energy and Chemicals Sectors

By: Preeti Srivastav, Mark Schenkel, Goher Ur Rehman Mir, Tom Berg, Maarten Staats

Navigant Netherlands B.V.
Stadsplateau 15
3521 AZ Utrecht
+31 30 662 3300
navigant.com

TABLE OF CONTENTS

EXECUTIVE SUMMARY

To combat climate change, Singapore pledged to reduce emissions intensity by 36% from 2005 levels by 2030 and stabilise emissions with the aim of peaking around 2030. Beyond 2030, Singapore's Long-term Low-Emissions Development Strategy (LEDS) aspires to halve emissions from its peak to 33MtCO_2e by 2050, with a view to achieving net-zero emissions as soon as viable in the second half of the century. Carbon capture, utilization and storage (CCUS) offers the potential for the energy and chemicals sectors to decarbonize while reducing the costs of climate mitigation in the transition to a fully decarbonised energy system. This study evaluates the potential for CCUS technologies to abate Greenhouse Gas (GHG) emissions from the energy and chemicals sectors in Singapore. Note that the analysis performed in this work is based on the latest data available as of 2019.

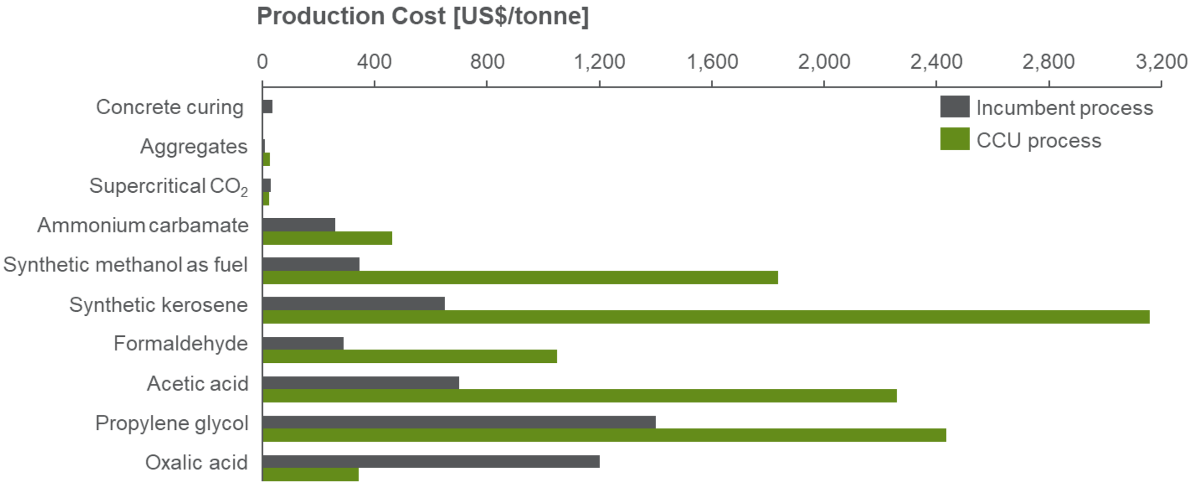
The estimated total emissions of major point sources from the energy and chemicals sectors, as well as the power sector, in Singapore was **38.8 million tonnes of CO_2** in 2016/2017, 56% of this was from power generation followed by refineries at 24% of total emissions.

The majority (96%) of carbon dioxide emissions from stationary point sources **are dilute (3%-8%)**, but smaller sources with higher concentrations exist. Capture costs are estimated based on these concentrations. Based on Singapore's emissions profile, **weighted average cost for carbon capture and concentration is US\$85/tCO_2 (full range US\$14–100)**. Further capture technology development and upscaling is needed to realise these cost levels at the scale applicable to Singapore's emission profile.

With this emissions profile and cost range established, the study explores next how CCUS technologies may play a role in abating emissions, and at what costs. Singapore does not have any known suitable reservoirs for the permanent storage of CO_2 in its subsurface, but analyses of geological storage potential in neighbouring countries indicated an estimated **regional storage potential of 84.8 giga tonnes** and there might be opportunities for Enhanced Oil Recovery that could be explored further.

For CO_2 utilization, the study provides an assessment framework for 49 identified CCU technologies to select the ten technologies that are most promising for Singapore to explore further. By 2050, all ten shortlisted CCU technologies may reach maturity. Their net **abatement potentials range between 0.3 – 2,000 kilo tonnes of CO_2,** based on one reference plant per technology. **All technologies with substantial abatement potential require significant amounts of hydrogen or ammonia**. For CCU technologies to be effective climate mitigation measures, this feedstock needs to be low-carbon. It is important to explore the future availability and costs of these low-carbon commodities.

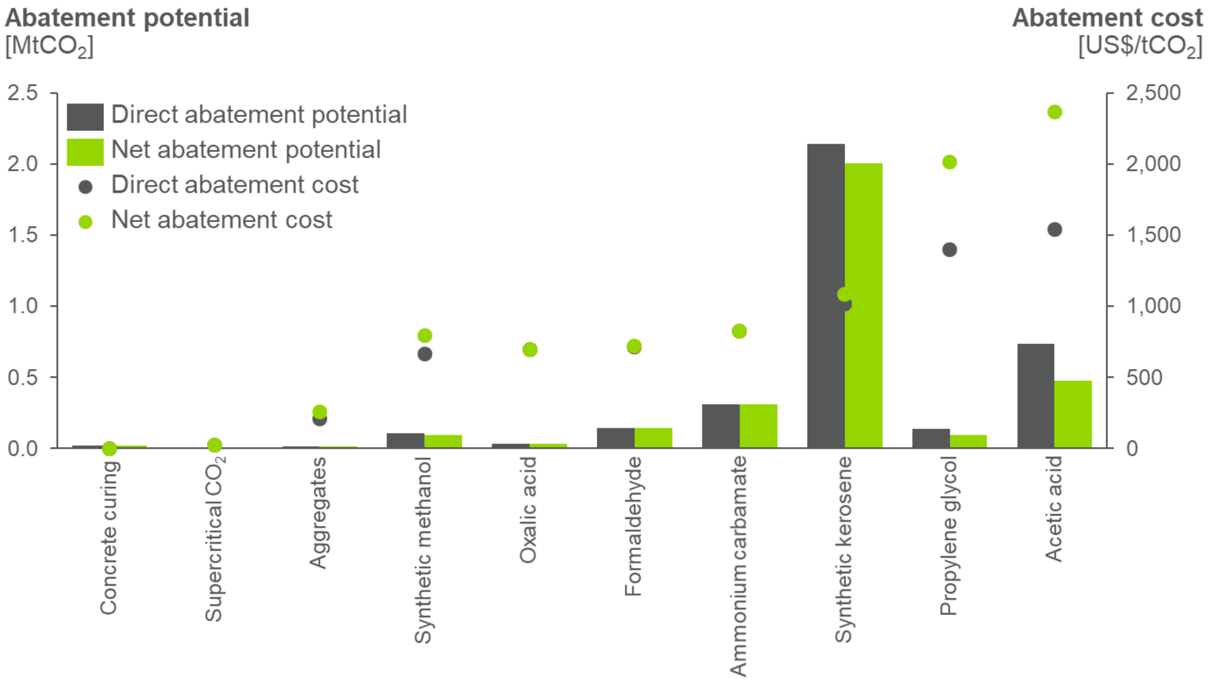
Figure 1: Comparison of production costs between conventional process and CCU process



Source: Navigant analysis, reference scenario. Section 4.4.2.

The modelling exercise in this study indicates that most of these technologies are more expensive than the incumbent processes under reference scenario assumptions, Figure 1. Expressed in net abatement costs, it becomes clear that **most of these pathways are expensive under reference scenario assumptions**, see Figure 2. In this figure, and throughout the study, direct abatement represents total CO_2 consumed by CCUS technologies and net abatement includes the effect of CO_2 emitted in CCUS processes. As such, net abatement does not account for permanence of CO_2 storage. A more detailed description of these concepts can be found in Annex A.1.4.

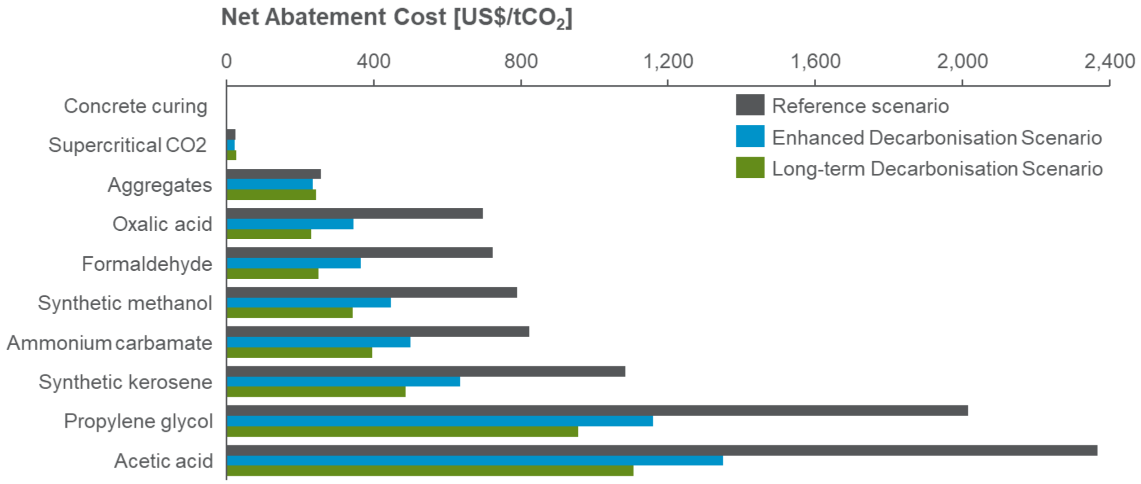
Figure 2: Abatement potential and costs for 2050 in the reference scenario



Source: Navigant analysis, reference scenario. Excluding CO_2 capture costs and product revenue streams. Abatement potential is based on the capacity of a single reference plant. See Section 4.4.3 for details.

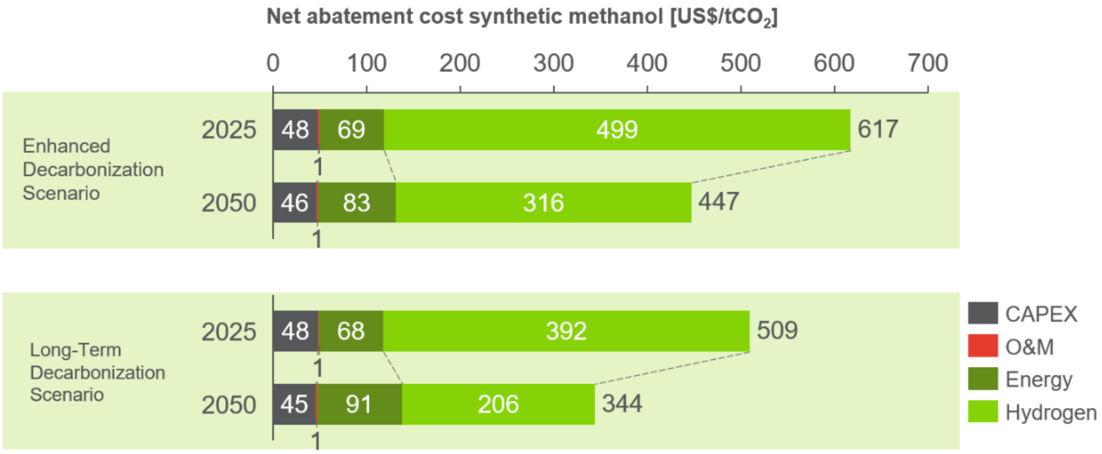
Production costs, and with that abatement costs, will need to come down further. The study explores this using scenario analysis. We test the impact of changing costs of imported low-carbon feedstock, local electricity and a carbon price, by defining two more scenarios with increasing climate ambitions. The result is a clear drop in net abatement cost (Figure 3), which can be attributed to a large extent to lowering costs of hydrogen and ammonia imports. Figure 4 shows this effect for synthetic methanol.

Figure 3: Decreasing net abatement costs by 2050 at increasing climate ambition levels under the scenarios defined in this study



Source: Navigant analysis, Section 5.4

Figure 4: Net abatement cost development for synthetic methanol production in the EDS and LTDS scenarios



Source: Navigant analysis, Section 5.3

What becomes clear through this analysis is that to increase the probability of realising most of these CCU technologies at industrial scale in Singapore, **economics needs to improve** through cost reductions, technology development and other supporting mechanisms. Concrete curing and supercritical CO_2 are at or close to being economically feasible in the reference scenario. The other technologies require further cost reduction to compete with incumbent production methods, such as reducing the cost of hydrogen feedstock. Besides this, a level playing field can aid CCU further, such as harmonised certification or accounting for negative externalities such as GHG emissions from incumbent production methods. To this end, the following recommendations are made:

- For higher TRL technologies, **further cost reductions** related to hydrogen feedstock or a **level playing field are required** to compete with incumbent production methods and overcome commercial barriers.
    - Supporting the development of low-carbon hydrogen and renewable energy production pilots to reduce production costs.
    - Especially for globally traded commodities, international certification needs to be adopted and harmonised to accept CCU-derived products.
- For the lower TRL technologies, **technological breakthroughs are required** to scale and improve efficiency. Targeted R&D support may help to achieve this.
- Other supporting mechanisms can aid CCU further.
    - In incumbent markets, enhanced uptake of low-carbon alternatives such as CCU can increase abatement potential. Examples are prescribing a fuel blend for sustainable fuels, or a green building certification system favouring low-carbon materials.
    - Carbon pricing policies would also incentivise the development of a CO_2 market.

1. STUDY BACKGROUND AND OBJECTIVE

Globally, CO_2 emissions have been rising at 3% a year, propelling countries, organisations, private investors, and companies to increase their efforts and commitment to combating climate change. At COP21 in 2015, Singapore pledged to reduce emissions intensity by 36% from 2005 levels by 2030 and stabilise emissions with the aim of peaking around 2030. Beyond 2030, Singapore's Long-term Low-Emissions Development Strategy (LEDS) aspires to halve emissions from its peak to $33MtCO_2e$ by 2050, with a view to achieving net-zero emissions as soon as viable in the second half of the century.

The energy and chemicals (E&C) sector is an important contributor to Singapore's economy, making up approximately one-third of Singapore's annual manufacturing output and employing 26,000 people. Government agencies are planning strategies for carbon mitigation in the industry. Carbon capture, utilization and storage offers the potential for these sectors to decarbonize while reducing the costs of climate mitigation in the transition to a fully decarbonised energy system.[1] Especially for emissions-intensive industrial sectors, CCUS can be cost-effective compared to other mitigation options. Due to a renewables-constrained Singapore, CCUS can also be of special interest for the power sector in the national context. The agencies are looking at identifying and analysing suitable carbon capture, utilisation and storage (CCUS) technologies that could be implemented by Singapore.

Navigant Consulting, Inc. (Navigant) evaluated potential CCUS pathways in this study (2019), building on EDB's internal study in 2017 and the National University of Singapore (NUS) CCUS technology roadmap developed in 2013. The study would help agencies prioritise near-term (5-10 years) implementation and research, development, and demonstration pathways up to 2050 for Singapore.

The study looks at four main points:

(i) Updating CO_2 emissions profile of the E&C sector

(ii) Analysing the carbon abatement potential[2] and cost of implementing CCUS pathways and technologies (implementable by 2025-2030[3] and by 2050)

(iii) Developing marginal abatement cost curves (MACCs), and ranking the potential pathways/technologies by abatement potential and associated costs

(iv) Identifying technical and commercial barriers to near (by 2025-2030) and long-term (2050) implementation; identify enablers required to facilitate successful implementation; and recommending the pathways/ technologies for implementation in Singapore.

This study was conducted in a two-phase process. The team conducted extensive external consultation through workshops and discussions with local & global subject matter experts and large emitter companies.

Phase 1: Longlist and Workshop

The first phase focussed on collating a longlist of key CCUS technologies and pathways. This longlist was then assessed on a framework of selected attributes which are pertinent for Singapore. The longlist and assessment framework were presented in a workshop with local and global subject matter experts and large emitter companies.

---

[1] IEA, 2018. *Industrial applications of CCS.* https://www.iea.org/topics/carbon-capture-and-storage/industrialapplicationsofccs/

[2] Direct abatement means the total CO_2 consumed by carbon capture, utilisation and storage (CCUS) technologies and net abatement includes the effect of CO_2 emitted in CCUS processes. A more detailed description is in Annex A.1.4

[3] This study uses 2025 and 2050 as target years. 2025 is used as a milestone for near-term implementation by 2030.

Phase 2: Shortlist and Deep Dive

A shortlist of technologies and pathways was developed from the inputs of the workshop. This shortlist was then further investigated in a deep-dive assessment phase. In this phase, both qualitative and quantitative models for calculating carbon abatement potential and associated costs of CCUS technologies/pathways was developed.

2. EMISSIONS PROFILE OF STATIONARY POINT SOURCES

To assess which CCUS options are appropriate for Singapore it is important to have more insight into the emissions profiles of stationary point sources. In this chapter, we present the results of updating the CO_2 emissions profile of the E&C sector developed in the 2013-2014 CCUS roadmap including the key industrial processes, concentration, and volumes of CO_2 streams.

The analyses are based on publicly available information. Where data for Singapore was not available, the analyses were supported by assumptions and proxies.

2.1 Emissions from stationary point sources

In this section, we explored the various emissions per stationary point sources. This is based on different methodologies, which are detailed for the specific sectors.

2.1.1 Emissions from the power sector

Following the methodology used in the 2013-2014 CCUS study[4] we identified two methods for estimating emissions from the power sector: the input and the output. This allows for validation of estimates and helps validates the robustness of results. It is also used by other organisations, for example, EMA uses these methods to calculate the fuel mix for electricity generation.[5] We use the input and output method to estimate the emissions from the power sector. [6] The definitions and our approach for estimating emissions using these methods are explained below.

Input method: This method calculates the electricity fuel mix based on the ratio of fuel that is fed into electricity generation units. It does not consider fuel to electricity conversion efficiencies of electricity generation units or the variations in the energy content of different fuels.

We used Singapore's Grid Emission Factor (GEF) of 0.4192 kg CO_2/kWh from 2017 for emissions using the input method. The GEF is a measure of average CO_2 emissions per unit of net electricity output. We applied that emission factor to the total electricity generation volumes of 52.2 TWh[7] in 2017. This results in total emissions of **21.9 $MtCO_2$/yr**.

Output method: This method differentiates between the fuel type and the power plant used to produce electricity to estimate the fuel mix for electricity generation. It also includes the domestic fuel to electricity conversion efficiency of power plants.

---

[4] Iftekhar A. Karimi et al., *Carbon Capture & Storage/Utilization Singapore Perspectives*, National Climate Change Secretariat and National Research Foundation Prime Minister's Office Singapore, 2014. https://www.nccs.gov.sg/docs/default-source/default-document-library/carbon-capture-and-storage-utilisation-singapore-perspectives.pdf

[5] Energy Market Authority, *Singapore Energy Statistics*, 2018. https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/SES18/Publication_Singapore_Energy_Statistics_2018.pdf

[6] There are four Waste to Energy (WtE) plants currently in operation in Singapore. Together they meet around 2%-3% of Singapore's electricity needs. See: National Environment Agency, *Singapore's Fourth National Communication and Third Biennial Update Report: Under the United Nations Framework Convention on Climate Change*, 2018. https://www.nccs.gov.sg/docs/default-source/default-document-library/singapore's-fourth-national-communication-and-third-biennial-update-repo.pdf

The fossil-based waste incineration contributes to the emissions profile of the country. Since the electricity generation capacity of WtE plants has stayed the same since 2010, we assume similar emissions from WtE plants for today as they are reported in Singapore's Fourth National Communication. The reported emissions are around 1.6 $MtCO_2$ for 2014.

[7] Energy Market Authority, *Energy Balances*, 2018. https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/ses/2018/downloads/SES18_Chap4.pdf

For emissions, we obtained the fuel mix data from Singapore Energy Statisics.[5] Natural gas (95.1%) has the largest share, followed by coal (1.3%) and fuel oil (0.7%). The remaining fuel mix (2.9%) includes sources like biomass, municipal waste and solar PV.

As a first step, we retrieved the default emissions factors for the fuels from the International Panel on Climate Change's (IPCC) 2006 Guidelines on National Greenhouse Gas Inventories (see Table 1).[8] We estimated the average energy to electricity conversion efficiency of power plants in Singapore using figures on total energy input to electricity generators and gross electricity generated in 2017.[5] This led to an average conversion efficiency of 46.7%. Using this average conversion efficiency, we derived electricity emissions factors for different fuels that are used in the power sector. The kilowatt-hours from fuels refer to the energy contained in fuels whereas the kilowatt-hours from electricity accounts for fuel to electricity conversion efficiency.

Table 1. CO_2 emission factors for fuels used in the power sector[8]

Fuel type	Fuel emission factor (gCO_2/kWh)	Electricity emission factor (gCO_2/kWh)
Natural gas	202	432
Coal[9]	346	741
Fuel oil	279	597
Renewable sources	0	0

Source: Energy Market Authority[5], IPCC[8]

Based on this percentage fuel mix and the electricity emission factors for each fuel we estimate emissions from power sector to be 22.2 $MtCO_2/yr$. Adding emissions from Waste-to-Energy (WtE) plants would increase the total to **23.8 $MtCO_2/yr$**.[6]

The total emissions in Singapore are different based on the two methods. The average GEF from the output method comes out to be 0.4559 kg CO_2/kWh against the 2017 fuel mix. This is slightly higher than 0.4192 kg CO_2/kWh that came out of the input method.

We used the results from the input method since they directly originate from an official source. Therefore, the assumed emissions from the power sector are **21.9 $MtCO_2$.**

2.1.2 Emissions from refineries

There are three refineries currently operating in Singapore. The emissions from refineries were calculated using their crude distillation capacity, operating hours, and emissions factor per tonne of processed crude oil.

ExxonMobil (592 kbbl/day)[10] has the largest refining capacity, followed by Shell (500 kbbl/day)[11] and Singapore Refining Company (SRC)[12] (290 kbbl/day).[13] The total refining capacity in Singapore is 1,382 kbbl/day. The nameplate capacity is converted to units of k-tonne of oil equivalent/day using a conversion

---

[8] IPCC, *Chapter 2: Stationary Combustion*, 2006. https://www.ipccnggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf

[9] Sub-bituminous coal

[10] ExxonMobil, Singapore Refinery Overview, https://www.exxonmobil.com.sg/en-sg/company/business-and-operations/operations/singapore-refinery-overview

[11] Shell, Pulau Bukom Manufacturing Site, https://www.shell.com.sg/about-us/projects-and-sites/pulau-bukom-manufacturing-site.html

[12] Singapore Refining Company (SRC) is a joint venture between Singapore Petroleum Company (SPC) on one part and Chevron (namely, Chevron Singapore Pte. Ltd. & Chevron Trading Pte. Ltd.) on the other. http://www.src.com.sg/

[13] Singapore Refining Company (SRC), Welcome to Singapore Refining Company, http://www.src.com.sg/

of 0.1364 ktoe/kbbl, taken from OPEC website[14]. Operation hours in Singapore refineries are assumed to be 8,300 hours/year, which roughly results in a capacity factor of 95%.Using the capacity factor and the crude oil processing capacity of refineries, total annual volumes for processed crude oil were estimated, see Table 2.

Table 2. Crude oil distillation capacity and the associated emissions in Singapore

Refinery	Crude oil processing capacity (kbbl/day)	Crude oil processing capacity (ktoe/day)	Capacity factor (%)	Annual processed crude oil (Mtoe/yr)	Total emissions ($MtCO_2$/yr)
ExxonMobil	592	81	95%	28	4.0
Shell	500	68	95%	24	3.4
Singapore Refining Company (SRC)	292	40	95%	14	1.9
Total	**1,382**	**189**		**66**	**9.3**

Source: references indicated in main text, Navigant analysis

An emissions factor for Singapore refineries was not available from public sources. We used the emissions factor from the 2013-2014 CCUS report,[4] which based its estimates on data provided for natural gas-based refineries in the US. Since Singapore refineries are mostly gas-based, it is assumed that Singapore refineries are similar to an average gas-based refinery in the US. The report used the Energy Bandwidth for Petroleum Refining Processes[15] to arrive at an emissions factor of 0.01934 tonne CO_2/bbl.

Using the emissions factor and the total annual volumes of processed crude oil, we estimate emissions from refineries to be **9.3 $MtCO_2$/yr**.

2.1.3 Emissions from hydrogen production

In Singapore, hydrogen is produced largely by steam methane and naphtha-based reforming. A considerable fraction is also produced from partial oxidation of residual fuel oil and refinery off gases; however, this production share and their corresponding emissions have been implicitly considered in emissions estimates of refineries. The emissions estimates from hydrogen in this section are based on production volumes from Air Liquide and IEA GHG Emissions Database. Air Liquide (80 ktpa)[16] has the largest production volumes and is based on steam methane reforming. Singapore also has facilitie, such as SRC, which produce hydrogen based on steam naphtha reforming. The production data in Table 3 are derived from Air Liquide production capacity and IEA's GHG Emissions Database from 2008[17]. Although this database is dated, no updates or alternative sources are available. There is a possibility that the actual production volumes have changed considerably since then.

---

[14] OPEC, Conversion Factors, https://www.opec.org/library/Annual%20Statistical%20Bulletin/interactive/current/FileZ/cfpage.htm

[15] U.S. Department of Energy, *Energy Bandwidth for Petroleum Refining Processes*, 2006. https://www.energy.gov/sites/prod/files/2013/11/f4/bandwidth.pdf

[16] Air Liquide, Our Capabilities, https://industry.airliquide.sg/about-us/our-capabilities

[17] International Energy Agency, *IEA GHG CO_2 Emissions Database*, 2008.

Table 3. Selected hydrogen production capacities and associated emissions in Singapore

Production Approach	Hydrogen production capacity (ktpa)	Capacity factor (%)	Hydrogen production volumes (ktpa)	Total emissions ($MtCO_2$/yr)
Hydrogen produced via steam methane reforming	114	80%	91	0.73
Hydrogen produced via steam naphtha reforming	29	80%	23	0.23
Total	**143**		**114**	**0.95**

Source: references indicated in main text, Navigant analysis

We assumed operating hours of around 7,000/year which result in a capacity factor of 80%. Using this capacity factor, we derived annual hydrogen production volumes for Singapore. The emissions factors for steam methane reforming and steam naphtha reforming are 8.0 tonne CO_2/tonne of hydrogen and 9.7 tonne CO_2/tonne of hydrogen, respectively.[18,19]

The total CO_2 emissions from hydrogen production in Singapore are estimated to be **0.95 $MtCO_2$/yr**, excluding hydrogen production emissions using residual fuel oil and refinery off gases.

2.1.4 Emissions from ethylene production

Ethylene is produced through steam cracking of naphtha in Singapore. Currently, three companies are producing ethylene, ExxonMobil, Singapore Petrochemical Complex (PCS), and Shell. ExxonMobil (1.9 million tonnes)[20] has the largest ethylene production capacity followed by PCS (1.1 million tonnes)[21] and Shell (1 million tonnes).[11] The CO_2 emissions are estimated using production capacity of ethylene crackers, operating hours, and CO_2 emissions factor per tonne of ethylene.

Table 4. Ethylene production capacity and the associated emissions in Singapore

Company	Ethylene production capacity (Mtpa)	Capacity factor (%)	Ethylene production volumes (Mtpa)	Total emissions ($MtCO_2$/yr)
ExxonMobil	1.9	90%	1.7	3.1
Singapore Petrochemical Complex (PCS)	1.1	90%	1.0	1.8
Shell	1	90%	0.9	1.7
Total	**4.0**		**3.6**	**6.6**

Source: references indicated in main text, Navigant analysis

---

[18] TOPSOE Technologies, *Large scale Hydrogen Production*, 2007. https://www.topsoe.com/sites/default/files/topsoe_large_scale_hydrogen_produc.pdf

[19] U.S. Environmental Protection Agency, *Technical Support Document for Hydrogen Production: Proposed Rule for Mandatory Reporting of Greenhouse Gases,* 2008.

[20] ExxonMobil, ExxonMobil in Singapore, https://www.exxonmobil.com.sg/en-sg/company/about-us/company-info/exxonmobil-in-singapore

[21] Petroleum Corporation of Singapore, Our Plant, Facilities & Products, http://www.pcs.com.sg/plant-facilities-products/

Operation hours in Singapore ethylene crackers are assumed to be 7,880 hours/year, which roughly results in a capacity factor of 90%. Annual production volumes for ethylene production were calculated using ethylene production capacity and the operating hours for steam crackers. The CO_2 emissions factor for naphtha-based refineries in Singapore is 1.84 tonne CO_2/tonne of ethylene and is obtained from IEA GHG Emissions Database from 2008. Although the source is old, the emissions factor is not expected to change since the standard steam cracking processes have been used.

Using the emissions factor and the total annual ethylene production volumes, we estimate emissions from ethylene production to be **6.6 $MtCO_2$/yr**.

2.1.5 Emissions from ethylene oxide production

Currently, only the production capacity for ethylene oxide that is publicly available is from Shell. Hence using that as a proxy, the total production capacity for ethylene oxide in Singapore is estimated to around 210 kilo tonnes[22]. Ethylene oxide could be produced through two processes: air process and oxygen process. The default CO_2 emissions factor for the air process is 0.863 which assumes a catalyst selectivity of 70%, and the default emissions factor for the oxygen process is 0.663 which assumes a catalyst selectivity of 75%.[23] It is very likely that the facilities for ethylene oxide production in Singapore have a catalyst selectivity data different from the default catalyst selectivity. Since data on Singapore was not available, we assumed default CO_2 emissions factors.

Shell is operating its MASTER process, which is based on catalytic conversion of ethylene to ethylene oxide and thermal conversion of ethylene oxide to ethylene glycol.[24] Almost all of the ethylene oxide production globally is based on direct oxygen.[25] The use of oxygen is preferred over air because of higher yields and less downtime in larger plants.[25] We used the emissions factor from the oxygen process to estimate emissions from ethylene oxide in Singapore. The average full load hours or the capacity factor for ethylene oxide production facilities is assumed to be 80%.

Table 5. Ethylene Oxide production capacity and the associated emissions in Singapore

Ethylene oxide production capacity (ktpa)	Capacity factor (%)	Ethylene oxide production volumes (ktpa)	Total emissions ($MtCO_2$/yr)
210	80%	168	0.11

Source: National Environment Agency[23], Shell[24], Navigant analysis

The total CO_2 emissions from ethylene oxide production in Singapore are estimated to be **0.11 $MtCO_2$/yr**.

2.1.6 Summary and validation of CO_2 emissions from Singapore

The total emissions of major point sources from different sectors in Singapore add up to **38.8 $MtCO_2$** in 2016/2017. Figure. 5 provides an overview of these CO_2 emissions. The largest contribution is from point

---

[22] Shell Production capacity for Ethylene Oxide, https://www.shell.com/business-customers/chemicals/factsheets-speeches-and-articles/factsheets/shell-chemicals-singapore.html

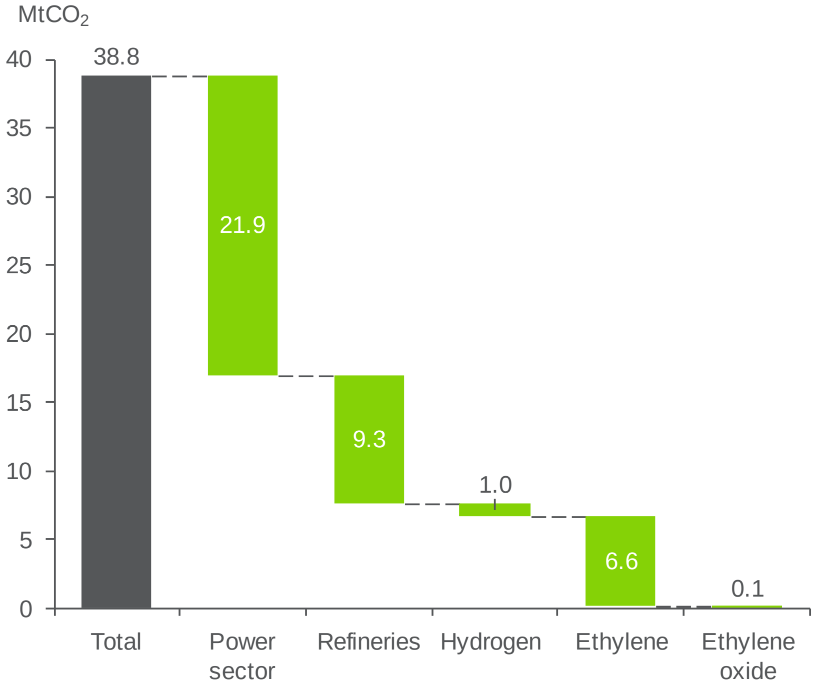
[23] National Environment Agency, *Greenhouse Gas (GHG) Emissions Measurement and Reporting Guidelines*, 2018. https://www.nea.gov.sg/docs/default-source/our-services/climate-change/m-r-appendix-(ver-14-feb-2018).pdf

[24] Shell, Ethylene Oxide/Ethylene Glycol (EO/EG) Processes, https://www.shell.com/business-customers/global-solutions/petrochemicals-technologies-licensing/ethylene-oxide-ethylene-glycol-processes.html

[25] Global CCS Institute, *CCS Roadmap for Industry: High-purity CO_2 Sources*, 2010. https://hub.globalccsinstitute.com/publications/ccs-roadmap-industry-high-purity-co2-sources-sectoral-assessment-%E2%80%93-final-draft-report-2

sources in the power sector (56%) followed by refineries (24%). The CO_2 emissions from ethylene production are also substantial whereas the share from hydrogen and ethylene oxide is marginal.

Figure. 5 CO_2 emissions from various sectors in Singapore



Source: Navigant analysis

The emissions are compared to the figures shared by IEA in its 2018 energy balances. The IEA World Energy Balances report emissions of **37.1 $MtCO_2$** for 2015 (latest year available in IEA 2018) excluding emissions from transport. The categorization of IEA for different sectors is different from our classification except for power sector. Estimates for the power sector are in line with IEA estimates of 21.9 $MtCO_2$. For other sectors it is not possible to compare emissions from point source to point source. However, our overall estimates are within a 5% error margin compared to the IEA estimates.

2.2 Concentration profiles for CO_2 emissions

The concentration of CO_2 in different flue gas streams is an important parameter that dictates the costs of CO_2 captured. If the concentration of CO_2 in a flue gas or process stream is low, then the costs for CO_2 capture and concentration would be high and vice versa. In this section, we present the CO_2 concentration from flue gases originating from point sources identified in Section 2.1. The concentration of CO_2 from different point sources are mainly obtained from the 2013-2014 CCUS report and are cross-checked with literature where necessary. Based on our conversations with experts from the industry and from the authors of the previous study, the situation on ground has not changed in the last 5 years.

Singapore's power sector uses natural gas, coal, and fuel oil. The concentration of CO_2 from natural gas-based power plants is lowest, around 3%. The CO_2 concentration from fuel oil-based power production is 8% whereas for coal-fired power plants it is 15%. More than 95% of the power produced in Singapore is natural gas based which means that the concentration of CO_2 in flue gas streams is around 3% for majority of the power plants.

Typically, refineries have complex processes which are associated with numerous point sources of emissions distributed over a large site. Global CCS Institute (GCCSI) reports that the emissions from utilities and process heaters can contribute around 20%-50% and 30%-60%, respectively, to the total refinery emissions.[26] We assume a 50%-50% split in emissions between utilities and process heaters. The concentration of CO_2 from process heaters could range between 8%-10% whereas for combined heat and power plant (CHP) units it could be 3%-4%.[26] Not all the refineries have fluidised catalytic crackers (FCC) units,[27] but they can account for as much as 50% of the refinery CO_2 emissions.[26] The emissions from FCC units are process-related rather than combustion related. The 2013-2014 report assumes only 0.1% of the emissions from FCC which have a CO_2 concentration of around 10%-20%.[28] The remaining emissions (99.9%) are split between utilities and process heaters with 3% and 8% CO_2 concentration, respectively.

For hydrogen production using natural gas, around 60% of the total CO_2 is emitted from the shifted syngas and the remaining CO_2 is released from the combustion of fuel for steam reformer.[29] Both gas streams have different CO_2 concentrations. The concentration of CO_2 in the shifted syngas is 15% whereas in flue gas from steam reformer it is around 20%. With a pressure swing adsorption (PSA) unit, which is installed for hydrogen purification from shifted syngas, the concentration of CO_2 in tail gas exiting a PSA unit can increase up to 45%.[29,30] This means there are three different gas streams which offer an opportunity for CO_2 separation: (i) shifted syngas before entering PSA unit, (ii) tail gas exiting PSA unit and (iii) steam reformer flue gas. In theory it is also possible to combine the CO_2 removal of (i) or (ii) with (iii).

Around 50% of the global hydrogen production is used for ammonia synthesis and about 25% is used in the refining industry.[31, 32] The hydrogen production usually takes place onsite since the transport and distribution of hydrogen is challenging. Around 80% of all the ammonia globally is used to produce nitrogen-based fertilisers. In fertiliser production, CO_2 is needed which is usually captured from the hydrogen production process. The fertiliser industry is already capturing CO_2 from the shifted syngas because the gas pressure is very high and CO_2 separation is rather easy and cheap. However, the CO_2 removal of flue gas from steam reformer is considered relatively more complicated and expensive compared to syngas CO_2 removal.[29] Currently, there is no ammonia production in Singapore and refineries have no major incentive for CO_2 removal from hydrogen production; therefore, we assume that CO_2-specific separation techniques are not currently applied. This indicates that the CO_2 concentration from hydrogen production could range from 20%-45% in Singapore. For our assessment we assume an average CO_2 concentration of around 30%.

Emissions from ethylene production are partly process-related. However, mainly fuel oil is combusted in furnaces which correspond to CO_2 concentration of 8%, whereas ethylene oxide produces a pure stream of CO_2 with 100% CO_2 concentration.

---

[26] DNV, *Global Technology Roadmap for CCS in Industry, Sectoral Assessment: Refineries,* 2010. http://hub.globalccsinstitute.com/sites/default/files/publications/15691/global-technology-roadmap-ccs-industry-sectoral-assessment-refineries.pdf

[27] Shell has an FCC in its secondary unit, it was shut down after a fire incident in 2011. https://www.asiaone.com/News/AsiaOne%2BNews/Singapore/Story/A1Story20110929-302208.html

[28] Note that other sources provide a different emission share for FCC. IEA reports an emission share of less than 10% whereas GCCSI specified that in a few cases FCC can account for as much as 50% of refinery CO_2 emissions.

[29] Collodi. G. & Wheeler, F., *Hydrogen Production via Steam Reforming with CO_2 Capture,* 2010.

[30] Bains et al, *CO_2 Capture from the Industry Sector*, 2017. https://users.wpi.edu/~jlwilcox/documents/bains_industry.pdf

[31] International Energy Agency, Global Trends and Outlook for Hydrogen, 2017. http://ieahydrogen.org/pdfs/Global-Outlook-and-Trends-for-Hydrogen_Dec2017_WEB.aspx

[32] UNIDO, *Carbon Capture and Storage in Industrial Applications: Technology Synthesis Report, Working Paper – November 2010*, 2010. https://open.unido.org/api/documents/4785712/download/Carbon%20Capture%20and%20Storage%20in%20Industrial%20Applications%20-%20Technology%20Synthesis%20Report

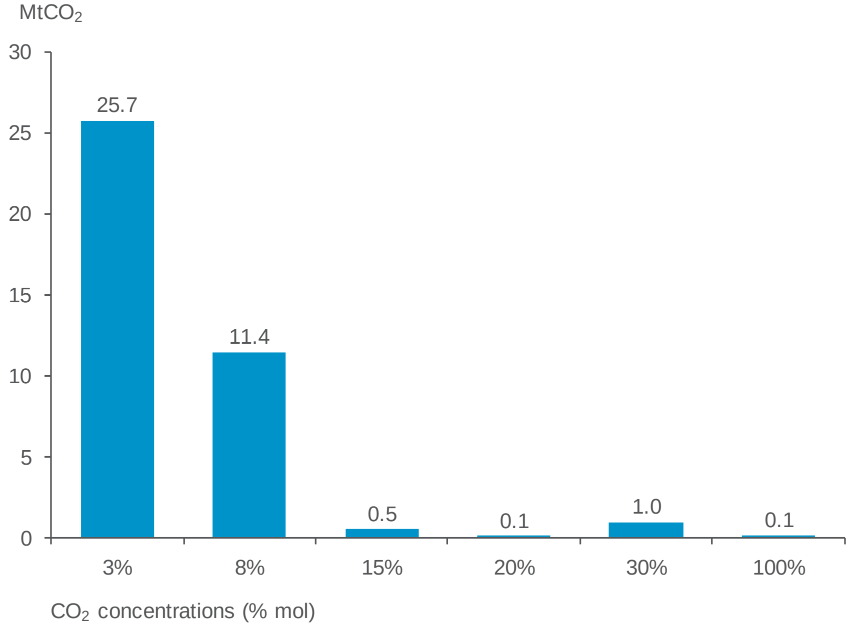
Table 6. CO_2 concentrations from flue gases against major point sources

Sector	Point source	CO_2 concentration (% mol)
Power sector	Natural gas	3%
	Coal	15%
	Fuel oil	8%
Refineries	Utilities	3%
	Process heaters	8%
	Fluidised Catalytic Crackers (FCC)	10-20%
	Hydrogen	30%
	Ethylene	8%
	Ethylene oxide	100%

Source: references identified in main text, Navigant analysis

The concentration profiles and the corresponding emissions in Singapore are depicted in Figure 6.

Figure 6. Concentration profiles of CO_2 emissions in Singapore



Source: Navigant analysis

3. RESEARCH AND LONGLIST OF CCUS TECHNOLOGIES

In this chapter we analyse the long list of CCUS technologies which are categorized into three categories namely; carbon capture and concentration, carbon utilisation and carbon storage. We based our analysis on the information gathered from literature which is complemented with the inputs we received from experts during the workshop. We performed the analysis in close consultation with PMO & EDB to ensure alignment on goals, approach and criteria for prioritising pathways and technologies. We furthermore conducted interviews with external subject matter experts (SMEs) to test our assumptions for pathway analysis.

For carbon capture as well as carbon storage technologies, we performed an extensive literature review on their current developmental status and analysed the economic, technical as well as regulatory challenges for their deployment in Singapore. For the assessment of carbon utilisation technologies, we devised an assessment framework to arrive at a shortlist of the promising CCU technologies and pathways for Singapore. These shortlisted technologies are further analysed in the following chapters of the report.

This chapter is divided into three sections covering one category of the CCUS technologies and ends with a section on key barriers and opportunities for Singapore.

3.1 Carbon capture and concentration

To use or store CO_2 emitted by the industry or power generation sector, the CO_2 must first be captured and often concentrated and subsequently purified. In general, there are three notable groups of CO_2 capture technology that relate to the method of fuel combustion in an industrial process, or the phase in which the CO_2 is captured: post-combustion capture, pre-combustion capture, and oxyfuel combustion capture. A fourth method, direct air capture, is described in Box 1.

- **Post-combustion capture** involves the capture of CO_2 from the flue gas stream exiting the combustion process. This mode of capture is applicable for most existing power and industrial plants. The advantage of this method is that plants can more easily be retrofitted with post-combustion technologies compared to the other methods. Since air is used for combustion, most of the flue gas is nitrogen, and CO_2 concentrations are low. Thus, the energy for post-combustion capture is the energy required to separate CO_2 from N_2, moisture, and other contaminants in the flue gas such as SO_x and NO_x.

- **Oxy-combustion processes** use enriched oxygen instead of air for the combustion of fuels. The oxygen must first be enriched from air using an air separation unit or industrial symbiosis. The flue gas from such a process has a minimal nitrogen content, so oxy-combustion CO_2 capture mainly involves the condensation of water from the flue gas. Neglecting the energy for this condensation, the energy required for CO_2 capture via oxy combustion equals the energy required for air separation.

- **Pre-combustion capture** involves gasification of a fossil fuel via enriched oxygen to obtain a mixture of CO and H_2. This mixture is converted to a CO_2-H_2 mixture via the water gas shift reaction. H_2 and CO, separated from CO_2, can be combusted to generate heat or power onsite or elsewhere or used as a feedstock. In contrast to the first two modes, pre-combustion capture involves two separations, but with lower overall energy requirements. The first is to enrich oxygen from air, and the second is to separate CO_2 from H_2. The energy requirement for pre-combustion capture is therefore equal to the sum of the energy needed for air and CO_2-H_2 separation.

It should be emphasized that there is an energy penalty associated with the integration of a capture unit that can compromise system efficiency or lead to additional indirect emissions of CO_2 from increased energy demand.

Box 1. Direct air capture

Direct air capture (DAC) involves the capture of CO_2 from the atmosphere. Various start-ups have emerged that foresee an important role for direct air capture to play in climate change mitigation and work with technologies that are also used for industrial CO_2 capture like absorption, adsorption, membranes and mineralization. The rationale for direct air capture is mainly that carbon-neutral hydrocarbons (e.g. fuels, plastics) can be produced where using fossil industrial or power emissions cannot do this. In some cases, DAC is also foreseen to be less costly compared to CO_2 capture from flue gas with a low CO_2 concentration due to the reduced need for retrofitting and CO_2 transport. It furthermore represents a cap to the cost of mitigation globally, since, as it is based on atmospheric CO_2 it can capture CO_2 emissions from any source. Basic estimates of the cost of DAC vary widely, between US\$50–1,000/tCO_2. Limited detailed engineering studies have been performed, though recently Carbon Engineering, who developed an aqueous potassium carbonate-based system with existing technologies, have estimated costs of US\$94–232 for a 1 MtCO_2/a plant, depending on energy costs, financial assumptions and system set-up.[33] The lower-end estimates include a heat demand of around 5 GJ/tCO_2, which if met with natural gas would emit around 300 grams of CO_2 per tonne of CO_2 captured. Other notable companies in the field of DAC include Climeworks and Global Thermostat. Climeworks is a Swiss-based firm operating an adsorption-desorption process using a novel filter material,[34] whereas Global Thermostat is US-based and uses a proprietary amine-based system.[35] Although promising as a technology to produce low-carbon fuels, due to the significant land demand of DAC technology, large-scale deployment is not likely in Singapore. It is estimated that around 500 km^2 is needed to capture 1 MtCO_2.[36]

3.1.1 Carbon capture technologies and their developmental status

There are several methods available for the capture of CO_2 emissions, which can be categorized into physical, chemical, or biological pathways. Physical pathways include physical absorption, adsorption, cryogenic separation and membrane separation. Chemical pathways use solvents which chemically react with CO_2 to separate it from other gases. Biological pathways employ microorganisms such as algae for CO_2 capture.

The large-scale separation technologies such as cryogenic distillation and amine-based absorption have high energy penalties. The relatively new adsorption-based and membrane-based separation processes are emerging as energy efficient alternatives for industrial gas separation. These technologies are heavily researched areas and no singular technology has emerged as the most promising solution. In the following sub-sections, we discuss different methods of carbon capture and share their current developmental status.

3.1.1.1 Absorption-based capture

Absorption refers to the uptake of CO_2 into the bulk phase of another material—for example, dissolving CO_2 molecules into a solvent such as an aqueous amine. The solvent based carbon capture is the most commercially ready technology and has been deployed to capture carbon from flue gases of large-scale power plants and numerous carbon-intensive industries.[37]

Most chemical solvents are amine-based[38] and the most widely used is mono-ethanolamine (MEA). These solvents chemically bind CO_2 to separate it from other gases in flue gas streams and thus high CO_2 recovery rate and product purity can be achieved. However, CO_2 capture through chemical solvents faces challenges because solvents require a large amount of energy to regenerate. The rate of solvent degradation is high, especially in the oxidising environment of a flue gas. The solvents also have high equipment corrosion rates

---

[33] Keith et al., 2018. *A Process for Capturing CO_2 from the Atmosphere*. https://doi.org/10.1016/j.joule.2018.05.006

[34] Climeworks, 2017. *World-first Climeworks plant: Capturing CO_2 from air to boost growing vegetables*. http://www.climeworks.com/wp-content/uploads/2017/05/02_PR-Climeworks-DAC-Plant-Case-Study.pdf

[35] Global Thermostat, 2019. *A Unique Capture Process*. https://globalthermostat.com/a-unique-capture-process/

[36] Ranjan, 2010. *Feasibility of Air Capture*. https://sequestration.mit.edu/pdf/ManyaRanjan_Thesis_June2010.pdf

[37] Eni Oko et al., Current Status and Future Development of Solvent-Based Carbon Capture, "International Journal of Coal Science & Technology", no. 4 (2017), https://doi.org/10.1007/s40789-017-0159-0

[38] Other amine-based solvents are Methyl Diethylamine (MDEA), 2-amino-2-methyl-1-propanol (AMP), piperazine (PZ), etc. Chemicals such as aqueous ammonia and potassium or sodium carbonates can also be used for CO_2 scrubbing. https://hub.globalccsinstitute.com/publications/co2-capture-cement-industry/34-types-co2-capture-technology#h4_23

unless additives are used. New solvents that are non-corrosive and have high CO_2 loading capacity with lower energy needs for solvent regeneration are required to reduce the costs of carbon capture.[37] The chilled ammonia process (CAP) or precipitating solvents such as amino acid salts[39] and biphasic solvents[40] are also being researched and are expected to reduce costs and require a lower energy for solvent regeneration. But these solvents have yet to be proven at commercial scale and are in early stages of technological development. CO_2 concentrations of up to 98% can be attained using chemical absorption methods. The resulting concentration of CO_2 in the flue gas after amine absorption is close to 100%. Absorption efficiencies are usually above 90% but depend on the concentration of CO_2 already present in the flue gas.[41]

Physical solvents such as Selexol are also used for CO_2 scrubbing which weakly absorb the acid gases from the feed gas at relatively high pressure. Alternatives include Rectisol, Purisol, and Fluor solvent.[42] The CO_2 that is absorbed in the solvent can be released mainly by depressurisation. The method, therefore, avoids the high heat consumption as is the case in amine scrubbing processes. This method of CO_2 separation is more suitable where partial pressure of CO_2 is high, such as in an integrated gasification combined cycle pre-combustion capture plant.[42] The CO_2 concentrations are usually 35%-40%. This CO_2 capture is generally not considered appropriate for post-combustion capture where CO_2 partial pressure is low, and concentration can only go up to 15%. A considerable amount of energy would be needed for pressurisation before physical solvents could be effectively applied for CO_2 scrubbing in post-combustion processes.

Carbon capture from gas-fired power plants can be challenging due to the low concentration of CO_2 in the flue gas. The least costly option to capture CO_2 at these point sources is likely mono-ethanolamine or a close variation. However, cooling the flue gas and recycling this to the turbine compressor inlet would increase the CO_2 concentration in the feed. This would then facilitate capture and slightly increase the thermal efficiency of the plant.[43] Retrofitting a post-combustion capture installation onto a CCGT plant also carries other considerations. Heat integration options are one of the key considerations, where for example heat can be sourced from the CCGT plant itself, from auxiliary boilers or a separate dedicated CHP plant to regenerate solvents. Which option is most suitable depends on many factors like transmission export capacity, land availability and running power supply contracts (see Section 3.1.4 for more considerations on retrofitting).[44] CAPEX and OPEX depend strongly on the type of technology chosen and the capacity of the power plant, since this determines the size of the carbon capture facility and the energy requirements and possibly other consumables. Investments needed per kW, are in the order of $1,500/kW for CCGT plants with post-combustion CCS if 90% capture is pursued, which compares to around $785/kW for a CCGT plant without CCS.[45]

---

[39] Eva Sanchez-Fernandez et al., Precipitating Amino Acid Solvents for CO_2 Capture. Opportunities to Reduce Costs in Post Combustion Capture, "Energy Procedia", no. 63 (2014), https://doi.org/10.1016/j.egypro.2014.11.080

[40] Jiafei Zhang et al., Development of an Energy-efficient CO_2 Capture Process Using Thermo morphic Biphasic Solvents, "Energy Procedia", no. 37 (2013), https://doi.org/10.1016/j.egypro.2013.05.224

[41] Leung et al., 2014. *An overview of current status of carbon dioxide capture and storage technologies.* https://reader.elsevier.com/reader/sd/pii/S1364032114005450?token=A7E556CC558863C3841918CE53A03547B2C022039ECFB20120F86F165F6538D696684A09E3873D903DE3275631550A0F

[42] Currently, these solvents are mainly used for acid gas removal in syngas for the purification of hydrogen. The solvents are typically proprietary to industrial gas producers like Linde Gas, Air Liquide, Honeywell UOP, Lurgi AG and Fluor. Source: IEAGHG, CO_2 Capture in the Cement Industry, 2008. https://ieaghg.org/docs/General_Docs/Reports/2008-3.pdf

[43] IEAGHG, 2012. CO_2 Capture at Gas-Fired Power Plants. https://ieaghg.org/docs/General_Docs/Reports/2012-08.pdf

[44] IEAGHG, 2010. *CCGT with CCS – integration options*. https://ieaghg.org/docs/General_Docs/PCCC1/Abstracts_Final/pccc1Abstract00055.pdf

[45] Mathieu & Bolland, 2013. *Comparison of costs for natural gas power generation with CO_2 capture*. Energy Procedia 37 (2013) 2406 – 2419.

3.1.1.2 Adsorption-based capture

Adsorption refers to uptake of CO_2 molecules onto the surface of another material, for example, adhering CO_2 molecules onto the surfaces of a solid sorbent such as zeolites.

Gas separation through sorbents is in its infancy compared to solvents. The capacity and CO_2 selectivity of available sorbents, such as zeolites, alumina, and activated carbon, is low. Therefore, physical adsorption using sorbents is not yet attractive for large-scale separation of CO_2 from flue gases. There are three main types of adsorption processes, (i) PSA, (ii) temperature swing adsorption (TSA), and (iii) electric swing adsorption (ESA).

PSA and TSA are commercial methods of gas separation and are used to some extent in hydrogen production and natural gas processing. When compared with PSA, TSA requires more energy, more time for sorbent regeneration and larger adsorbent beds which effectively limit its applications to the removal of small quantities of strongly adsorbed impurities.[42] PSA, on the other hand, has rapid sorbent recycling rates and can remove large quantities of impurities. Within the group of PSA, we can also distinguish vacuum swing adsorption (VSA). Using special solids, or adsorbents, VSA segregates certain gases from a gaseous mixture under minimal pressure according to the molecular characteristics of the gas and affinity for the adsorbents. These adsorbents (e.g., zeolites) form a molecular sieve and preferentially adsorb the target gas at near-ambient pressure. The process then swings to a vacuum to regenerate the adsorbent material. VSA differs from cryogenic separation methods and PSA because it operates at near-ambient temperatures and pressures. It differs primarily from PSA in that PSA typically vents to atmospheric pressures and uses a pressurised gas feed into the separation process. VSA typically draws the gas through the separation process with a vacuum.[46,47] It is worthwhile to mention that the presence of moisture in the flue gas reduces the cyclic CO_2 adsorption capacity in VSA.[48] VSA process has been demonstrated at a pilot plant in Singapore.[49]

In PSA, a gas mixture passes through a bed of adsorbent at elevated pressure. When the concentration of the target gas reaches equilibrium, the adsorption bed is regenerated by reducing the pressure. In TSA, the adsorbent is regenerated by elevating its temperature. The regeneration of adsorbent in ESA also takes place by increasing the temperature of the adsorbent using the Joule effect, where a low voltage electric current is passed through the adsorbing material to raise its temperature. The principle of operation for ESA process is the same as for the TSA process. However, there are differences with regards to the heating time and adsorbent characteristics. The ESA technology is still in very early stages of development for carbon capture.[50,51]

Adsorption-based techniques can typically get CO_2 to concentrations above 95%.[52] Adsorption efficiencies of above 85% can be achieved.

---

[46] Haghpanah, Rajendran, Farooq & Karimi, 2013. *Cycle synthesis and optimization of a VSA process for post-combustion CO_2 capture*. AIChE;59:4735–48.

[47] Ruthven, Farooq & Knaebel. *Pressure Swing Adsorption*. VCH Publishers Inc., New York; 1994.

[48] Anne andersen et al., "On the development of Vacuum Swing adsorption (VSA) technology for post-combustion CO_2 capture", Energy Procedia 37, (2013), https://core.ac.uk/download/pdf/82198166.pdf

[49] Krishnamurthy et al., 2014. *CO_2 capture from dry flue gas by vacuum swing adsorption: A pilot plant study*. https://onlinelibrary.wiley.com/doi/pdf/10.1002/aic.14435

[50] IEAGHG, *Assessment of Emerging CO_2 Capture Technologies and their Potential to Reduce Costs*, 2014. http://www.canadiancleanpowercoalition.com/files/7614/4717/0789/CCS30_-_2014-TR4.pdf

[51] R. P. P. L. Ribeiro et al., Electric Swing Adsorption for Gas Separation and Purification: A Review, "Separation Science and Technology", no. 49 (2014), https://doi.org/10.1080/01496395.2014.915854

[52] Leung et al., 2014. *An overview of current status of carbon dioxide capture and storage technologies.* https://reader.elsevier.com/reader/sd/pii/S1364032114005450?token=A7E556CC558863C3841918CE53A03547B2C022039ECFB20120F86F165F6538D696684A09E3873D903DE3275631550A0F

3.1.1.3 Membrane separation

Membranes can separate CO_2 from flue gas by selectively permeating it through the membrane material. If CO_2 has a higher permeability in the membrane relative to other species in the flue gas, then CO_2 will selectively permeate the membrane. In some cases, chemical agents or solvents that selectively react with CO_2 are also added to the membrane to increase the membrane's selectivity for CO_2. Membrane separation appears to have considerable potential for cost reduction due to lower energy consumption in membrane processes, but the unit costs (CAPEX) of membranes are unclear at scale, which could still make them an expensive method of CO_2 capture.[50] To achieve desired levels of CO_2 purity multiple membranes could be required which can increase the costs substantially. Current research is focussed on cost reduction of membranes and separation performance improvement. Membrane capture efficiencies of up to 88% have been demonstrated,[52] but since membranes are particularly effective at partial capture of CO_2, lower capture efficiencies of around 60% can currently be achieved at lower cost.[53]

Hybrid membrane-absorption setups can also be developed, where absorbers first remove half of the CO_2, after which the membrane further separates the CO_2 to achieve rates of around 90%. The advantage here is that the absorber tower capacity can be significantly reduced which saves on CAPEX.[54]

3.1.1.4 Cryogenic separation

Cryogenic distillation is already applied commercially for gas streams that have high CO_2 concentrations, typically greater than 95%. For more dilute gas streams, cryogenic separation would require large amounts of energy to provide necessary refrigeration. Gases are separated from each other by cooling until they liquefy. The difference in boiling temperatures of gases allows for selective distillation.

The process can produce high purity gases but is energy intensive. Cryogenic separation, therefore, would normally be applied to high concentration and high-pressure gases which is usually the case in pre-combustion or oxyfuel combustion processes.

3.1.1.5 Chemical/Solid looping

Among new emerging proposals for CO_2 capture, high temperature looping systems have an advantage due to the possibility to recover significant amounts of energy thus causing low energy penalty for CO_2 capture integration.

Solid looping technologies function in cyclical processes, which involve the use of a solid carrier to transfer either CO_2 or O_2 from one reactor to another. In calcium/carbonate looping, usually lime (CaO) captures CO_2 from a gas mixture to form limestone ($CaCO_3$), and eventually lime is regenerated to yield a pure CO_2 stream.

In chemical looping, a metal oxide transports oxygen from the air to the fuel, thereby avoiding mixing fuel and air, to generate a pure stream of CO_2 and H_2O. From the mixture of CO_2 and H_2O, CO_2 can be easily separately for subsequent storage. Chemical looping is a method of indirect oxy combustion of hydrocarbons which eliminates the need for an Air Separation Unit (ASU).[50]

---

[53] MTR, 2018. Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process. https://netl.doe.gov/sites/default/files/netl-file/R-Baker-MTR-Membrane-Large-Pilot-Testing.pdf

[54] Freeman et al., 2014. *Hybrid Membrane-absorption CO_2 Capture Process*. https://www.sciencedirect.com/science/article/pii/S1876610214018803

3.1.1.6 Others

Fuel cells

Fuel cells are also being researched to be used for CO_2 capture. The technology was first investigated for capture purposes back in 1950s. With fuel cells, it is possible to capture and concentrate CO_2 coming from an existing power plant in combination with electricity generation. The method uses fuel cell's pumping action to concentrate and collect carbon dioxide at the anode. The technology is currently relatively expensive but could see synergies with the existing use for fuel cells, which is for power purposes[55]. Fuel Cell Energy and ExxonMobil have demonstrated the use of this technology to capture CO_2 from a coal power plant exhaust and are currently collaborating to adapt the technology for CO_2 capture from natural gas power plant exhaust.

Algae based CO_2 capture

Algae based CO_2 capture is a low-tech approach to carbon capture specifically suitable for smaller amounts of CO_2. Since biomass, specifically algae in this case, captures CO_2 as it grows, it has the potential to absorb CO_2. This process is referred to as microalgal photosynthesis. Microalgae are chosen due to their rapid growth rate and large amounts of CO_2 captured per unit of land area compared to other types of biomass like plants. After capture, this biomass could be used as a feedstock or fuel after conversion. Sequestering the CO_2 itself is difficult since it is embedded in the biomass. As a CO_2 capture technology using natural biomass, it can also be considered a CCU technology. In an optimistic case, up to 13% of the CO_2 in the flue gas can be captured by the algae, with the highest rates achieved at concentrations of 15% CO_2 in the flue gas.[56]

3.1.1.7 Comparison of carbon capture technologies

As seen in Table 7, capture technologies considered to present a good cost reduction potential are highlighted in light green and dark green for small and significant potential respectively. Advanced amines, CAP, K_2CO_3, temperature swing adsorption and polymeric membranes have all reached high TRLs and present possible cost reduction potential. Membrane separation shows very good prospects for cost reduction, considering its TRL level and its high prospect for carbon capture cost reduction. Technology providers GTI and MTR report costs in the order of \$30–50/tCO_2.[57] GTI, which has developed a hybrid solution with membranes and amines, expects it will be able to meet the US Department of Energy's capture cost target of \$40/tCO_2 by the year 2025.[58]

The use of cryogenic distillation capture for post-combustion capture has been reported to present an interesting cost reduction potential.[59] Although only at TRL 4 for post-combustion, cryogenic distillation has been developed in the past mainly for oxy-fuel combustion and pre-combustion applications. If there is sufficient R&D accompanied by market demand, this technology could also reach TRL 9 quickly for post-combustion.

---

[55] IEEE Spectrum, Fuel Cells Finally Find a Killer App: Carbon Capture, 2018, https://spectrum.ieee.org/green-tech/fuel-cells/fuel-cells-finally-find-a-killer-app-carbon-capture

[56] Abubakar Sithik Ali, Vignesh, Boomapriya & Prasanya, 2016. *Feasibility study on carbon sequestration using algae.* https://www.irjet.net/archives/V3/i6/IRJET-V3I6137.pdf

[57] MTR, 2018. *Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process*. https://netl.doe.gov/sites/default/files/netl-file/R-Baker-MTR-Membrane-Large-Pilot-Testing.pdf

[58] GTI, 2014. Hybrid Membrane/Absorption Process for Post-combustion CO_2 Capture. https://www.osti.gov/servlets/purl/1155005

[59] IEA Greenhouse Gas R&D Programme, *Assessment of emerging CO_2 capture technologies and their potential to reduce costs*, 2014. http://www.canadiancleanpowercoalition.com/files/7614/4717/0789/CCS30_-_2014-TR4.pdf

Table 7: Assessment of TRL for capture technologies and cost reduction prospects

Capture method	Capture technology	TRL	Prospects to reduce costs compared to amine technology
Chemical absorption	Benchmark proprietary MEA amine process	9	N/A
	Advanced amines *(improved conventional solvents)*	9	Incremental reductions possible
	Chilled ammonia process (CAP)	6-8	Incremental reductions possible
	Potassium carbonate (K_2CO_3) *(precipitating solvent)*	4-5	5-10%
Solid physical adsorption	Temperature swing adsorption	7	Uncertain
Membrane separation	Polymeric membrane	6 (fast development possible due to modular set-up)	30%
Chemical looping	Calcium carbonate looping in cement production	6	Too early to assess
Other	Cryogenic distillation	4	Moderate reduction possible if favourable assumptions are valid

Source: IEA Greenhouse Gas R&D Programme[60]*, John Wood Group PLC*[61]

Calcium looping technology has reached TRL 6, but because the application of chemical looping in the cement industry is at an earlier stage of development compared to chemical looping used in oxy-fuel capture methods, the cost reduction potential is still unknown. This prevents further conclusions to be made compared to the other capture technologies considered. This technology has not been selected for further assessment due to the high volumes of calcium oxides produced as a medium to transport the oxygen when not located near a cement plant. With no cement plants in Singapore, this technology is less suitable for application in Singapore.[62] Temperature swing absorption was not selected for this comparison.

---

[60] IEA Greenhouse Gas R&D Programme, 2014. *Assessment of emerging CO_2 capture technologies and their potential to reduce costs*. http://www.canadiancleanpowercoalition.com/files/7614/4717/0789/CCS30_-_2014-TR4.pdf

[61] John Wood Group PLC, 2018. *Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology* https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/730560/Literature_Review_Report_Rev_2A__1_.pdf

[62] One of the important challenges in calcium looping is the decay of sorbent reactivity during capture/regeneration cycles. As a result, the solid sorbent needs to be purged, creating a large-scale mass handling and disposal issue. In a cement plant the calcium oxide sorbent can be recycled in the cement product, which creates an essential synergy.

Although this technique has developed very rapidly in the last few years, the cost reduction potential is uncertain.

This technological assessment has led to a shortlist of capture technologies that are potentially of interest for Singapore based on TRL and cost considerations. Improved conventional solvent capture technologies such as CAP, potassium carbonate, as well as less developed capture technologies such as membrane separation and cryogenic distillation seem to offer the highest probability of application & development in the future. However, based on current technology status, amine-based capture seems the go-to technology if a capture project were started now, in 2019. The Petra Nova and Boundary Dam carbon capture projects (see next section) have shown that amine-based technology can be used at a scale above 1 $MtCO_2$/yr.

3.1.2 Noteworthy carbon capture projects

There are several carbon capture projects globally that are either operational or in planning phase. Some of the projects that are more relevant for large emitting sectors in Singapore are presented in Table 8. Most of the installations are post-combustion setups that use either amine based, or sometimes chilled ammonia based chemical absorbents. Some of the specified projects use the captured CO_2 for underground storage, sometimes combining it with EOR. Projects like Mongstad, Quest, and Tomakomai require more attention as they already apply capture technologies on point sources that are closely aligned with the emissions profile of Singapore.

Mongstad is a CO_2 test centre in Norway that offers opportunities to test capture technologies from the emissions of a catalytic cracker in refinery and a gas-fired CHP plant. The test site started its operations in 2012, and so far, several post-combustion absorption-based capture technologies have been tested successfully. These include Alstom's Chilled Ammonia Process (CAP), Aker's Clean Carbon, Shell's CanSolv,[63] and Siemens' post-combustion capture technology for steam turbines, among others. The test centre is developed by a consortium consisting of Gassnova (Norwegian state enterprise for carbon capture and storage), Equinor, Sasol, and Shell.[37] Technology Centre Mongstad (TCM) has been instrumental in commercialising CO_2 capture technologies by testing them at a large scale. There have been no public statements made by TCM regarding changes to operation.

Another noteworthy project is the Quest project in Edmonton Canada. The Quest facility is operated by Shell on behalf of Athabasca Oil Sands Project. Shell is the majority shareholder in the project, partnering with Chevron and Marathon Canadian Oil Sands. In this project, CO_2 is captured from the process gas streams of three hydrogen production units using an amine-based solvent. The CO_2 is captured before the PSA, meaning that the CO_2 concentration in that stream is around 40%.[64] A CO_2 concentration of 95% is achieved with the solvents, and the captured CO_2 is subsequently compressed and transported 84 km to an underground storage site in Thorhild, Alberta.[65] During the 3 years of operation, Shell states that 3 million tonnes of CO_2 have been captured and safely stored underground.[66] Total costs of the project were $1.35 billion, including FEED and ten years of OPEX.

Tomakomai Project initiated by Japanese government is a CO_2 capture system that captures CO_2 from hydrogen production unit of an oil refinery located in the coastal area of Tomakomai port. The project also uses an amine scrubbing process to separate CO_2 from the off gases. The captured CO_2 is compressed

---

[63] This Shell technology has been used in the commercial scale Boundary Dam project in Saskatchewan, Canada.

[64] Hufton et al., 2011. *Advanced Hydrogen and CO_2 Capture Technology for Sour Syngas;* Stantec Consulting, 2010. *Quest Carbon Capture and Storage Project*. https://s05.static-shell.com/content/dam/shell-new/local/country/can/downloads/pdf/aboutshell/our-business/oil-sands/quest/01-quest-vol-1-mainreportprojectdescription.pdf

[65] Natural Resources Canada, Shell Canada Energy Quest Project, 2018, https://www.nrcan.gc.ca/energy/funding/cef/18168

[66] Shell, Quest Carbon Capture and Storage, https://www.shell.ca/en_ca/about-us/projects-and-sites/quest-carbon-capture-and-storage-project.html

and injected into two different offshore reservoirs, both saline aquifers. The project began CO_2 injection into the reservoirs in April 2016.[67]

NET Power is demonstrating its Allam Cycle Technology that combines oxy combustion of fossil fuels with super critical CO_2 turbine to generate electricity. The technology claims to produce power at efficiencies greater than natural gas combined cycle (NGCC) integrated with CCS. Currently, a 50 MW facility is in operation that uses natural gas for fuel combustion. [68] These facilities require green field constructions and Singapore could consideration such options once existing natural gas power plants reach its end-of-life. NET Power is planning to add 300 MW_e of capacity in 2021 using this technology.

In addition, there are a couple of post-combustion carbon capture projects for gas-fired plants that are still in the planning phase. Taweelah project, initiated by a consortium of Abu Dhabi Future Energy Company (Masdar), Taweelah Asia Power Company (TAPCO) and Emirates Aluminium (EMAL), aims to integrate CCS with two natural gas-fired power plants, one from TAPCO and the other form EMAL. The initiative is part of a planned city project in Abu Dhabi that targets to become the world's first zero carbon city.[69] The initiative was launched in 2008 but recent developments on the status of carbon capture project were not identified. Peterhead project was initially planned to operate by 2019 was put on hold due to the UK government's withdrawal of funding for the UK CCS Commercialisation Competition in 2015. The project was aimed to capture CO_2 from a natural gas-fired power plant at Peterhead in Aberdeenshire, Scotland.[70]

Another noteworthy carbon capture project is the one announced by OGCI Climate Investments in 2018. OGCI has entered into a strategic partnership with BP, ENI, Equinor, Occidental Petroleum, Shell and Total to develop the UK's Clean Gas Project.[71] The project is supposed to be UK's first commercial full chain Carbon Capture Utilisation and Storage (CCUS) project located in Teesside. In this project, CO_2 will be captured from a gas fired power plant and will be transported and stored in the Southern North Sea. The captured CO_2 will also be used by industries to make valuable CCU products.

Apart from the projects discussed above, Table 8 lists a few other carbon capture projects that could be interesting for Singapore. The list of carbon capture projects in Table 8 is not supposed to be exhaustive.

Table 8. Carbon capture projects relevant for Singapore that are currently operational or in planning globally

Sector	Project	Location	Technology	Capture capacity ($MtCO_2$)	Emission source and sink (status)
Power plant, refinery	Mongstad	Hordaland, Norway	Two post-combustion capture plants; one based on chilled ammonia and one based on amine technology	Not applicable	Emissions from Residue Fluid Catalytic Cracker and natural gas-fired CHP unit. Captured emissions are vented into the atmosphere. (operational since 2012)

---

[67] Yutaka Takana et al., Tomakomai CCS Demonstration Project of Japan, CO_2 Injection in Process, "Ënergy Procedia", no. 114 (2017), https://doi.org/10.1016/j.egypro.2017.03.1721

[68] David Roberts, That Natural Gas Power Pant with no Carbon Emissions or Air Pollution? It Works, 2018, https://www.vox.com/energy-and-environment/2018/6/1/17416444/net-power-natural-gas-carbon-air-pollution-allam-cycle

[69] CC&ST, Power Plant CCS Projects: Taweelah, 2016, http://sequestration.mit.edu/tools/projects/taweelah.html

[70] Alissa Cotton et al., Learnings from the Shell Peterhead CCS Project Front End Engineering Design, "Energy Procedia", no. 114 (2017), https://www.sciencedirect.com/science/article/pii/S1876610217319069

[71] OGCI, "OGCI Climate Investments announces progression of the UK's first commercial full-chain Carbon Capture, Utilization and Storage Project", November 28, 2018.

Sector	Project	Location	Technology	Capture capacity (MtCO$_2$)	Emission source and sink (status)
Hydrogen production	Quest	Edmonton, Canada	Post-combustion activated amine process	1.2	Process gas streams of three hydrogen production units. Emissions are stored underground. (operational since 2015)
Hydrogen production	Tomakomai	Hokkaido Islands, Japan	Post-combustion activated amine process	0.10	Hydrogen production in an oil refinery. Emissions are stored underground. (operational since 2016)
Power plant (biomass-based)	Toshiba CCS	Mikawa (Kyushu), Japan	Post-combustion amine-based chemical absorption	0.18	Currently under construction, it will capture 500 tonnes CO$_2$ per day starting in 2020 from a biomass waste fired power plant. (planning)
Power plant	Net Power	Texas, USA	Oxy combustion combined with super critical CO$_2$	Not identified	Natural gas: Allam cycle technology. Emissions are currently vented into atmosphere but will be used for enhanced oil recovery (EOR). NET Power has plans for upscaling from 25 to 300 MW$_e$ by 2021 (operational since 2018).
Power plant	Taweelah	Abu Dhabi, UAE	Post-combustion absorption	Not identified	Two natural gas-fired power plants. Emissions will be used for EOR. Operation was expected by 2018 but has faced delays (planning).
Chemical plant	Yanchang Integrated Carbon Capture and Storage Demonstration	Yanchang, China	Pre-combustion capture (gasification)	0.41	This project will be capable of capturing around 0.41 MtCO$_2$ per year from coal gasification facilities at chemical plants. The captured CO$_2$ would be transported by pipeline to oil fields for use in EOR operations (planning).
Power plant	Boundary Dam (SaskPower)	Saskatchewan, Canada	Post-combustion amine	1.0	813 MW coal-fired power plant where on 113 MW unit CO$_2$ emissions are captured and used for EOR (operational since 2016).
Power plant	Petra Nova	Houston, US	Post-combustion amine	1.4	CO$_2$ is captured from a coal fired power plant which is then used for EOR at the West Ranch oil field. (operational since 2016).
Chemical and petrochemical industry	Porthos (Port of Rotterdam)	Rotterdam, Netherlands	Unclear	2–5	Post-2020 between 2 to 5 MtCO$_2$ per year will be captured from refineries and other chemical facilities in the Port region, with the aim of extending the network further towards 2030 (planning).

Sector	Project	Location	Technology	Capture capacity ($MtCO_2$)	Emission source and sink (status)
Hydrogen production	Liverpool-Manchester Hydrogen Cluster	Liverpool-Manchester Region, UK	Likely pre-combustion	1.5	Around 1.5 $MtCO_2$ per year will be captured from various industrial producers in the Liverpool-Manchester area and stored in a depleted oil & gas field and could start in 2021/2022 (planning).
Power plant	Clean Gas	Teesside, UK	Likely post-combustion	0.8	The project would capture CO_2 from a natural gas fired power plant which will be stored in a formation under Southern North Sea. Initial CO_2 capture capacity would be 0.8 $MtCO_2$ per year that could grow up to 10 $MtCO_2$. Expected to run from mid 2020s. (Planning).
Power plant (biomass-fired)	Drax CCS	North Yorkshire, UK	"solvent-free" post-combustion (from C-Capture)	<0.01	The pilot plant went into operation in 2018, capturing 1 tonne of CO_2 per day, with the aim of scaling this up to 10,000 tonnes per day eventually. Power plant feedstock is biomass pellets (operational since 2018).

Source: Eni Oko et al., [37], Hufton et al., [64], Natural Resources Canada[65], Yutaka Takana et al., [67], David Roberts[68], CC&ST[69], Alissa Cotton et al., [70], OGCI[71], CC&ST[72], MIT [73], New Mobility[74], Ethical Corp[75], Cadent[76], Global CCS Institute[77]

3.1.3 Costs of carbon capture against point sources identified in Singapore

In this section, capture costs for different point sources in Singapore are presented. The capture costs were obtained from a US literature source.[30] The costs are derived from a technology-agnostic relationship between cost and process characteristics, so the capture costs that are illustrated do not represent one specific capture technology. The literature source used employs CO_2 concentration in flue gas stream and process temperature to calculate minimum work needed for CO_2 separation from other gases in the flue gas, and subsequently estimates associated capture costs assuming a capture rate of 90%.[78] The capture costs include the capital costs of installing a capture system, operational and maintenance costs in addition to the energy costs of CO_2 separation. It should be noted that the costs are estimated considering nth-of-a-kind capture technology which means that capture technologies have been assumed to have attained full

---

[72] CC&ST, Pilot CCS Projects, 2016, http://sequestration.mit.edu/tools/projects/index_pilots.html

[73] MIT, 2016. *Boundary Dam Fact Sheet: Carbon Dioxide Capture and Storage Project.* https://sequestration.mit.edu/tools/projects/boundary_dam.html

[74] New Mobility, 2018. *Port of Rotterdam to capture CO2 and store it under the sea-floor*. https://newmobility.news/2018/04/10/port-of-rotterdam-to-capture-co2-and-store-it-under-the-sea-floor/

[75] Ethical Corp, 2019. ***Drax targets negative emissions with world's first biomass CCS project***. http://www.ethicalcorp.com/drax-targets-negative-emissions-worlds-first-biomass-ccs-project

[76] Cadent, 2018. *Project summary.* https://cadentgas.com/getattachment/About-us/Innovation/Projects/Liverpool-Manchester-Hydrogen-Cluster/Promo-LMHC-downloads/Overview.pdf

[77] Global CCS Institute, Facilities Database, https://co2re.co/FacilityData

[78] Typically assumed CO_2 capture rates are 90% or above. The costs per tonne of CO_2 captured can be lower if high CO_2 recovery rates are not targeted.

commercial maturity.[79] These costs also exclude the costs of compression. Hence the cost estimates are optimistic in some cases and only serve to provide an indication. In practice, the CO_2 capture costs are sensitive to site conditions such as availability of waste heat, process synergies with the capture method, scale or size of plant, capture technology used, etc.

Table 9 provides an overview on the minimum energy required for CO_2 separation and the related capture costs against typical CO_2 concentrations for different CO_2 emitting sources. The 2013-2014 CCUS roadmap also estimates minimum energy for the power sector and the figures appear to be in line. The literature source used employs the following equation to estimate CO_2 capture costs. The capture costs are a function of mole fraction of CO_2 in gas streams:

$$\log(\boldsymbol{Price}\ \frac{\$}{\boldsymbol{kg}}) = -\mathbf{0.5558} * \log\ (\boldsymbol{mole\ fraction\ of\ CO_2}[\%]) - \mathbf{1.8462}$$

Table 9. Minimum energy and the cost estimates from major CO_2 emitting sources relevant for Singapore

Source	CO_2 concentration (%mol)	Minimum energy (kJ/mol CO_2 captured)	Capture costs (US$/t$CO_2$)	Flue gas components
Natural gas	3-5	10.7–12.7	75–100	CO_2, NO_x, CO, O_2, N_2,
Coal	10-15	6.2–7.9	41–51	CO_2, NO_x, SO_x, CO, O_2, N_2, Hg, As, Se
Fuel oil	3-8	7.8–11.3	58–100	CO_2, NO_x, SO_x, O_2, N_2
Refineries	3-20	7.4–15.5	35–100	For FCC: O_2, CO_2, H_2O, N_2, Ar, CO, NO_x, SO_x. For process heaters/utilities it depends on the fuel.
Hydrogen	30-45, 98-100	0–4.0	14–28	CO_2, H_2, CO, CH_4
Ethylene	7-12	9.4–12.8	46–62	H_2O, CO, NO_x, SO_x, O_2, N_2, CO_2
Ethylene oxide	30, 98-100	0–4.0	14–28	Mainly CO_2, H_2O, N_2 (air oxidation) and some CH_4

Source: Bains et al. [30]

The minimum energy for CO_2 separation could range from near zero up to around 13 kJ per mole of CO_2 captured, and the costs range from $14 to $100 per tonne of CO_2 captured. We used the same logarithmic equation and derived the CO_2 capture costs against concentration profiles of point sources in Singapore, as presented in section 2.2. Table 10 provides the capture costs against the identified CO_2 emission sources in Singapore.

---

[79] These cost calculations use the same cost estimating methodology which is used for mature plant designs. This means that these estimates do not account for cost premiums associated with complex integration of emerging technologies in a commercial setting. It is very likely that the initial carbon capture deployment would incur higher costs than those estimated in this report. See, National Energy Technology Laboratory, *Cost and Performance Baseline for Fossil Energy Plants. Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity, Revision 3*, 2015.

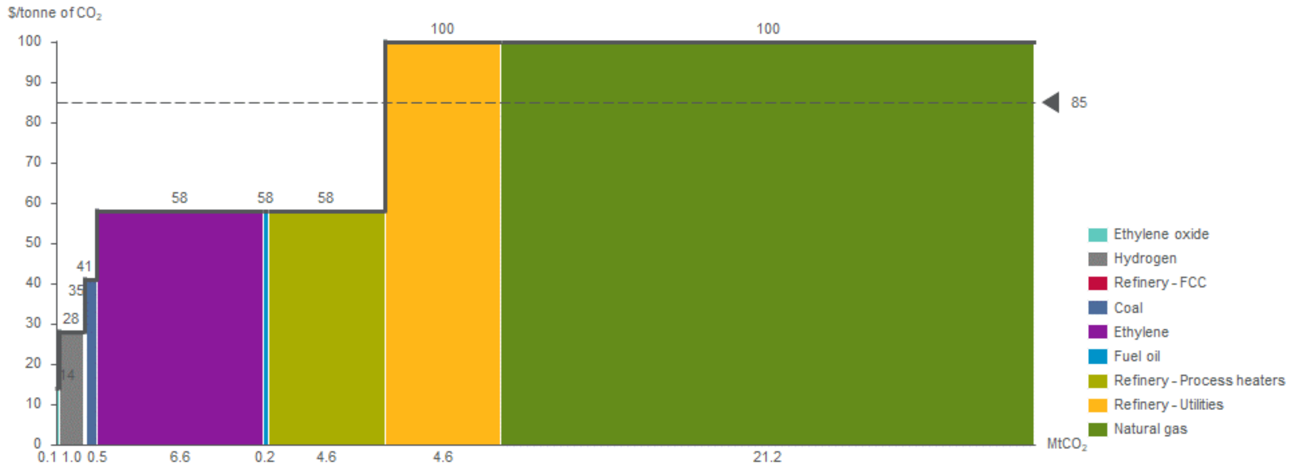
Table 10 CO_2 capture cost estimates for major CO_2 emitting sources in Singapore

Sector	Point source	CO_2 concentration (% mol)	Capture costs (US$/t$CO_2$)
Power sector	Natural gas	3%	100
	Coal	15%	41
	Fuel oil	8%	58
Refineries	Utilities	3%	100
	Process heaters	8%	58
	Fluidised Catalytic Crackers (FCC)	10-20%[80]	35
	Hydrogen	30%	28
	Ethylene	8%	58
	Ethylene oxide	100%	14

Source: Bains et al. [30]

Since capture costs are displayed as a function of mole fraction, there are numerous point sources that have similar CO_2 concentration in the gas stream and, therefore, show similar costs. Figure 7 provides an illustration of the estimated capture costs. It should be emphasised that these are the costs assuming CO_2 is captured and concentrated to 90%. Costs could be lower when a lower capture rate is taken. Against each point source there are a certain amount of emissions associated in Singapore which are displayed on x-axis. These are total emissions from the specified point source type.

Figure 7. CO_2 capture costs weighted average costs, and emissions from point sources of CO_2 in Singapore



Source: Bains et al. [30] *Capture rate for cost estimates equals 90% while emission amounts show total emissions from the indicated point sources in Singapore.*

---

[80] Assumed 20% CO_2 concentration for capture cost estimation

Figure 7 indicates that the large point sources (e.g., natural gas-fired power and utilities in refineries) are also the most expensive, since these CO_2 emissions are the most dilute.[81] Because of this, the weighted average capture cost for Singapore is relatively high at US$85/t$CO_2$. Ethylene oxide and hydrogen offer opportunities for cheap CO_2 capture, although their emissions are not substantial but can be considered an easy opportunity. The weighted average is a useful tool to estimate the costs if one would like to mitigate all emissions using CCS, but it is likely that the cheapest options will be captured first.

As mentioned, costs of separation can be lower when partial CO_2 capture is pursued, or novel carbon capture approaches are used. The US Department of Energy has set a goal of achieving a CO_2 capture cost of below $40/t$CO_2$ within the 2020-2025 timeframe.[82] Furthermore, South Korea aims to commercialize CCS projects by 2030 with its national CCS master plan. The objective is to attain a CCS cost of below $30/t$CO_2$ (including transport and storage of below $10/t$CO_2$).[83] Japan's CCS Strategy mentions an R&D target of similar magnitude, aiming to reduce the CO_2 capture cost to JPY1000 ($10/t$CO_2$).[84]

3.1.4 Key barriers and opportunities for Singapore

Costs for carbon capture are relatively high in Singapore. Generally, capture costs are lower for processes that have a high output pressure of flue gas and high concentrations of CO_2. These sources do exist in Singapore and represent fairly small amounts of CO_2. The largest share of emissions comes from gas-fired power plants, which also represents the highest cost. In addition, CO_2 capture units would need to be retrofitted to the existing plants in Singapore. Specifically, for low-concentration CO_2 streams, the absorber capacity needs to be significant and solvent-based capture units would require a substantial amount of land which is a barrier in a country that is already land-constrained. The land footprint of a post-combustion capture unit with amine-based scrubbing is around 250m x 150m (3.75 ha) for a CCGT plant of around 800 MW.[85, 86] Pre-combustion or oxy-fuel set-ups running on syngas or hydrogen generally require less land since the CO_2 concentrations are higher and therefore require less separation work. However, this requires significant redesign of the plant itself, if possible at all. Namely, retrofitting carbon capture into a refinery can be very challenging due to the ducting, interconnections, modifications and additional CHP and utility units that needs to be installed in case of post-combustion capture.[87] Another barrier is that there are few incentives for emitting industries to address their CO_2 emissions since the carbon tax currently stands at levels that are (much) lower to the costs illustrated in Figure 7.[88]

---

[81] The high CC costs for natural gas fired power plants would likely push their position up in the merit order resulting in reduced load factor. Less operating hours substantially affect plant economics. It is recommended to investigate if it could be more cost-effective for natural gas fired power plants to be converted to hydrogen or biomethane, provided the supply security of such fuels can be guaranteed. Nuon, a subsidiary of Vattenfall, are currently converting one of three 440 MW gas-fired combined cycle power generating units to hydrogen at Magnum power station. The power station is situated at the Energy Park Eemshaven in the Netherlands and is aimed to run on hydrogen by 2023. The initiative is led by Nuon, Equinor (formerly Statoil) and Gasunie. See, Compelo, "Nuon Magnum Power Plant", https://www.compelo.com/energy/projects/nuon-magnum-power-plant/

[82] US DoE, 2019. *Carbon Capture R&D*. https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd

[83] Ministry of Science, ICT and Future Planning, 2015. *Korea CCS R&D Strategy & Korea CCS 2020 Project.* https://www.greenfinancelac.org/wp-content/uploads/2016/10/INTRODUCTION_KCRC-1.pptx

[84] IEAGHG, 2012. *Update to the Development of CO_2 Capture Technologies in Far East Asia*. http://www.ccop.or.th/eppm/projects/42/docs/(3.)%20S.%20Santos%20-%20Far%20East%20Asia%20Activity%20-%20Final%20Version.pdf

[85] IEAGHG, *Retrofit of CO_2 Capture to Natural Gas Combined Cycle Power Plants*, 2005.

[86] The following reference provides site dimensions for post, pre and oxy-combustion capture units for coal and gas fired power plants. These land requirements for capture units should be treated with caution as it is likely that improvements in carbon capture technology may alter space requirements substantially. See, IEAGHG, *CO_2 Capture as a Factor in Power Station Investment Decisions*, 2006.

[87] CONCAWE, 2018. *The importance of carbon capture and storage technology in European refineries*. https://www.concawe.eu/wp-content/uploads/Importance-of-CCS-in-European-refineries-Concawe-27-1.pdf

[88] Singapore's carbon tax is set at a rate of S$5/t$CO_2$e from 2019 to 2023. Singapore will review the carbon tax rate by 2023, with plans to increase it to between S$10 to S$15 (US$11) per tonne of CO_2e by 2030.

Despite the challenges, carbon capture presents some promising opportunities. Developing incentives to capture CO_2 can enable the chemical sector to decarbonise, since one of the options that can contribute to the sector's decarbonisation is using CO_2 as a feedstock to produce organic chemicals. As climate policies become more stringent internationally, emission-intense companies will need solutions like carbon capture to keep up with regulation. In some cases, it can even lead to additional revenue streams for companies, if they manage to capture CO_2 at low cost and utilise the CO_2 effectively (e.g. export CO_2 for use in EOR, where the value of CO_2 can reach US$63 per tonne CO_2, depending on the oil price).[89] Simultaneously, costs for CO_2 capture are decreasing. Related to this, CCUS can spur innovation via research initiatives. Various Singapore institutions have a strong reputation internationally in chemical engineering and can export their knowledge to the rest of the world if they are able to develop solutions domestically to capture CO_2 at low cost. Among these institutions are the National University of Singapore (NUS), Nanyang Technological University (NTU) , Agency for Science, Technology and Research (A*STAR) and NRF's Campus for Research Excellence and Technological Enterprise (CREATE).

3.2 Carbon storage and sequestration

Once CO_2 is captured at the point source, it can be transported to a suitable location for storage. The transport of CO_2 can take place via pipeline, vessel, or even by truck. The CO_2 can then be stored in suitable storage formations which can occur in both onshore and offshore settings. Scientific research in recent years has pointed out that CCS is a safe mitigation option, able to keep 98% of the stored CO_2 locked away for a period of 10,000 years.[90] However, each storage option presents different opportunities and challenges. The safe geological storage of CO_2 should be warranted by legislative frameworks, as is the case in the EU with the CCS Directive,[91,92] and dedicated legislation in Canada, the US and Australia, among others.[93] In 2005, the IPCC developed a Special Report on Carbon Dioxide Capture and Storage, containing regulatory and accounting considerations.[94] Throughout CCS literature, the following types of geological storage options are most commonly considered:

- **Depleted oil and gas fields:** Depleted hydrocarbon reservoirs that are no longer operational are considered an appropriate location for CO_2 storage. In the depleted field, the CO_2 would occupy some of the void space that was previously occupied by oil or natural gas. The characteristics of these fields are well-known due to exploration and production, and infrastructure is usually in place which can facilitate CO_2 storage and reduces infrastructure development cost.

- **Saline aquifers:** These are geological formations that consist of water permeable rocks saturated with salt water, called brine. CO_2 can be injected in these sedimentary rocks, and it chemically reacts with salt water to form precipitates that cannot leak up back into the atmosphere.

- **Unmineable coal seams:** Methane gas entrapped in unmineable coal seams can be produced with coal bed methane (CBM) recovery methods. The coal seams can subsequently be used for CO_2 storage. In most literature, CO_2 storage in coal seams is combined with increasing methane recovery from those coal seams; enhanced CBM (ECBM). ECBM, like enhanced oil recovery

---

[89] Roussanaly & Grimstad, 2014. *The economic value of CO_2 for EOR applications*. https://www.eco-business.com/opinion/singapores-carbon-tax-too-small-a-step-in-the-right-direction/

[90] Alcade et al., 2018. *Estimating geological CO_2 storage security to deliver on climate mitigation.* https://www.nature.com/articles/s41467-018-04423-*1*

[91] European Commission, 2019. *A legal framework for the safe geological storage of carbon dioxide*. https://ec.europa.eu/clima/policies/innovation-fund/ccs/directive_en

[92] Wéber, 2017. *NUS Centre for Maritime Law Working Paper 17/08: The legal issues behind stagnating CCS deployment in the European Union — is it the Member States' turn*? https://law.nus.edu.sg/cml/pdfs/wps/CML-WPS-1708.pdf

[93] University College London, 2012. *Dedicated CCS Legislation.* https://www.ucl.ac.uk/cclp/ccsdedleg.php

[94] IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport-1.pdf

(EOR), is considered a CO_2 utilisation technology, but has fewer commercial developments to date. Sorption of CO_2 to coal adversely effects permeability of the rock which in coals seams is usually already low.

3.2.1 CO_2 transport and storage costs

Transport and storage costs of CO_2 can vary significantly. Tables in this section provide an overview of CO_2 transport and storage costs from different literature sources. Costs depend on location, terrain factors, material choices, availability of existing infrastructure and eventually also on policy and regulations across the entire CCS value chain.[95] These estimates provide a sense of scale of the transport and storage costs and indicate some key parameters that can impact these transport and storage costs.

There are two main methods that are usually considered for CO_2 transport: pipelines and ships. Key factors that influence pipeline costs include CO_2 volume transported, pipeline length, pipeline diameter and the cost of financing. Capital costs usually contribute more than 90% to the total annual pipeline costs.[100] It is therefore expected that pipelines will show a linear cost increase with transported distance. Commercial success for pipeline transport requires high utilisation from the start to achieve lowest costs. Because of the difficulty of maintaining pipelines in offshore conditions and increased complexity and risk, offshore pipelines are usually more expensive than onshore pipelines for same CO_2 volumes transported over equal distances. However, for offshore pipelines it may be less difficult to obtain right-of-way permits and there are less issues related to safety and regulatory approval due to the absence of population centres.[96] The European Zero Emissions Platform estimates that onshore pipeline costs in the EU would range between US$0.2–25/t$CO_2$, whereas offshore pipelines costs can vary between US$3–46/t$CO_2$. Kjärstad et al. also cite offshore pipeline costs in the same range, i.e. US$4−35/t$CO_2$. For more details see Table 11.

Literature suggests that CO_2 transport pipeline can be constructed in a similar manner as natural gas transmission pipeline. However, the thermodynamic properties of CO_2 and natural gas are different which means that the temperature and pressure conditions are to be planned differently to ensure single phase transport of CO_2 from inlet to outlet of the pipeline. In addition, the presence of water in CO_2 streams can cause severe corrosion in standard steel pipes. Either pipeline material that is resistant to corrosion would need to be used or the CO_2 stream would need to be made non-corrosive. More R&D is needed to fully understand such mechanisms.[100]

For ship transport, operating and maintenance costs are more substantial whereas capital costs contribute less than 40% to the total annual costs.[100] Shipping costs are, therefore, relatively insensitive to capacity and distance, rendering this a more flexible mode of transport. CO_2 transport by ship is more attractive in scenarios where small CO_2 volumes need to be transported over long distances. Table 11 shows that the costs range between US$12–31/ t$CO_2$. [99,100] These costs are developed against different ships sizes which are adjusted to the assumed CO_2 volumes. The cost estimates include costs of liquefaction, vessel costs, port and offshore terminal costs, loading and offloading equipment costs, on-board heating and discharge pump costs, etc (for more details refer to cited references). The ships for CO_2 transport at large scale (10,000–40,000 m^3) have been proposed but are not built yet. Combining CO_2 transport with multi-purpose ships that are used for LNG/ethylene transport seems feasible and may prove to be a cost-efficient way of transporting CO_2.[97]

---

[95] For example, liability of geologically sequestered CO_2 is ideally transferred to a state entity. If not, storage costs can significantly increase.

[96] DNV GL, 2017. *Design and operation of carbon dioxide pipelines*. https://rules.dnvgl.com/docs/pdf/DNVGL/RP/2017-07/DNVGL-RP-J202.pdf

[97] CATO, *Transportation and Unloading of CO_2 by Ships – a Comparative Assessment: WP9 Final Report*, 2016.

Table 11. Overview of CO_2 transport costs from literature

Literature source	Geographical coverage	Costs	Key parameters specified in the study
Global CCS Institute (2017)[98]	US-mid West	Combined onshore transport and storage: US\$8−13/tCO_2 Combined offshore transport and storage: US\$17−40/tCO_2	Onshore pipeline length: 100 km Reservoir type for onshore storage: saline formations
Kjärstad et al. (2016)[99]	Nordic region	Offshore pipeline: US\$4−35/tCO_2	Offshore pipeline length: 50−1200 km Transported volumes: 0.5−20 MtCO_2 per year
		Ship transport including liquefaction: US\$12−29/tCO_2	Transported distance: 50–1200 km Transported volumes: 0.5−20 MtCO_2 per year Ship size: max. 40,000 tonne
Zero Emissions Platform (2011)[100]	EU	Onshore pipeline: US\$0.2−25/tCO_2 Offshore pipeline:[101] US\$3−46/tCO_2	Onshore pipeline length: 10–1500 km Offshore pipeline length: 10–1500 km Transported volumes: 2.5, 10 and 20 MtCO_2 per year CAPEX contributes more than 90% to the total annual costs (\$/tCO_2/year) CAPEX onshore: US\$19 mil. to US\$3.4 billion CAPEX offshore: U\$119 mil. to US\$5.5 billion

---

[98] Global CCS Institute, *Global Costs of Carbon Capture and Storage,* 2017.

[99] Kjärstad et al., *Ship transport—A low cost and low risk CO2 transport option in the Nordic countries*, 2016.

[100] Zero Emissions Platform, *The Costs of CO_2 Transport,* 2011.

[101] For offshore pipeline, the scenario where 2.5 MtCO_2 are transported over 1500 km are ignored while indicating cost ranges as this is an expensive way of transporting relatively small CO_2 volumes over long distances and it is less likely to be a preferred option in practice.

Literature source	Geographical coverage	Costs	Key parameters specified in the study
		Ship transport including liquefaction: US\$16−31/tCO_2	Transported distance: 180–1500 km Transported volumes: 2.5 and 20 $MtCO_2$ per year Ship size: 22,000–41,000 m^3 OPEX has a major share in ship transport costs. CAPEX contributes less than 40% to the total annual costs (\$/tCO_2/year) CAPEX: US\$217 mil. to US\$1.7 billion

Source: Global CCS Institute[98], Kjärstad et al.[99], ZEP[100]

CO_2 storage costs are also sensitive to many factors, including reservoir type, field capacity and well injection rate. CO_2 storage in depleted oil and gas fields is usually cheaper than saline formations due to the possibility of re-using existing infrastructure. In addition, onshore storage is less costly than offshore storage.[102] Zero Emissions Platform reports that costs for storage in the EU can vary between US\$2–19/tCO_2 onshore, and between US\$3–31/tCO_2 offshore, see Table 12. The storage costs include cost of drilling and completing new wells, costs of well workovers, costs of structures associated with offshore wells, injection tubing costs and the costs of corrosion-resistant alloys for lower well section where injection takes place. It is assumed that the CO_2 stream arrives at a well head in a fit for purpose state that is ready to be injected (CO_2 separation and compression are not required, and the associated costs are not considered). Prior to operation, other costs also need to be made, like injection tests (~\$1.1 million per well) and permitting. Reusing offshore legacy wells can save between \$55 and \$85 million per project (\$1–5/tCO_2).[102] For more details please see the cited references.

Table 12. Overview of CO_2 storage costs from literature

Literature source	Geographical coverage	Costs	Key parameters specified in the study
Zero Emissions Platform (2011)[102]	EU	Onshore storage: US\$2−19/tCO_2 Offshore storage: US\$3−31/tCO_2	Reservoir type – Depleted oil & gas fields (with and without legacy wells) and saline aquifers CO_2 flow rate: 1.2 and 5 $MtCO_2$ per year Total reservoir capacity: 40 and 200 $MtCO_2$ CAPEX: US\$42 mil. to US\$ 374 mil.

---

[102] Zero Emissions Platform, *The Costs of CO_2 Storage*, 2011.

Source: ZEP[103]

As per Zero Emissions Platform (which derives estimates specific to European conditions) the combined CO_2 transport and storage costs can range from US\$2–44/tCO_2 onshore and US\$6–77/tCO_2 offshore. Global CCS Institute also reports combined transport and storage costs of US\$8−13/tCO_2 onshore and US\$17−40/tCO_2 offshore. The reason for this cost difference is that the GCCSI estimates are developed for the US mid-West region where terrain characteristics are different. In addition, the assumed transported distance, pipeline characteristics and CO_2 volumes are also different from assumptions used by Zero Emissions Platform, see Table 11.

The combined transport and storage costs for the Porthos (Port of Rotterdam CO_2 Transport Hub & Offshore Storage) project are reported to vary between US\$29–40/tCO_2.[103] The intention is to store CO_2 in the P18 depleted gas reservoirs 20 km off the coast of Rotterdam, using an existing platform and wells. A permit for underground CO_2 storage is already in place and an EU-funded front-end engineering design (FEED) study is ongoing.[104] Post-2020 between 2–5 MtCO_2 per year will be captured from refineries and other chemical facilities in the Port region, with the aim of extending the network further towards 2030.[105] For the Quest project, the estimated costs for onshore pipeline transport are US\$153 million, which roughly translate into US\$12/tCO_2 transported.[106,107] Around 1.2 mil tonne of CO_2 are transported over 84 km and are stored in an onshore saline aquifer, though storage costs for this project are not known.[106] These stated CO_2 transport and storage costs from the projects that are already operational or in planning are roughly in line with the cost ranges that were found in the literature, see Table 11 and 12.

3.2.2 Available subsurface storage and sequestration potential in the region

Singapore does not have any known suitable reservoirs for the permanent storage of CO_2 in its subsurface.[108] The country would therefore have to rely on the export of its CO_2 to neighbouring countries or to lock away CO_2 permanently through mineralisation in aggregates. In this study, we consider the latter a carbon capture and utilisation option, and these options are further discussed in Chapter 4. Analyses of geological storage potential in neighbouring countries are available and known potentials are provided in Table 13, totalling an estimated 84.8 giga tonnes CO_2 of storage potential. It should be noted that not all these storage sites are equally attractive for EOR schemes that use CO_2. The EOR schemes are reservoir specific.[109]

Table 13. Overview of countries near Singapore with known geological storage potentials for CO_2 (in GtCO_2)

Country	Depleted oil & gas fields	Saline aquifers	CBM	Total
Indonesia[110]	0.9	7.7	2.7	
Vietnam	1.3	10.4	0.5	
Thailand	1.4	8.9	-	

---

[103] Processcontrol, Vier vragen over CCS onder de Noordzee, May 17, 2018. https://www.processcontrol.nl/vier-vragen-over-ccs-onder-de-noordzee/

[104] Royal HaskoningDHV, 2019. Concept - Notitie Reikwijdte en Detailniveau - Rotterdam CCUS Project (Porthos). https://energeia-binary-external-prod.imgix.net/8Qw7H5M0FXKITwsd2ZXBpZ59s4g.pdf?dl=Notitie+reikwijdte+en+detailniveau+Porthos.pdf

[105] Ebn, CO_2-opslag onder Noordzee technisch haalbaar en kosteneffectief, April 9, 2018, https://www.ebn.nl/co%E2%82%82-opslag-onder-noordzee-technisch-haalbaar-en-kosteneffectief/

[106] IEAGHG, *CO_2 Pipeline Infrastructure*, 2013.

[107] Assuming project lifetime of 40 years and WACC of 8%. The contribution of CAPEX in total annual costs is assumed to be 90%.

[108] NCCS, 2011. *Carbon capture and storage/utilisation technology primer: a summary.* https://www.nccs.gov.sg/docs/default-source/default-document-library/carbon-capture-and-storage-utilisation-technology-primer-a-summary.pdf

[109] Gbadamos et al., "A Review of Gas Enhanced Oil Recovery Schemes used in the North Sea", Journal of Petroleum Exploration and Production Technology 8, no.4 (2018), https://link.springer.com/article/10.1007/s13202-018-0451-6

[110] Only for South Sumatra.

Country	Depleted oil & gas fields	Saline aquifers	CBM	Total
Malaysia				28
Philippines				23

Source: ADB[111]

According to the GCCSI, Malaysia is active in identifying offshore CCS opportunities.[112] At the moment, there is a lot of petroleum activity in Malay basin which may offer an opportunity for EOR. Some existing infrastructure can be leveraged to establish EOR using CO_2. Indonesia is also exploring its options, with the ADB, Japan International Cooperation Agency and Pertamina (the state-owned oil & gas company) collaborating on a pilot case in South Sumatra, which is scheduled to capture 29 kilo tonnes of CO_2 from a gas processing plant for EOR.[113] Since this study focussed on domestic options, CCS and EOR are not considered further. However, supplying CO_2 to CCS or EOR projects in the wider region should be explored further. Such options would entail shipping or piping CO_2 over considerable distances. In this context, it is worth pointing out that in Norway, plans are underway to capture CO_2 in the Eastern part of the country to a facility on the West coast before being transported offshore to a permanent sequestration site under the North Sea. In a later phase of the project, CO_2 from other parts of Europe could be shipped in to Norway's injection site.[114] Research shows CO_2 tankers are similar in characteristics to LPG tankers. Therefore, empty backhauls can be reduced using such multi-purpose ships – and these are being considered for CO_2 transport in Norway. [97]

It should be stressed that internationally, barriers exist for the maritime transport of CO_2 by ship, as defined in the London Protocol signed by Parties to the International Maritime Organization, see Box 2. This means that the transport of CO_2 by ship for underground sea storage is prohibited. Countries like Norway that explore this method to import CO_2 from other countries in Europe are stimulating parties to the International Maritime Organisation (IMO) to sign the amendment, but progress is slow. Alternatively, countries can transport CO_2 cross-border to shore, and transport CO_2 further by pipeline. Not all countries have signed the Protocol. None of the ASEAN countries apart from the Philippines have signed it, which would reduce the impact of the Protocol on regional CO_2 transport for offshore geological storage purposes.[115]

Box 2. The London Protocol is a hurdle for shipping CO_2 to subsea storage

Article 6 of the London Protocol, an agreement between 50 states aimed at creating a modern and comprehensive waste management system for the seas, says that: "*Contracting Parties shall not allow the export of wastes or other matter to other countries for dumping or incineration at sea*," thus prohibiting transport of CO_2 from across national boundaries prior to subsea sequestration. An amendment to this article was already devised by 2009, where an exempt is made for CO_2 streams for export. This amendment has however not (yet) been accepted by the two-third majority needed and therefore has not entered into force. During the 39th meeting of the London Convention and the 12th meeting of the London Protocol in 2017, Iran and Finland had ratified, setting the total to only five of the 32 needed parties to ratify.

---

[111] ADB, 2013. *Prospects for Carbon Capture and Storage in Southeast Asia.* https://www.adb.org/sites/default/files/publication/31122/carbon-capture-storage-southeast-asia.pdf; Consoli & Wildgust, 2017. *Current status of global storage resources.* http://decarboni.se/sites/default/files/publications/201748/consoli-wildgust-2017-global-storage.pdf

[112] Global CCS Institute, 2018. *CCS Storage Indicator*. http://decarboni.se/sites/default/files/publications/202110/ccs-storage-indicatorglobal-ccs-institute2018digital.pdf

[113] Indonesian Ministry of Energy and Mineral Resources, 2018. *Current Status and Future Path of Developments for CCUS in Indonesia*. https://d2oc0ihd6a5bt.cloudfront.net/wp-content/uploads/sites/837/2018/06/Usman-Pasarai-Current-Status-and-Future-Path-of-Developments-for-CCUS-in-Indonesia.pdf

[114] Gassnova, CCS in Norway entering a new phase, https://www.gassnova.no/en/ccs-in-norway-entering-a-new-phase

[115] IMO, 2019. *Map of Parties to the London Convention/Protocol.* http://www.imo.org/en/OurWork/Environment/LCLP/Documents/Parties%20to%20the%20LCLP%20February%202019.pdf

3.2.3 Key barriers and opportunities for Singapore

One of the main barriers to carbon capture and sequestration in Singapore is a clear absence of geological storage potential. To permanently sequester CO_2 for emissions mitigation, Singapore will need to rely on permanent CCU technologies such as CO_2 mineralisation in aggregates or the export of CO_2. Cross-border transport of CO_2 is challenging because of the differences in legislation between countries and regulations around permits. The financing of infrastructure and associated responsibilities require additional coordination. Moreover, for the cost-effective CO_2 sequestration, CO_2 supply security is very important. Under-utilized transport and storage infrastructure assets would make sequestration expensive thereby endangering the commercial success of CCS deployment. Finally, the London Protocol is currently prohibiting the export of CO_2 prior to geological sequestration in various countries worldwide. Most of the ASEAN countries did not sign the Protocol, hence this would not impact a regional offshore storage effort.

CCS could also provide large infrastructural opportunities for Singapore as it is well-positioned in a large port area. Access to vessels that are capable of transporting CO_2 can be easily facilitated. If the previously mentioned barriers are overcome, the country will have access to a cost-effective opportunity to permanently mitigate CO_2 emissions in the medium term.

3.3 Carbon capture and utilisation

Utilisation of captured CO_2 comes in many different categories and technologies. In this section we present 49 identified CCU technologies and evaluate them against an assessment framework. This assessment is used to arrive at a shortlist of utilisation technologies that are explored further in the next deep dive chapter.

CCU technologies can be grouped into six different categories based on the application of the CO_2:

1. **Chemical production:** CO_2 can be used in the synthesis of a range of intermediates required in different chemical and pharmaceutical production. Conversion methods require the use of catalysts, heat, and/or pressure to break the stable CO_2 structure, and enable electrochemical reduction. One of the most promising technologies is the use of CO_2 to make various polymers, such as polycarbonates.

2. **CO_2 mineralisation:** This group of technologies relies on the accelerated chemical weathering of calcium (Ca) or magnesium (Mg) based minerals using CO_2, which can be found in natural form and waste streams. These aggregates can be used in a range of applications, typically involving the production of construction materials (e.g., concrete curing or novel cements) or in more niche circumstances such as mine tailing stabilisation.

3. **CO_2 to fuels:** Within this group, technologies that can provide a means for new types of energy vectors are covered. This partly consist of commercially established technologies linked to newer use (e.g., synthetic methanol), and more embryonic forms of energy carrier development (e.g., biofuels from algae).

4. **Enhanced commodity production:** This group of technologies involve using CO_2 to boost production of certain products, typically where CO_2 is already used but could be modified (e.g., urea or methanol yield boosting). It also includes using CO_2 as a substitute in existing technologies (e.g., for steam in power cycles). These technologies generally involve applying new methods to techniques which are in commercial practice today but could be modified to use CO_2.

5. **Food and drink:** High purity (food or beverage grade) CO_2 is currently used for beverage carbonation, in food freezing, chilling, and packaging as well as in horticulture to enhance the production of crops.

6. **Other – industrial applications:** Industrial grade CO_2 is currently used in a wide range of industry applications (e.g. electronics, metal working, as a refrigerant gas, and in water treatment and pH control). Supercritical CO_2 is also used in coffee decaffeination, extraction of aromas or flavours and plant substances, pharmaceutical processes, and as a solvent in dry cleaning. Other uses of CO_2 include fire suppression and as dry ice.

3.3.1 Assessment framework

All 49 technologies across the six categories listed above are evaluated against the same assessment framework. This framework contains six assessment attributes, described in Table 14.

Table 14. All attributes of the longlist assessment framework

Assessment attribute	Description	Unit of measure
Technology Readiness Level (TRL)	Globally accepted scale to rank maturity of technologies under development.	TRL1-9
Land footprint	The amount of land area required for the technology to be deployed at scale.	m^2 $tonne^{-1}$ $year^{-1}$
Global CO_2 demand	The amount of CO_2 required for the technology if it were to fully replace existing (incumbent) production, meeting global demand for the resulting product.	$MtCO_2$ $year^{-1}$
CO_2 emitted	The amount of CO_2 emitted in producing one tonne of CO_2-derived product, resulting from energy input and energy-related feedstock requirements.	tCO_2 $tonne^{-1}$
Net abatement effect	Represents the amount of CO_2 utilised per tonne of product minus the amount emitted in the process per tonne of product. Calculated as (CO_2 utilised - CO_2 emitted)/CO_2 utilised.[116]	%
Net abatement effect with CO_2 demand	The same as above but scaled to consider global abatement potential. Calculated by multiplying net abatement effect with global CO_2 demand.	$MtCO_2$ $year^{-1}$

Source: Navigant analysis

The above attributes require quantitative inputs, mostly derived from literature. Annex A.1.1 describes these inputs and any further analysis to enable quantification.

Calculating CO_2 emitted

The calculation for CO_2 emitted requires several underlying inputs. We use a merit order of preferred calculation approach. This attribute is derived by multiplying energy demand per tonne of product as identified from literature with appropriate emissions factors (EFs). We only applied a theoretical approach when no literature data were available. The theoretical energy demand is calculated from stoichiometry and scaled to approximate real world energy demand using an average defined difference as identified in literature.[117] As a next step, feedstock demand is translated to associated emissions by identifying the amount of feedstock required per tonne of product from literature or, in absence of literature, from

---

[116] Note this metric as defined here does not represent the full abatement effect of a CCU technology as it does not consider permanence of CO_2 removal, end-of-life (e.g., combustion) emission factors and potential fossil displacement effects. These effects are not accounted for in this assessment, see Box 3.

[117] This approach and the used emission factors are described at greater detail in Annex A.1.1. The assessment framework to evaluate all 49 technologies assumes local production of hydrogen and ammonia, with associated local production emission factors. In the deep dive phase, all 10 shortlisted technologies are evaluated with the assumption that the required feedstock is produced abroad and as such do not have local production emissions. This approach is described in greater detail in Section 4.3.

stoichiometry. This feedstock need is subsequently multiplied by the associated local emission factor.[117] The approach as described above can be summarised in the following formula:

$$
\begin{aligned}
CO_2\ emitted[tCO_2/tonne] \\
&= \sum_{i=electricity,heat} (Energy\ demand_i[GJ\ tonne^{-1}] \times EF_i[tCO_2\ GJ^{-1}]) \\
&+ Demand_{feedstock}[tonne_{feedstock}\ tonne^{-1}] \times EF[tCO_2\ tonne^{-1}_{feedstock}]
\end{aligned}
$$

Box 3. How long products can store CO_2 is a key factor influencing the abatement potential of CCU technologies

CCU technologies use CO_2 as a feedstock to create products. The lifetime of these products is an important (but not the only) characteristic to assess the abatement potential of the technology as it describes how long carbon is stored in this product. One may distinct this *permanence* of technologies by classifying products that have permanent, semi-permanent and displacement abatement effects. Permanent technologies bind or store carbon on timescales over a century; such as mineralising industrial waste to produce aggregates for the construction sector. Chemical products with a long lifetime, such as polyurethane insulating foam for buildings are classified as semi-permanent; such products can have a lifetime of 50 years or more. The final category are products with a shorter lifetime after which carbon is (re-)emitted into the atmosphere, such as fuels. Their abatement potential is mostly linked to the displaced fossil product. In the present study, the abatement potential of CCU technologies is approximated by considering the amount of CO_2 required for the product and discounting CO_2 emitted in the production process. As such, permanence is not directly considered, nor is the displacement effect. If we take fuel as an example, the CO_2 embedded in the product is close to CO_2 released when combusting the displaced fossil fuel. Hence, the short lifetime and the displacement are adverse effects. The simplified metric as applied here can be considered a first estimate.

For a more accurate understanding of the abatement potential of a CCU-derived product, a full lifecycle analysis (LCA) should be performed, comparing the CCU process against a fossil baseline process. For most of the technologies presented in this study, no harmonised LCAs are available.[118] Harmonised LCAs in this context means that there is consistency in system scope and other assumptions such as on baseline reference and footprints of inputs. There is no CCU protocol to interpret ISO standards for such LCAs. Several European universities recently published guidelines for establishing LCAs for CCU technologies which are aimed towards developing globalised harmonised standards.[119]

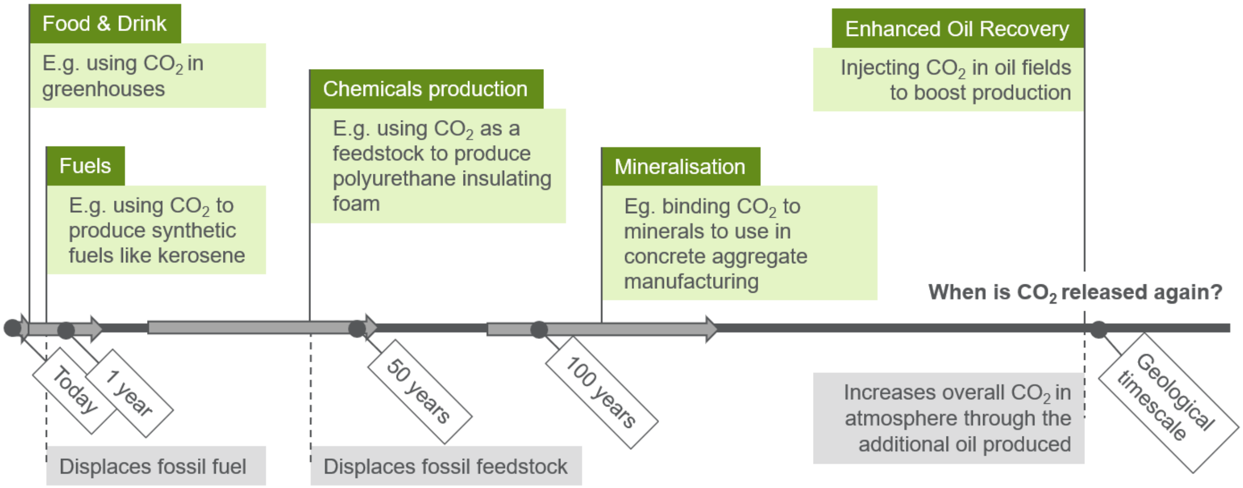


Image by Navigant created in collaboration with EIT Climate-KIC

---

[118] Individual LCAs do exist for a number of the technologies described further on in this study, such as for synthetic methanol (https://doi.org/10.1016/j.apenergy.2015.07.067) or synthetic methane (ACS Sustainable Chem. Eng. 2016, 4, 8, 4156-4165)

[119] Zimmerman et al., Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO2 Utilization, 2018, DOI: 10.3998/2027.42/145436

3.3.2 Technology longlist

Table 15 provides a high-level overview and description of all utilisation technologies that have been assessed for this longlist study. Most of these descriptions are reproduced from CarbonNext.[120]

Table 15. Long list of CCU technologies: overview and description

CCU category	CCU technology	Description
CO_2 to fuels	Algae cultivation	Algae cultivation using nutrient-rich, typically saline or brackish water in open ponds or closed bioreactors, where CO_2 is bubbled through to accelerate biomass production rates/yield. The lipid (fatty) fraction of the biomass can be used to make biodiesel and other liquid fuel substitutes. Microalgal-derived biofuels are currently developed both through heterotrophic cultivation and phototrophic growth. Non-fuel applications for algae include wastewater remediation, high value pharmaceuticals, cosmetics, and chemicals.
	Hydrocarbons excreting microorganisms (Helioculture)	The cultivation of photosynthetic microorganisms that are circulated in a solution of micronutrients, brackish water and CO_2, which directly excrete hydrocarbons that can be used as fossil fuel substitutes (e.g., ethanol, diesel). The process uses unconcentrated solar energy.
	Formic acid as a fuel	Electrochemical reduction of CO_2 (ERC) combines captured CO_2 and water to produce formic acid (HCOOH) and O_2. The formic acid is used as a hydrogen carrier in fuel cells (for use in transportation; CHP units etc.); hydrogen is released from the liquid formic acid as required when an aqueous solution of formic acid is exposed to an appropriate catalyst).
	Synthetic diesel	Syngas produced from CO_2 and H_2 undergoes F-T reactions to produce linear waxes. Hydrocracking converts to synthetic diesel.
	Synthetic kerosene	Gas fermentation of syngas produced from CO_2 by anaerobic bacteria to produce ethanol. This then undergoes oligomerisation and dehydration/hydrogenation to produce hydrocarbons suitable for use as kerosene-type aviation fuel (LanzaTech - Virgin Atlantic Process)
	Synthetic methane	In an exothermal reaction between hydrogen and carbon dioxide, methane and water are produced. The reaction is usually carried out in the presence of a catalyst. To be considered low carbon fuel production, the process energy would need to be renewable.
	Synthetic methanol	The electrolysis of water produces H_2 which is combined with CO_2, compressed and reacted over a metal/metal oxide catalyst to produce methanol and water. The separated methanol can be blended with different grades of gasoline for use as a transport fuel. To be considered low carbon fuel production, the process energy would need to be renewable.
Chemicals production	Acetic acid	Acetic acid can be produced by the oxidation of methane with CO_2. Current catalysts show selectivity to acetic acid so the development of novel catalysts with higher yields and selectivity is needed (TRL: 3). Another route is being explored which involves anaerobic gas fermenting micro-organisms that convert CO_2 and H_2 mixture to acetic acid. LanzaTech, in collaboration with the Malaysian oil company Petronas, is developing this technology (TRL: 2-4).
	Acrylic acid	The process involves the reaction of ethylene with CO_2 in the presence of a catalyst. BASF and Dow Chemicals have reported progress on the synthesis of acrylic acid using this route.
	Benzoic acid	Aromatics (e.g., benzene) react with CO_2 to form benzoic acid. The process is currently being tested at lab scale (TRL: 1-3). Using Kolbe-Schmitt reaction, p-hydroxybenzoic acid is produced commercially. The reaction utilises CO_2 to make potassium phenolate which yields p-hydroxybenzoic acid (TRL: 9).
	Butyric acid	It can be produced through gas fermentation of CO_2 by anaerobic bacteria.

---

[120] CarbonNext, 2017. Report on fully integrated and intensified value chain concepts for process selection http://carbonnext.eu/Deliverables/_/D2.1%20Value%20Chains%2031%2010%202017.pdf

CCU category	CCU technology	Description
	Formic acid	Electrochemical reduction of CO_2 (ERC) combines captured CO_2 and water to produce formic acid (HCOOH) and O_2. The formic acid is used as a hydrogen carrier in fuel cells (for use in transportation; CHP units, etc.); hydrogen is released from the liquid formic acid as required when an aqueous solution of formic acid is exposed to an appropriate catalyst).
	Oxalic acid	Electrochemical reduction of CO_2 combines captured CO_2 and hydrogen to produce oxalic acid.
	Salicylic acid	In this process, sodium phenoxide is carboxylated with CO_2 in the Kolbe-Schmidt reaction to form salicylic acid. Salicylic acid is currently produced commercially utilising CO_2.
	Benzene	Methanol can be converted to a range of aromatic compounds simultaneously using a zeolite catalyst. The process is developed by Mobil. High conversion rates of 95%–100% are achievable with an aromatic(s) yield of 60%–70% of which 80% are BTX, resulting in a total BTX yield of around 56%.
	Toluene	
	Xylene	
	Ethylene	First dehydration of two methanol molecules form one molecule of dimethyl ether (DME), prior to conversion to olefins. Referred to as the Methanol-To-Olefin (MTO) process. Catalysts include silico-aluminophosphate (SAPO-34 or MTO100) or zeolite systems. Several MTO technologies are licensed; UOP LLC & Norsk Hydro; ExxonMobil; Lurgi & Statoil; SYN Energy Technology Co. & Lummus Technology. MTO has started to enter commercialisation with several plants built in China.
	Propylene	
	Ethylene oxide	Carboxylation of olefin results in ethylene oxide. The reaction is mediated by metal oxide catalysts. Ethylene oxide is mainly used in the production of ethylene glycol. Currently, it is commercially produced by the direct oxidation of ethylene.
	Ethylene glycol	Electrochemical reduction of CO_2 can result in polyols. A highly efficient catalyst is needed that can yield glycols without producing unwanted by-products.
	Propylene glycol	
	Sodium bicarbonate	The CO_2 gas stream is passed through an aqueous solution of sodium hydroxide to produce sodium carbonate. This follows bi-carbonation of sodium carbonate to sodium bicarbonate.
	Ethylene carbonate	It is currently commercially produced using CO_2. The process involves carbonation of ethylene (or propylene) oxide to ethylene (or propylene) carbonate.
	Dimethyl carbonate	Carboxylation of alcohols (e.g., methanol) produce dimethyl carbonate. The two most studied catalytic systems for these reactions are tin oxides and ceria-zirconia oxides.
	Polyethylene carbonate	The CO_2 can be made to react with an epoxide such as ethylene (or propylene) oxide resulting in poly ethylene (or propylene) carbonate. These low molecular weight polycarbonates can be used as replacements for polyether polyols which are a component of polyurethanes which have a global annual production of around 18 million tonnes. These polycarbonates also find their applications in ceramics, adhesives, biomedical as well as packaging materials.
	Polypropylene carbonate	
	Ammonium carbamate	The inorganic compound ammonium carbamate is produced as an intermediate in the production of urea when CO_2 reacts with ammonia. This production process using CO_2 is the current commercial route to making urea.
	Methyl carbamate	The organic carbamates are generally synthesised by reacting an alcohol (which in case of methyl carbamate can be methanol) with urea. Both methanol and urea can be produced using CO_2. Methyl carbamate is produced by reacting methanol with urea using boron trifluoride or cupric acetate as a catalyst. Methyl carbamate is used as a reactive intermediate in textile and polymer industries.

CCU category	CCU technology	Description
	Ethane diol dicarbamate	Dicarbamates (ethane diol dicarbamate) are formed by the reaction of CO_2 with diamines (ethylene diamine) and an alcohol (methanol) in the presence of a basic catalyst. They are also formed by the reaction of CO_2 with diamines in the presence of a basic catalyst and the subsequent reaction of the product with an organic halide. The potential market for dicarbamates is large as it relates to the substitution of diisocyanates which are currently used in the manufacturing of polyurethanes.
	Polyurethane	Conventionally, polyurethane is produced by reacting an isocyanate (R-N=C=O) with a polyol (HO-ROH) to form polymer chains of these two monomers which are joined together using carbamate links. Polyurethanes can also be produced using CO_2 based polyols such as polyether polycarbonate polyol which is reacted with isocyanate to produce flexible polyurethane foam (Covestro process).
	DME	DME is conventionally produced by condensing two methanol molecules. For this process to be a CCU process, methanol needs to be produced via a CO_2 based route. However, DME can also be produced by dry reforming of methane and CO_2 to make syngas. This syngas is reacted with more H_2 over a Cu-ZnO-Al2O3Zeolite catalyst in a Fischer-Tropsch (F-T) type reaction to make DME. In an alternative lab development, DME can also be produced in a single-step CO_2 hydrogenation process using a bifunctional catalyst which produces methanol and causes its dehydration in the same reactor.
	Formaldehyde	Formaldehyde can be synthesised from CO_2 via hydrogenation. Hydrogenation results in formic acid which is an intermediary that undergoes reduction to formaldehyde.
CO_2 mineralisation	Carbonate mineralisation - natural minerals	Carbon mineralisation is the conversion of CO_2 to solid inorganic carbonates using chemical reactions. Mineral carbonation occurs naturally and is a very slow process. For carbonate mineralisation to be a viable method to capture and reuse CO_2 from anthropogenic sources such as coal-fired power plants, this process must be accelerated considerably. The carbonates that are produced are stable over long timescales and therefore can be used for construction, mine reclamation or disposed of without the need for monitoring or the concern of potential CO_2 leaks that could pose safety or environmental risks.
	Carbonate mineralisation - industrial waste streams	Similar as above but applied to industrial waste streams such as fly ash, bauxite residue, and steel slag.
	Concrete curing	Concrete curing is an important application, to achieve best strength and hardness. This happens after the concrete has been placed. Cement requires a moist, controlled environment to gain strength and harden fully. The cement paste hardens over time, initially setting and becoming rigid though very weak and gaining in strength in the weeks following. Instead of using traditional energy intensive steam curing methods an alternative method reusing CO_2 can be used.
Enhanced commodity production	Methanol yield boosting	The yield of methanol from conventional methanol synthesis can be increased (estimated by up to 20%) by the injection of additional CO_2 upstream of the methanol reformer.
	EOR	The injection of CO_2 into partly depleted oil reservoirs to boost production. Part of the CO_2 stays in the reservoir, the remainder is produced with the oil and re-injected.

CCU category	CCU technology	Description
	Enhanced coal bed methane (CBM) recovery	The injection of CO_2 into coal seams to produce methane. Part of the CO_2 stays behind.
	Supercritical CO_2 power cycles	The use of supercritical CO_2 in closed loop power cycles as a replacement for steam (e.g., in fossil fuel-fired or nuclear power plants). Benefits include increased electricity conversion efficiency and less thermal fatigue and corrosion.
	Urea yield boosting	Urea yield boosting is a well-known application of CO_2 and is used to produce fertilisers (urea granules and other fertiliser derivatives).
Food and drink	Beverage carbonation	Captured (food-grade) CO_2 may be utilised directly in food-related applications, such as beverages. This replaces the use of industrial CO_2.
	Food freezing, chilling and packaging	CO_2 may be utilised directly in food-related applications, such as freezing food using dry ice. In packaging applications, CO_2 is used in modified atmosphere packaging with products such as cheese, poultry, snacks, produce, and red meat, or in controlled atmosphere packaging, where food products are packaged in an atmosphere designed to extend shelf life. This replaces the use of industrial CO_2. (See also refrigerant gas in the other industrial applications category)
	Horticulture (glasshouses)	Growth rates of several plant species increase with elevated CO_2 levels if all other nutrients, water and sunlight are available in abundance. Greenhouses often employ gas engines or buy technical CO_2. In case of a gas engine, a CO_2 vaporizer collects CO_2 from the flue gases and distributes it inside the greenhouse via diffusers. External CO_2 supply reduces energy costs for greenhouse farmers.
Other industrial applications	Metal working	The mould for CO_2 casting is made of a mixture of sand and liquid silicate binder which is hardened by passing CO_2 gas over the mould. The equipment of the moulding process includes CO_2 cylinder, regulator, hoses, and hand-held applicator gun or nozzle. CO_2 moulding delivers great accuracy in production. CO_2 is also used in welding as a shrouding gas to prevent oxidation of the weld metal.
	Refrigerant gas	CO_2 is used as the working fluid in refrigeration plant, particularly for larger industrial air conditioning and refrigeration systems. It replaces more toxic refrigerant gases that also have significantly greater global warming potential.
	Electronics	Printed circuit board manufacture uses small quantities of CO_2 in niche applications predominantly as a cleaning fluid.
	Water treatment and pH control	CO_2 is used for remineralisation of water following reverse osmosis and for pH control (reduction). CO_2 is used for pH control in swimming pools.
	Supercritical CO_2	Supercritical CO_2 can be used in a wide range of applications. These include: coffee decaffeination, extraction of aromas or flavours and plant substances, pharmaceutical processes, and as a solvent in dry cleaning. Benefits of using CO_2 compared to other chemicals traditionally used are that it is inert and non-toxic. Furthermore, because of its low critical temperature and moderate pressure requirements, natural substances can be treated particularly gently.

Source: CarbonNext, Navigant

3.3.3 The shortlisting process

An assessment process was used to shortlist the 10 technologies that are most promising for Singapore to explore further. This was done with the following method:

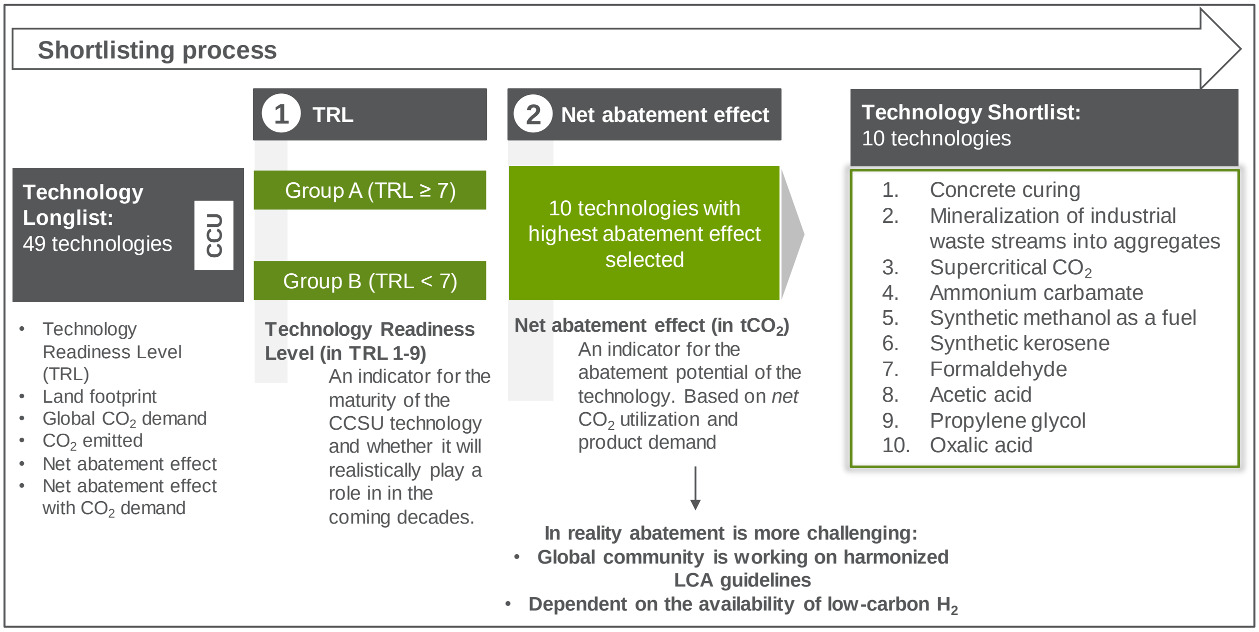
- Technologies were divided in two groups based on technology maturity.
    - Group A includes technologies of TRL 7 or up.
    - Group B includes technologies below TRL 7.
- Technologies were subsequently ranked according to their net abatement considering the global CO_2 demand using the last assessment framework attribute from Table 14.
- Technologies were evaluated on whether Singapore could exert some form of control over the supply chain of the particular CO_2-derived product. The technologies where this was not the case were screened out.
- The five top-ranking technologies per group were selected for deep dive analysis.

Chapter 4 describes the shortlist and the deep dive analysis methodology and results.

4. DEEP DIVE ON SHORTLISTED CCU TECHNOLOGIES

4.1 Shortlist of CCU technologies

A total of 49 CO_2 utilization technologies have been shortlisted, which led to an in-depth assessment of 10 utilization technologies.



The 10 utilisation technologies shortlisted using the assessment attributes from the previous chapter include the following:

1. Concrete curing
2. Carbonate mineralisation of industrial waste streams
3. Supercritical CO_2
4. Ammonium carbamate
5. Synthetic methanol as a fuel
6. Synthetic kerosene
7. Formaldehyde
8. Acetic acid
9. Propylene glycol
10. Oxalic acid

This chapter will provide a deeper analysis of these selected technologies following the assessment framework, as detailed in the next section.

4.2 Attributes for the assessment of shortlist

Table 16 describes all aspects of technologies that are analysed. Each section is dedicated to a single technology and the assessment attributes serve as subheadings in this analysis.

Table 16. Overview of attributes considered in the deep dives on shortlisted technologies

Category	Attribute	Description
Technological	Technology outline and features including technical performance and expected lifespan of each technology	A description of the main features of the technology option, including a basic overview of the process such as energy and material inputs required.
	Current technology status/ technology readiness level	Assessment of the current technological status of the technology, its level of deployment and the associated CO_2 demand. Information on any research efforts to advance the technology.
	Energy intensity per unit of product	Analysis of the amount of energy required per tonne of product and assessment of direct and net CO_2 abatement.
Commercial	Market application	Assessment of the specific sectors and applications that the technology is, or could, be deployed in.
	Status quo	Overview of the current situation regarding the technology and product or production process the technology is supposed to replace.
	Future growth potential to 2030	Assessment of the potential deployment of the technology in 2030.
	Product value	Assessment of the value of the resulting product, considering incumbent products and markets.
	Investment and operating cost	Assessment of the investment cost & operating cost of each of the technology.
Operational	Scalability to match emissions profile or local demand	Assessment of the fit of a certain technology to meet local abatement needs and potential local constraints due to resource needs of the production process.
	Locations for deployment and land area requirements	Analysis of the key criteria for deployment of the technology in Singapore. Consideration as to whether the technology is more suited to clusters or standalone plants.
	Benefits and opportunities	Assessment of any additional opportunities of incentivising the deployment of the technology. This includes an assessment of if/how the deployment could benefit carbon capture technology or other CCUS developments.
	Barriers and required support	Identification of the key barriers the technology faces to be able to be deployed in practice. Recommendations on the possible forms of support that could assist in addressing these barriers help to advance technology deployment if desired.
Circular	By-products, if any, and their potential use case	Assessment of potential by-products resulting from the production process and any applications thereof.
	Potential to fit in circular production scheme	Assessment of what is required for this technology or process to fit a circular scheme.

Source: Navigant

4.3 Assessment of CCU technologies

All deep dive assessments are performed using the above framework, relying on available literature and information provided by technology providers, as indicated throughout the text.

Quantitative evaluations follow business-as-usual (BAU) assumptions. Costs associated with CO_2 capture and concentration in Singapore are discussed in Section 3.1.3 and excluded from scope in evaluating the utilisation technologies described here. In quantifying investment and volumes of feedstock and resulting products, a typical (reference) world-scale plant size has been modelled. Feedstock (hydrogen and ammonia) is assumed to be imported to Singapore. As such, production-related emissions do not contribute to Singapore national emissions. Having said that, the *global* abatement effect of CCU-derived products is determined primarily by the carbon footprint of energy and feedstock inputs required for the production process. Therefore, abundant renewable energy, including energy required to produce hydrogen and ammonia, is a prerequisite for these synthetic routes to materially contribute to mitigating climate change.[121,122] Other material input to CCU processes discussed here, such as cement for concrete, are considered to be produced via conventional means and imported.

With this model, we scaled to the capacity of a typical modern plant producing the same product, ideally following a similar process. Each deep dive explores the effect of other potential scales or volumes, usually reflecting existing production capacity in Singapore. In the next chapter we show Marginal Abatement Cost Curves (MACCs) that use the same underlying data to compare technologies and their impacts in the BAU scenario.

4.3.1 Concrete curing

Category	Summary
Technological	*Various companies have developed solutions to cure concrete with CO_2. CarbonCure, at TRL 9, is the most widely deployed and has a presence in Singapore. However, with a CO_2 utilisation factor of around 0.6 kg CO_2 per tonne of concrete this technology will likely not contribute significantly to large amounts of CO_2 utilisation in Singapore.*
Commercial	*Concrete demand is expected to rise continuously and currently is at around 34 Mt in Singapore. Precast concrete production is expected to increase in market share compared to ready-mix concrete, which offers potential to sequester larger amounts of CO_2 at once. CarbonCure aims to offer a cost-neutral business case to concrete producers from a combination of a technology licensing fee and manufacturing efficiencies.*
Operational	*A typical precast concrete plant would abate around 100 tonnes of CO_2 per year through concrete curing. However, since the technology does not put a strain on land demand it could easily be implemented in all concrete producing facilities, which would bring the sequestration potential total to 20 kilo tonne CO_2.*
Circular	*No by-products are produced in the concrete curing process. Concrete fits well in an already existing concrete recycling scheme.*

4.3.1.1 Technological

Technology outline and features

Efforts to reduce the carbon footprint of concrete and cement have largely followed two pathways: the reduction of CO_2 emissions in the production of cement/concrete and the capture of CO_2 in the final cement/concrete product. Besides capturing CO_2 and utilising it in cement, which is not considered here, it

---

[121] SAM, Novel carbon capture and utilisation technologies, Scientific Opinion 4/2018

[122] Bains et al., CO_2 Capture from the industry sector, Progress in Energy and Combustion Science 63 (2017) 146-172

is also possible to cure (or harden) concrete together with CO_2. Solidia and CarbonCure own a patent-protected concrete curing process which utilises CO_2.[123]

The Solidia process is referred to as hydrothermal liquid-phase densification and can also be applied to ceramics. Solidia provided a simplified overview of the process as follows: Solidia cement powder[124] and sand are packed together, CO_2 and water are added (80% less water than traditional curing), and the components react to produce calcium carbonate and silica concrete. The potential market for cement and concrete is large, and with traditional processes being both energy and emissions intensive any technology proven to reduce the negative environmental impact could have a significant impact on improving sustainability in the industry. Operating the process comes with relatively low CAPEX and a low OPEX which should decrease project risk. Solidia Concrete can be produced by manufacturers of traditional concretes and can be designed to address virtually any precast concrete application. LafargeHolcim, based in France with a presence in Singapore, is also investing in the technology wherein demonstration tests were done in the US.[125]

CarbonCure operates a concrete curing process with CO_2 where CO_2 is captured and injected into wet concrete while being mixed. The CarbonCure process can be applied in precast, ready-mix, and masonry concrete processes. However, the conditions of Singapore are stimulating the usage of precast concrete, which could see this share go up in the future.[126] The CarbonCure technology is an add-on solution to the batching system of the concrete producer and has no impact on normal operation. The required amount of carbon dioxide is injected in few seconds and the mixer serves as a contained reaction vessel for the carbonation of the concrete material. The only change to regular operation beyond CO_2 injection is the slight increase in the amount of water used. The CarbonCure process is a form of carbonation-curing; where CO_2 reacts with the minerals in the cement mixture to form carbonates. The CarbonCure process produces nanoparticles of calcium carbonate between the larger cement grains, which are known to enhance the material properties of concrete.[127] Because of this, manufacturing efficiencies can be achieved in the order of 15–20 kg/ cement savings per m^3 of concrete.

Current technology status

Solidia technology is in a post-demonstration phase and has been tested on a lab scale and in pilot plants, such as through its LafargeHolcim partnership in a US plant. The strength and durability of Solidia Concrete products has been tested and verified according to all market standards like ASTM, AASHTO, EN, and CSA.[128] This puts the TRL at 7. CarbonCure is currently deployed at a larger scale and is implemented in multiple concrete plants throughout North America and Singapore. Pan-United Corporation Ltd. in Singapore has formed a partnership with CarbonCure and will implement the technology in all its plants.[129]

Energy intensity per unit of product

CarbonCure' s concrete curing process with CO_2 does not lead to a lower energy demand in the concrete production process. However, embedded energy savings are achieved since potentially less cement is needed. For the Solidia process, energy savings can also be achieved higher up in the value chain with

---

[123] Solidia, 2018. *New US Patent for Solidia Technologies' CO_2-cured Concrete Advances the Performance and Sustainability of Building Materials*. http://solidiatech.com/wp-content/uploads/2018/01/Solidia-Technologies-release-US-Patents-Bonding-Element-FINAL-1-19-18.pdf

[124] Process can already start with cement that has CO_2 captured in it, by reacting calcium oxide with CO_2.

[125] LafargeHolcim, 2016. *LafargeHolcim's activities: CCS/U and low CO_2 cements, focus on Solidia Technologies®*. https://www.solidlife.eu/sites/solidlife/files/atoms/files/presentation_ccsu_ecra_mons_091116.pdf

[126] EBAWE, 2018. *Singapore relies on precast concrete elements.* https://www.ebawe.de/sites/default/files/medien/1801_progress_en.pdf

[127] Monkman et al. 2016. *Properties and durability of concrete produced using CO_2 as an accelerating admixture.* https://static1.squarespace.com/static/5aa66c98e2ccd14f733ddc19/t/5c70500ba4222fd8010441a9/1550864397173/Properties+and+Durability+of+Concrete+Produced+Using+CO2+as+an+Accelerating+Admixture.pdf

[128] Solidia, 2017. *The Science behind Solidia Cement™ and Solidia Concrete™*. http://solidiatech.com/wp-content/uploads/2017/01/Solidia-Technologies-Science-Backgrounder-Jan-2017-FINAL.pdf

[129] CarbonCure, 2018. *CarbonCure enters Asian market through partnership with Singapore concrete innovator Pan-United*. https://www.carboncure.com/news-press/2018/11/19/carboncure-enters-asian-market

Solidia cement. This process implies that the cement kiln is fired at a temperature that is around 250°C lower than conventional cement plants, which leads to additional energy savings for cement in the order of 30%. This would trickle down to embedded energy demand for concrete as well. However, since no cement is produced in Singapore and in the future will also likely be imported, we do not consider the embedded energy demand of concrete from cement in further calculations. For the traditional production of precast concrete, energy demand is 0.32 GJ/tonne, of which one-sixth in the form of electricity (15 kWh or 0.054 GJ).[130]

Emissions associated with the production of Portland cement vary but are on average 1 tCO_2 per tonne cement.[131] Solidia claims that due to the CO_2 embedded in the cement and eventually in the concrete, around 70% of the CO_2 is abated in the production process of Solidia cement and concrete.[132] The curing part, however, would contribute 40% to this reduction. For concrete, a traditional process includes only 10%-15% cement, plus aggregates, water, chemicals and other operating expenditures. CO_2 intensities for production of concrete are estimated at 0.15 tCO_2 per tonne concrete.[133] Per tonne of cement around 30 kg of CO_2 can be captured,[134] which reduces the CO_2 footprint of one tonne of concrete by around 10%.[135] CarbonCure mentions that its technology has the potential to save over 4,000 tonnes CO_2 annually at each Pan-United concrete plant, which includes the CO_2 savings from the reduction of cement in the concrete.[136] This means that CarbonCure has a significantly smaller CO_2 utilisation rate compared to Solidia. However, the Solidia technology is mainly applicable to precast concrete. It should be emphasised that the reduction of cement in both technologies leads to additional reductions in embedded emissions but are not reduced in Singapore since there is no cement produced domestically. Finally, emissions related to the capture, compression and transport of CO_2 should be considered.

4.3.1.2 Commercial

Market application

Precast concrete is a widely used construction material with a demand of around 1.15 million m^3 per year in Singapore alone (2011 figures), compared to 12–13 million m^3 for ready-mixed concrete (2018 figures).[137,138] Southeast Asia has some of the highest levels of adoption of precast concrete and developments in Singapore are strongly backed by government incentives.[139] Consequently, the production

---

[130] Hasanbeigi, Pryce & Lin, 2012. *Emerging Energy-efficiency and CO_2 Emission-reduction Technologies for Cement and Concrete Production*. https://understandchinaenergy.org/wp-content/uploads/2014/01/LBNL-2012-Emerging-Energy-efficiency-CO2-Emission-reduction-Tech-Cement-Concrete.pdf

[131] Davidovits (2015). False Values on CO_2 Emission for Geopolymer Cement/Concrete. http://www.geopolymer.org/fichiers_pdf/False-CO2-values.pdf

[132] Solidia, 2018. *Solidia Technologies Can Reduce the Carbon Footprint of Cement and Concrete in California by 7.4 Million Metric Tonnes*. http://solidiatech.com/wp-content/uploads/2018/03/CARB-Release-FINAL-1.pdf

[133] Assuming that one m^3 of concrete weighs 2.4 tonnes. http://www.geopolymer.org/fichiers_pdf/False-CO2-values.pdf

[134] This relates to 300 kg of CO_2 per tonne of cement used in the concrete mix. Solidia, 2017. *The Science behind Solidia Cement™ and Solidia Concrete™*. http://solidiatech.com/wp-content/uploads/2017/01/Solidia-Technologies-Science-Backgrounder-Jan-2017-FINAL.pdf

[135] NRMCA, 2016. *NRMCA Member Industry-Wide EPD for Ready Mixed Concrete*. https://www.nrmca.org/sustainability/EPDProgram/Downloads/EPD10080.pdf

[136] CarbonCure, 2018. *CarbonCure enters Asian market through partnership with Singapore concrete innovator Pan-United*. https://www.carboncure.com/news-press/2018/11/19/carboncure-enters-asian-market

[137] Personal communication with Ready-Mix Concrete Association of Singapore; Building and Construction Authority of Singapore, 2011. *Construction and Property Prospects.* https://www.bca.gov.sg/publications/pillars/others/pillars_11issue1.pdf

[138] Building and Construction Authority of Singapore, 2018. *Construction Material Market Prices.* https://www.bca.gov.sg/keyconstructioninfo/others/free_stats.pdf

[139] MCT, 2019. *Singapore precast company ride on Italian efficient and flexible concrete distribution and casting systems for growth*. http://www.marcantonini.com/singapore-precast-company-ride-italian-efficient-and-flexible-concrete-distribution-and-casting-systems-for-growth/

of precast concrete is expected to increase in tandem with trends towards higher productivity and adoption of better precast concrete methods in the future.[140]

Status quo

Conventional concrete is the incumbent product this CCU technology relates to; this includes either precast, ready-mix, or masonry concrete. Since the technology is adding on to the existing process, it can replace all existing cement production in the case of CarbonCure. The Solidia method could be implemented only in the precast concrete production process.

Future growth potential to 2030

The growth potential of the technology will depend largely on the ability to satisfy customer demands on quality and durability. Current market size for precast and ready-mix concrete in Singapore has been estimated at around 14 million m^3 per year.[141] This could grow to 16 and 18 million m^3 per year by 2025 and 2050, respectively, based on the same projections. CarbonCure has demonstrated that construction companies like Pan-United in Singapore are willing to adopt such technologies to develop more sustainable building materials. The Solidia technology has been tested on a lab scale and has been demonstrated but it remains to be seen whether construction companies will be comfortable adopting this on a large scale. A benefit for concrete producers is that existing infrastructure can be reused so no large capital investments would be required.

Product value

The market value of ready-mixed concrete lies around US$87/$m^3$.[142] Literature suggests that production costs of precast concrete can be lower for larger-scale projects.[143] For further research we assume the market value to be like that of ready-mixed concrete. Due to the low level of CO_2 utilisation per tonne of concrete, the value of concrete would not noticeably increase if it could serve as a CO_2 sink.

Investment and operating cost

The CarbonCure technology is considered to have low CAPEX since existing assets can be used. Since it is an add-on technology, no investments are required to the existing process. CarbonCure delivers the equipment needed to mix the CO_2 during the concrete batching process in either precast, ready-mix or masonry plants.

Typical plant sizes for a precast concrete facility range between 15,000 and 100,000 m^3/year.[144] Since the Singapore government is supporting the expansion of precast concrete, Singapore may be a sensible place to cure concrete with captured CO_2 since it can get to scale relatively rapidly. Additional OPEX relate to the purchase of CO_2 from suppliers. Effects on energy demand at the plant for the CarbonCure process are neutral; however, curing with CO_2 leads to material efficiencies such as the reduction of filler materials and cement that translate into monetary savings.

4.3.1.3 Operational

Scalability to match emissions profile or local demand

---

[140] Building and Construction Authority of Singapore, 2011. *Construction and Property Prospects.* https://www.bca.gov.sg/publications/pillars/others/pillars_11issue1.pdf

[141] Based on growth rates of cement for the region by Van Ruijven et al. (2016). These were used to estimate 2018 production figures for precast concrete. Van Ruijven et al., 2016. *Long-term model-based projections of energy use and CO2 emissions from the global steel and cement industries*. https://www.sciencedirect.com/science/article/pii/S0921344916301008

[142] Building and Construction Authority of Singapore, 2018. *Construction Material Market Prices.* https://www.bca.gov.sg/keyconstructioninfo/others/free_stats.pdf

[143] National Precast Concrete Association, 2010. *Why Precast Costs Less.* https://precast.org/2010/05/why-precast-costs-less/

[144] MCT, 2019. *Singapore precast company ride on Italian efficient and flexible concrete distribution and casting systems for growth*. http://www.marcantonini.com/singapore-precast-company-ride-italian-efficient-and-flexible-concrete-distribution-and-casting-systems-for-growth/

Depending on the availability of CO_2, the production of CO_2 cured concrete can be scaled up easily since one batch can be delivered with or without CO_2 mixed into the concrete. Assuming a local demand for concrete of 34 mil tonnes per year (~14 million m^3), and a CO_2 use factor of 0.6 kg CO_2 per tonne of concrete, the concrete curing process could support the mitigation of around 20 kilo tonne CO_2 in Singapore. Considering that Singapore's emissions from power generation and industry are 39 mil tonne CO_2, this CCU technology could mitigate around 0.05% of those emissions if implemented in all plants.

Locations for deployment

Singapore has various concrete producers with batching plants or precast concrete production. These include Holcim and Pan-United Corporation, which have batching plants throughout Singapore, and Poh Cheong and Hong Leong, which produce precast concrete in Sungei Kadut and Tuas, respectively. Due to the locations where CO_2 can be used in curing the delivery of CO_2, the use of this technology is relatively versatile. This CO_2 does not have to be 100% pure CO_2 and requires less purification. However, there have not yet been studies to determine the minimum CO_2 purity since to date food-grade CO_2 has been used. Since impurities may affect the concrete properties, concentrations of >90% should probably be expected.

Land requirement

The land requirement for this technology is negligible. It is an add-on technology that requires a small batching module to dose the CO_2 and some CO_2 injection equipment. The concrete plant may need to reserve some storage space for CO_2 tanks.

Benefits and opportunities

A benefit of engaging in CO_2 utilisation through concrete curing is that existing assets can be reused and that this technology is low in CAPEX.[145] Since the technology locks away the CO_2 permanently, the contribution to mitigation of climate change of the embedded CO_2 is stronger compared to non-permanent options. Developers have also stated that adding CO_2 during the curing process can increase compressive strength, which can lead to manufacturing efficiencies for the concrete producer and potentially earn points in green building schemes.[146] For the Solidia process, the curing time is also reduced. Time-savings can be beneficial for producers, since the time for curing is reduced significantly from 28 days to 1 day.

Barriers and required support

Potential barriers for the technology could be in its application in steel-reinforced concrete. Namely, when carbonation takes place, the alkalinity of concrete is lowered. If the pH value of the carbonated concrete drops below 10.5, the passive layer will decay and exposes the steel to moisture and oxygen, making it susceptible to corrosion. Rust increases the volume of the steel, which exerts a pressure on the surrounding concrete, causing cracking and spalling. Sulphur dioxide contamination in the flue gas would have a similar effect on the concrete.[147] This lowered pH would therefore require counter-measures. Methods exist to protect steel in concrete from corrosion, such as electrochemical chloride extraction, which applies a negative charge to the rebar so that corrosion are reduced at the reinforcing steel surface.[147]

Additionally, large construction projects often have standards in place that require a minimum percentage of cement in the concrete mix. Since carbon curing strengthens the concrete, less cement could be needed to achieve the same levels of strength, potentially leading to conflicts with these kinds of standards. Currently, CarbonCure's technology can be readily applied to non-structural concrete. For structural concrete, CO_2 cured concrete can be deployed when the product demonstrates compliance with the

---

[145] Hasanbeigi, Pryce & Lin, 2012. *Emerging Energy-efficiency and CO_2 Emission-reduction Technologies for Cement and Concrete Production*. https://understandchinaenergy.org/wp-content/uploads/2014/01/LBNL-2012-Emerging-Energy-efficiency-CO2-Emission-reduction-Tech-Cement-Concrete.pdf

[146] The Global CO_2 Initiative, 2016. *CO_2 Utilisation Roadmap.* https://www.icef-forum.org/platform/speakers/topic13/session3/CS2_6_Issam_Dairanieh_161007.pdf

[147] Jianxia, 2012. Comprehensive Renewable Energy: *Hydro Power*. https://www.sciencedirect.com/topics/engineering/carbonated-concrete

performance standards prescribed by Singapore's building codes and uncertainties surrounding the use of carbon curing in structural concrete are resolved.

4.3.1.4 Circular

By-products, if any, and their potential use case
The production process of cement curing with CO_2 does not result in any by-products that could contribute to a circular economy.

Potential to fit in circular production scheme
Currently, construction and demolition waste are almost fully recycled in Singapore. This is only expected to increase towards the future, meaning that CO_2 cured concrete fits well into an already existing circular scheme. Solidia additionally claims the CO_2 curing process leads to 20% less waste.[148]

---

[148] Rathi, 2017. *The material that built the modern world is also destroying it. Here's a fix*. https://qz.com/1123875/the-material-that-built-the-modern-world-is-also-destroying-it-heres-a-fix/

4.3.2 Aggregates based on carbonated waste

Category	Summary
Technological	*Accelerated carbonation technology (ACT) using waste streams is best commercialised by Carbon8 Aggregates. Various large-scale plants are operational, which puts the technology at TRL 9. With a CO_2 utilisation factor of 0.08 tCO_2 per tonne of aggregate, and half that when considering actual abatement, the overall CO_2 mitigation effect is relatively small compared to most other CCU options in this study.*
Commercial	*Similar to the demand for concrete, which is one of the largest applications for aggregates, demand is expected to rise. Costs for the ACT processes are higher compared to aggregate imports, mainly due to the cost of power and the purchase of CO_2.*
Operational	*A typical aggregate plant based on secondary waste streams would abate 0.02% of present-day industrial CO_2 emissions in Singapore. Land demand is low using the modular approach, which requires two to three shipping containers for one production line. The waste streams with the highest availability in Singapore are bottom ash, steel slag, and construction and demolition waste.*
Circular	*CO_2 mineralisation in aggregates can enable the treatment of calcium oxide and magnesium contained in waste streams that is otherwise difficult to treat.*

4.3.2.1 Technological

Technology outline

Various patented technologies exist that convert CO_2 and waste materials into construction aggregate. Carbon8 Systems, a UK-based company, was the first to commercialize an accelerated carbonation technology (ACT) and with a new company, Carbon8 Aggregates, was the first to demonstrate this technology at scale. Carbon8 Aggregates currently operates two plants in the UK with a combined production capacity of 130,000 tonnes of aggregate per year using air pollution control residue (APCr) from nearby WtE facilities.[149] Its strategy is to expand this to five sites with a combined capacity of 250,000 tonnes. Since this process is currently operating in a commercial environment at scale, this technology is assumed to be at TRL 9. While only APCr material from waste incinerators has been used on the industrial scale so far, successful tests have been made on material from cement kilns, shale ash, and other calcium oxide containing waste materials. Carbon8 Systems is currently working with a number of multinational organisations to expand the use of ACT to other wastes streams(e.g. incinerated bottom ash or IBA) and territories.

Until 2010, the majority of APCr in the UK were treated by sending them to either specialised hazardous landfill facilities or were placed in underground storage.[150] The lack of available facilities, high transport fees, high landfill gate fees and increasing landfill taxes (around 85 £/tonne) stimulated the use of other alternative waste management options to treat APCr wastes. These steered Carbon8 Aggregates to use the ACT process to produce aggregate materials in the UK.

The aggregate production process with CO_2 and APCr is as follows. First, the APCr material is stored in a silo and transported to a first stage mixer where it is blended with water and gaseous CO_2 that was stored in a liquid state on-site.[151] In the mixer the oxides of the group I and II metals, predominantly calcium oxide, are carbonated in the slurry formed. Calcium oxide is hydrated to calcium hydroxide in the presence of water, the hydroxide then reacts with CO_2 to produce calcium carbonate. The carbonated APCr is then transported via conveyor to the second stage mixer, where fillers and binders are added to the material. The material is then transported to a pelletiser, where gaseous CO_2 is injected to accelerate the cementation process resulting in the formation of a rounded aggregate. The cementation process is a chemical reaction in which more material is carbonated (the fillers and binders) to capture more CO_2. The

---

[149] Carbon8, 2016. *Carbon8 wins approval to build new plant in Leeds.* https://c8a.co.uk/carbon8-wins-approval-to-build-new-plant-in-leeds/

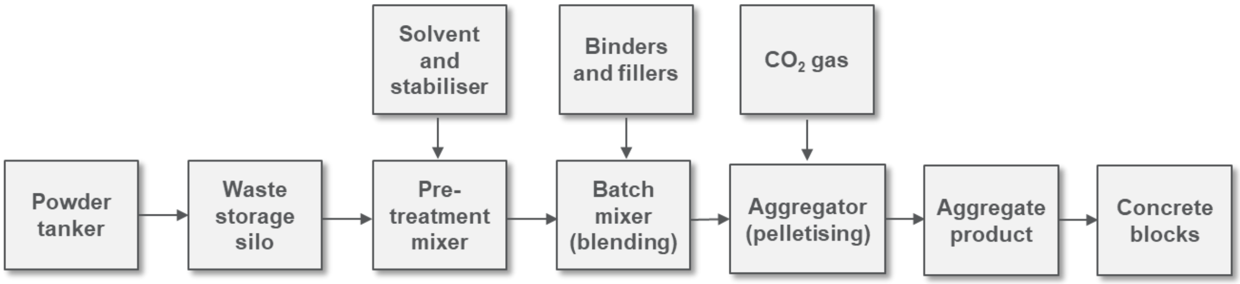
[150] Singh et al., 2017. *NexGen Technologies for Mining and Fuel Industries (Volume I and II)*. p.1005. ISBN: 9385926403

[151] C8A, 2019. *Our Process.* http://c8a.co.uk/our-process/

finished aggregate is then screened and stored before shipment. After this process the final product also receives the end-of-waste status by the UK Environmental Agency.[152]

Although Carbon8 Aggregates currently uses pure CO_2 in the ACT process, this is not necessarily required to optimally carbonate waste. Stefaan Simons, one of the founders of Carbon8 Systems, found that the optimum conditions for a rapid reaction depends not only on the concentration of the CO_2 gas, but also on the particle size of the waste being treated, as well as the water-to-solid ratio. The optimum gas concentration was shown to be around 30%.[153]

Figure 8. Carbon8's ACT process.



Source: Adapted from Carbon8[154]

Other initiatives worth mentioning include Blue Planet, which creates aggregates by dissolving CO_2 in an aqueous solution that contains divalent cations and a base. Carbonates and bicarbonates form and precipitate in the solution and after washing form solid aggregates. This last step of forming the precipitated mass into aggregate is energy intensive and requires quite some base material. However, some waste streams contain both base material and calcium or magnesium, which would solve this issue.[155] There is also CarbiCrete, from Canada, which convert steel slag and CO_2 into concrete blocks which outperformed traditional concrete in compressive strength. Orbix from Belgium has developed a similar process, which can recover useful metal from slag and carbonate the rest of the material. Since steel slag is not abundant in Singapore these methods may be less attractive for the local situation. Scientists from A*STAR ICES have developed a pH-swing carbonation process that precipitates magnesium carbonate and other minerals in an aqueous system at room temperature and atmospheric pressure.[156] A pH-swing process theoretically provides higher rates of conversion of CO_2 to carbonates. However, this process relies on imported silicate minerals like magnesium silicate ore, which is different from the waste-based silicates in the other technologies mentioned.

---

[152] The status is based on the EU End of Waste Regulation. Non-classified products undergo an end of waste test, which assesses whether the waste has been converted into a distinct and marketable product, the processed substance can be used in exactly the same way as a non-waste alternative and the processed substance can be stored and used with no worse environmental effects when compared to the material it is intended to replace. Source: UK Government, 2019. *Waste Management Guidance*. https://www.gov.uk/guidance/turn-your-waste-into-a-new-non-waste-product-or-material

[153] University College London, 2014. *Treating waste with carbon dioxide: growth of spinout Carbon8 Systems*. https://ref2014impact.azurewebsites.net/casestudies2/refservice.svc/GetCaseStudyPDF/29983

[154] Adapted from Carbon8, 2018. http://nas-sites.org/dels/files/2018/02/1-5-CAREY-Carbon8-Systems-NAS.pdf

[155] Kools, 2018. CO_2 sequestration and utilization in cement-based materials. https://esc.fnwi.uva.nl/thesis/centraal/files/f107703262.pdf

[156] Hemmati et al., 2014. Process Optimization for Mineral Carbonation in Aqueous Phase. https://s3.amazonaws.com/academia.edu.documents/50415898/j.minpro.2014.05.00720161119-22911-966b84.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1552914140&Signature=8CxhK66k9Bg3p%2B%2F80xuljYMz2xg%3D&response-content-disposition=inline%3B%20filename%3DProcess_optimization_for_mineral_carbona.pdf

Finally, Mineral Carbonation International (MCi) from Australia is developing another carbonation technology which is currently in research phase (TRL 3-4). They currently aim to develop a demonstration plant with a capacity of 5–10 kilo tonnes CO_2/y with the goal of ultimately sequestering 1 mil tonne of CO_2 per facility. The process binds CO_2 with crushed serpentinite rock to create magnesium carbonate, which can be turned into construction materials.[157] However, since Singapore has no serpentinite deposits the country would have to import to develop a facility based on MCI's technology.

Current technology status

Combined production capacity of all Carbon8 plants in the UK currently stands at 130,000 tonnes of aggregate per year and plans exist to expand this to 250,000 tonnes. With a CO_2 use factor of 0.08 tonnes of CO_2 per tonne aggregate, this means that after expansion, 20,000 tonnes of CO_2 are permanently sequestered in aggregates per year. This indicates that the technology has reached commercial scale and stands at TRL 9.

Energy intensity per unit of product

If Singapore were to produce aggregates from waste material, fillers and binders, and carbonate this using ACT, a power demand of 66 kWh (0.24 GJ) per tonne of aggregate would arise related to handling and injecting the CO_2.[158]

One tonne of APCr material produces 2.3 tonnes of aggregate material. The other 1.3 tonnes consist of CO_2, binders and fillers (predominantly quarry sand and cement), and water. Around 10% of the mass of the final product is CO_2, with the product having net CO_2 emissions of -45 kg to -50 kg CO_2 per tonne of aggregate, making the product carbon negative.[159] It should be noted that using APCr as a waste material to bind the CO_2 to has a relatively high CO_2 uptake compared to most other waste streams that contain calcium or magnesium oxide. Bottom ash for example, which is more abundant compared to APCr, generally has a CO_2 uptake of about half that of APCr,[160] which would lead to an abatement of CO_2 emissions of (near-)zero due to the energy-related emissions.

4.3.2.2 Commercial

Market application

Construction aggregate is a broadly defined material that can consist of sand, gravel, crushed stone, slag and recycled cement for example. Aggregates are used as foundations under buildings or roads and as a reinforcement material to add strength to for example asphalt or concrete. They can be mined directly from aggregate deposits and are among the most mined materials in the world, this is called primary aggregate. Secondary aggregates and recycled aggregates can also be distinguished. Recycled aggregates consist of material that has previously been used in construction projects, with secondary aggregates being by-products of other industries.[161] Examples of secondary aggregate materials include power station ash, air pollution control residue from waste incineration, blast furnace slag from steel production, China clay waste, and colliery spill.

---

[157] Schiffman, 2016. *Pilot plant to turn CO_2 into house parts and paving stones*. https://www.newscientist.com/article/2082112-pilot-plant-to-turn-co2-into-house-parts-and-paving-stones/

[158] Ecofys, a Navigant Company, Sheffield University & TNO, 2018. *Recovery and utilization of Gaseous Industrial Effluents in the chemical sector*. https://publications.europa.eu/en/publication-detail/-/publication/4c6a21a1-ec76-11e8-b690-01aa75ed71a1/language-en

[159] Adapted from -40 to -44 kg per tonne aggregate for a UK situation in which a grid emission factor of 0.527 $kgCO_2$/kWh was used. Singapore grid emission factor of 0.42 $kgCO_2$/kWh was used. Ecofys, a Navigant Company, Sheffield University & TNO, 2018. *Recovery and utilization of Gaseous Industrial Effluents in the chemical sector*. https://publications.europa.eu/en/publication-detail/-/publication/4c6a21a1-ec76-11e8-b690-01aa75ed71a1/language-en

[160] Carbon8, 2018. *Carbon8 Systems.* http://nas-sites.org/dels/files/2018/02/1-5-CAREY-Carbon8-Systems-NAS.pdf

[161] Mineral Products Association, 2019. *Recycled Aggregates*. https://mineralproducts.org/prod_agg_recy01.htm

Status quo

Singapore imports aggregates mostly from Indonesia, at a market price of between S$15 and S$20/tonne (US$11–$15).[162,163] Additionally, the Singapore Building and Construction Authority also maintains a stockpile that contractors can source aggregate from in case of shortages at higher rates varying between S$30–$50/tonne (US$22–$37).[164]

Future growth potential to 2030

Due to strongly growing urbanisation the demand for aggregates is projected to increase significantly in the coming decade. Over an 8-year projection period 2018–2026, PMR, a US-based global business market research consultancy, expects the market to see a compound annual growth rate (CAGR) of 6.8%.[165] For post-2026 we assume a similar growth rate as projected for cement, as used in the concrete curing deep dive. The PMR report also forecasts that aggregates recycling will potentially gain in popularity as the process of aggregate recycling leaves natural resources intact which is gaining in priority among national governments.[166] Singapore currently produces around 1.6 million tonnes of construction and demolition waste,[167,168] of which around 99% is recycled.[169] A spokesman for Samwoh, a Singapore building supply manufacturer who produces aggregates exclusively from recycled demolition waste, mentions that the amount of waste produced in Singapore exceeds the demand for aggregates.[170] Since no exact data is available on the demand for aggregates in Singapore, we estimate this to be around 1 million tonnes a year.[171]

Product value

The green premium associated with aggregates produced from mineralised CO_2 may increase its market value. Since around 0.08 tonnes of CO_2 can be sequestered in one tonne of aggregate,[172, 120] and the abatement effect is around half of that the value of this aggregate would increase by a minor US$0.50 per tonne aggregate, assuming a CO_2 price of US$11/t$CO_2$ in 2030. The average market rate for aggregates (granite from the national granite stockpile) is quoted to be around US$19[173]

Investment and operating cost

---

[162] Arcadis, 2018. *Singapore: Quarterly Construction Cost Overview*. https://images.arcadis.com/media/A/9/9/%7BA99DAC11-B1FC-4C93-A5D5-C97D8B8F9184%7DQuarterly%20Construction%20Cost%20Review%20Q1%202018%20-%20Singapore_001.pdf

[163] Straits Times, 2014. *Government charging more for granite from stockpile.* https://www.straitstimes.com/singapore/government-charging-more-for-granite-from-stockpile

[164] Straits Times, 2014. *Government charging more for granite from stockpile.* https://www.straitstimes.com/singapore/government-charging-more-for-granite-from-stockpile

[165] Aggregates Business, 2018. *Global construction aggregates market worth over US$565.8 bn by end of 2026.* http://www.aggbusiness.com/categories/quarry-products/news/global-construction-aggregates-market-worth-over-us5658bn-by-end-of-2026/

[166] Aggregates Business, 2018. *Global construction aggregates market worth over US$565.8 bn by end of 2026.* http://www.aggbusiness.com/categories/quarry-products/news/global-construction-aggregates-market-worth-over-us5658bn-by-end-of-2026/

[167] Samwoh, 2018. *Engineering a First World: 50 Feats that Transformed Singapore*. https://www.samwoh.com.sg/images/documents/807/2018_04_07%20-%20IES%20-%20Engineering%20a%20First%20World%20(Pg%20136-139).pdf

[168] Singapore National Environment Agency, 2018. *Waste Statistics and Recycling Rate for 2016.* https://www.nea.gov.sg/docs/default-source/our-services/waste-management/wastestats-2003-20164197a3fd04d34770bafba09393d0fdf0.pdf

[169] Orissa, 2018. *Material Handling in Southeast Asia.* https://secure.investni.com/static/library/invest-ni/documents/material-handling-in-south-east-asia-july-2018.pdf

[170] Marusiak, 2012. *Sustainable construction: More waste wanted*. https://www.eco-business.com/news/sustainable-construction-more-waste-wanted/

[171] Volume was rounded down to be on the conservative side. Concrete demand could not be taken as a proxy for the aggregate production capacity, since a lot of it is likely imported directly through aggregate handling infrastructure to produce concrete.

[172] Ecofys, a Navigant Company, Sheffield University & TNO, 2018. *Recovery and utilization of Gaseous Industrial Effluents in the chemical sector*. https://publications.europa.eu/en/publication-detail/-/publication/4c6a21a1-ec76-11e8-b690-01aa75ed71a1/language-en

[173] Straits Times, 2014, https://www.straitstimes.com/singapore/government-charging-more-for-granite-from-stockpile

Costs to produce aggregates in the carbon-negative way would imply purchasing filler materials and binding materials at around US$8 per tonne and US$1 per tonne, respectively.[174] Additionally, CO_2 would need to be purchased. This is not considered for this part of the analysis but can be a differentiator for this technology since a CO_2 purity as low as 30% can be used in aggregates. Carbon8 Systems is also looking into the possibility to carbonate waste streams using regular flue gas with a CO_2 concentration of 10%. This could significantly reduce the costs to deliver CO_2 in Singapore, which can be relatively high compared to the low value of aggregates. Flue gas from CCGTs would be too dilute to use directly, but hydrogen manufacturing units could have suitable flue gas characteristics at concentrations above 30%.

Additional power demand to produce the aggregates would add another $12 per tonne at today's energy prices,[175] which brings the OPEX to around US$21/tonne aggregate, excluding the purchase of CO_2. CAPEX also adds to this cost. Total costs for a 110,000 tonne per year aggregate plant are reported to be US$5.2 million.[176] At an assumed plant life of 20 years, the CAPEX costs are around US$6/tonne. As seen from these cost items, making a profit will be challenging if CO_2 needs to be purchased as well. However, the business case in the UK is driven by a high landfill tax that has to be paid by industrial companies like WtE plants. These companies pay a fee that is lower than the landfill tax to an aggregate producer to treat this secondary waste stream, which improves the business case of producing aggregates through CO_2 mineralisation. Singapore currently does not maintain a landfill tax,[177] but does levy a *refuse disposal fee* to send non-incinerable waste to the Semakau landfill. It is expected that WtE plants need to pay this fee (S$97 per tonne [US$72]),[178] to send their APCr or other non-incinerable waste. The WtE plant would therefore be better off economically to have the residues converted into aggregates at a lower fee. Such a fee could enable a business case for the aggregate manufacturer and would likely offset any additional cost incurred compared to the traditional production process.

Table 17. CAPEX and OPEX estimates for producing aggregates using CO_2 mineralisation in reference scenario

Cost parameter	Value 2025	Value 2050	Approach or source
OPEX	US$20/tonne	US$23/tonne	At power prices of US$0.160 and US$0.204 in 2025 and 2050, respectively, plus 3% fixed O&M, the OPEX add up to US$20 and US$23/tonne aggregate. This includes the costs for other consumables such as fillers and binders, which adds US$9/tonne.
CAPEX	US$6/tonne	US$6/tonne	For a typical plant of 110,000 tonnes per year, the required CAPEX would be around US$0.6 million per year, annualised over 20 years. A total CAPEX investment cost of US$5.2 million per 110,000 tonne plant was assumed here.
Total	**US$26/tonne**	**US$29/tonne**	**Expressed in US$ (2019) per tonne of aggregate.**

Source: references indicated, Navigant analysis

---

[174] Ecofys, a Navigant Company, Sheffield University & TNO, 2018. *Recovery and utilization of Gaseous Industrial Effluents in the chemical sector*. https://publications.europa.eu/en/publication-detail/-/publication/4c6a21a1-ec76-11e8-b690-01aa75ed71a1/language-en

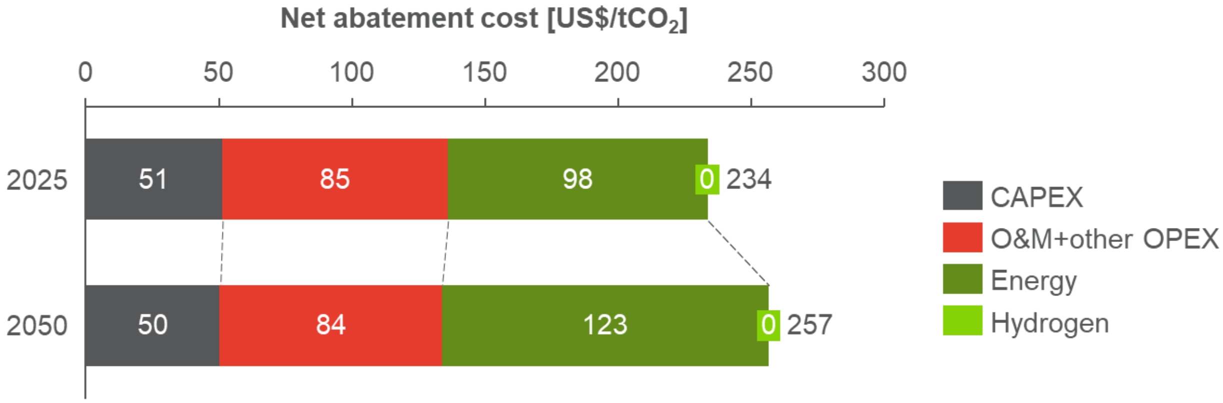
[175] Converted from an electricity price of S$0.205/kWh.

[176] Carbon8 Aggregates, 2015. *Production of Carbon8 Aggregate set to double by end of 2015.* http://c8a.co.uk/production-of-carbon8-aggregate-set-to-double-by-end-of-2015/

[177] Waste Management World, 2010. *Taking recycling lessons from super Singapore*. https://waste-management-world.com/a/taking-recycling-lessons-from-super-singapore

[178] Singapore National Environment Agency, 2019. *Refuse Disposal Facility.* https://www.nea.gov.sg/our-services/waste-management/waste-management-infrastructure/refuse-disposal-facility

Figure 9. Net abatement cost breakdown reference scenario – Mineralization of CO_2 in aggregates



Source: Navigant analysis

4.3.2.3 Operational

Scalability to match emissions profile or local demand

The secondary materials that contain calcium oxide that can be used for CO_2 mineralisation are available in Singapore. Each year about 600 kilo tonnes of bottom ash is produced in Singapore,[179] as well as 250 kilo tonnes of slag[180] and some of the mineral waste that was mentioned earlier. Pulverised fuel ash from coal-fired power plants in Singapore can also be used.[181] However, since recycling rates for slag and mineral waste are already close to 100%, the only waste source left with significant potential is bottom ash or air pollution control residue.

Given that the technology can sequester 0.08 tonnes of CO_2 per tonne of aggregate produced, and the local production capacity of aggregates is estimated at around 1 million tonnes per year, this CCU process could be scaled up to use around 80 kilo tonnes of CO_2. Due to the associated additional demand for power, the actual abatement effect would be half of the utilised CO_2 when the local power emission factor remains as is.

Locations for deployment

Singapore has developed a good aggregate infrastructure by utilising imported aggregates and sand from Indonesia, Malaysia, Vietnam, and Cambodia.[182] The aggregate production units are flexible but are best placed closed to the waste stream that is being utilised when considering logistics, such as the TuasOne or Sembcorp waste-to-energy plant in Tuas and Jurong Island, respectively.

---

[179] Samwoh, 2017. *Use of incineration bottom ash for road construction in Singapore.* https://www.samwoh.com.sg/success-stories/technical-publications.html

[180] Singapore National Environment Agency, 2018. *Waste Statistics and Recycling Rate for 2016.* https://www.nea.gov.sg/docs/default-source/our-services/waste-management/wastestats-2003-20164197a3fd04d34770bafba09393d0fdf0.pdf

[181] Carbon8, 2018. *Developing an innovative and profitable process that combines waste CO_2 and thermal residues, to create a carbon negative aggregate for construction and lock CO_2 in for good within our built environment*. http://nas-sites.org/dels/files/2018/02/1-5-CAREY-Carbon8-Systems-NAS.pdf

[182] Bhatawdekar & Mohmad, 2019. *Geological Study for Sourcing of Aggregates for Singapore: A Case Study.* https://www.researchgate.net/publication/331166557_GEOLOGICAL_STUDY_FOR_SOURCING_OF_AGGREGATES_FOR_SINGAPORE-A_CASE_STUDY

Land demand

Carbon8's current commercial model involves a mobile plant with the footprint of two or three large shipping containers. The system consists of two stacked containers but needs some area for conveyors and silos outside the container footprint.[183] One large shipping container has a surface of 30 m^2, so conservatively an area of 60 m^2 would suffice for their mobile plant setup. This mobile plant represents one production line capable of producing around 15,000 tonnes of aggregate per year.

Benefits and opportunities

A benefit of mineralisation technology is that it contributes to a circular economy by allowing for the processing of hazardous waste or waste that cannot be incinerated. Singapore's Semakau landfill is projected to have only have sufficient capacity until 2035,[184] so there is a clear incentive to divert these types of waste and create an end-of-waste status in different ways. In addition, CO_2 mineralisation allows for the use of less pure CO_2 and can contain impurities. This significantly reduces the cost for compression and purification. Existing infrastructure to produce aggregates from imported material also can be used.

Barriers and required support

R&D efforts have let regulators to allow up to 20% of recycled aggregates to be used in new buildings.[185] However, to produce aggregates from secondary or recycled materials in Singapore, it will have to fulfil the standards as defined under BS EN 12620: Specification for Aggregates for Concrete, which contains provisions for the use of manufactured and recycled concrete aggregates. Interest in sustainable aggregates is proven by the existence of a list of accredited recycled aggregates suppliers, managed by the Waste Management & Recycling Association of Singapore. Further research should focus on mobile plants for the treatment of smaller waste streams.[186]

Some barriers remain for the technology, even though it is currently commercially operating in the UK. To be able to function as a technology in Singapore, certain waste streams would need to receive an end-of-waste status to allow for storage in aggregates. CO_2 mineralisation in aggregates only has a sufficiently high incentive if there is a landfill tax in place that industries otherwise would have to pay to dispose of their waste. Without this, there is no financial incentive for industries to pay aggregate producers to handle their calcium oxide containing waste. Since there is a fee of S$97 (US$72) per tonne of waste in place to send waste to Semakau landfill, this could on its own be sufficient to stimulate the reversion of calcium oxide containing waste.

Another potential barrier is the risk of pollutants leaching from carbonated aggregates, as most of Singapore is a water catchment area. When carbonated aggregates containing waste are exposed to water, potential leaching effects could occur. Tests by Carbon8 show that the release of soluble salts, such as SO_4 and Cl is reduced after carbonation, but is still higher than the landfill acceptance limits for hazardous waste. The lead release from carbonated ash also generally lead to the reduction of lead mobility, though cadmium release was increased.[187] Carbon8's aggregates do comply with the European Standards on leaching of granular wastes and sludges but would require further research into the applicability for Singapore.

---

[183] Personal communication with Carbon8.

[184] Singapore Ministry of the Environment and Resources, 2019. *Managing our Waste: Landfill*. https://www.mewr.gov.sg/topic/landfill

[185] Samwoh, 2018. *Engineering a First World: 50 Feats that Transformed Singapore*. https://www.samwoh.com.sg/images/documents/807/2018_04_07%20-%20IES%20-%20Engineering%20a%20First%20World%20(Pg%20136-139).pdf

[186] Carbon8, 2018. *Developing an innovative and profitable process that combines waste CO_2 and thermal residues, to create a carbon negative aggregate for construction and lock CO_2 in for good within our built environment*. http://nas-sites.org/dels/files/2018/02/1-5-CAREY-Carbon8-Systems-NAS.pdf

[187] Li, X. et al, 2007. *Accelerated carbonation of municipal solid waste incineration fly ashes* http://www.ukqaa.org.uk/wp-content/uploads/2015/07/Carbon8-submission-for-EN-13055-v2.pdf

4.3.2.4 Circular

By-products and potential uses

Although CO_2 mineralised aggregates are not necessarily made from recycled concrete, it is worth mentioning that some traditional constituents of concrete may be potentially hazardous. This is especially relevant for the CO_2 utilisation process when construction and demolition waste is used. Tests performed on recycled concrete aggregate have found compounds of sulphate, chromium, antimony, and selenium, which can pose a health and environmental hazard when leached from the material.[188] Since large parts of Singapore are part of a water catchment, this is a relevant factor to consider.

Specifically, for Singapore, carbonation of waste into sand could also be worthwhile exploring further. Land reclamation and construction projects have a substantial demand for sand, and AT Kearney predicts that global sand shortages will impact the construction sector.[189] A scalable alternative to sand imports could therefore be the carbonation of waste into construction sand or sand for reclamation. Though environmental effects should be even more carefully considered in the case of land reclamation compared to its application in aggregates due to the interaction with water. Although no public information is available related to such a process, it is estimated to have a roughly similar energy demand to the Carbon8 process if we assume that compressing the carbonated material into aggregates has a similar energy demand as grinding the material into sand.

Potential to fit in circular production scheme

CO_2 mineralisation to produce aggregates fits very well into a circular scheme. It can treat various waste streams that are otherwise difficult to dispose of, such as residues from municipal solid waste incineration. In addition, it has the potential to upcycle various waste streams that are otherwise used as base material for road construction, but now recycled into aggregates. This attributes a higher value to the end-product.

4.3.3 Ammonium carbamate (green urea)

Category	Summary
Technological	*While it is projected that urea will not be produced from natural gas-based ammonia in the long-run (likely from green ammonia), CO_2 will still be needed to produce the intermediate ammonium carbamate. No additional energy demand is foreseen. Avoided emissions will be those related to the traditional production of hydrogen, i.e., 0.54 tonnes CO_2 per tonne urea. No large-scale green ammonia facilities exist to date.*
Commercial	*Due to increasing agricultural demand, urea demand will increase significantly in the coming decade. Local demand for urea in Singapore is negligible, so Singapore could export their CO_2 to produce green urea elsewhere.*
Operational	*Due to Singapore's land constraints, it is not likely that a urea synthesis facility would be built domestically. However, an average plant could offer potential to sequester 0.4 mil tonne of CO_2 per year.*
Circular	*Urea production does not leave any by-products.*

4.3.3.1 Technological

Technology outline and features

Ammonium carbamate is an important intermediate to produce urea. At the same time, it is also used for the denitrification of exhaust emission and as decomposition stabiliser. For most applications, ammonium

---

[188] Braga Maia et al., 2018. *Toxicity of Recycled Concrete Aggregates: Review on Leaching Tests*. https://www.researchgate.net/profile/Ana_Braga_Maia/publication/325766037_Toxicity_of_Recycled_Concrete_Aggregates_Review_on_Leaching_Tests/links/5b4773b5aca272c6093b6146/Toxicity-of-Recycled-Concrete-Aggregates-Review-on-Leaching-Tests.pdf?origin=publication_detail

[189] AT Kearney, 2018. *Year-Ahead Predictions 2019*. https://www.atkearney.com/web/global-business-policy-council/article/?/a/year-ahead-predictions-2019

carbamate substitutes ammonia.[190] Ammonium carbamate has also been approved as an inert ingredient present in aluminium phosphide pesticide formulations. This pesticide is commonly used for insect and rodent control in areas where agricultural products are stored. The reason for ammonium carbamate as an ingredient is to make the phosphine less flammable by freeing ammonia and CO_2 to dilute hydrogen phosphide formed by a hydrolysis reaction.

Urea is made from ammonia and CO_2. The first step in this process is the synthesis of ammonium carbamate. A mixture of compressed CO_2 and ammonia at 240 bar is reacted to form ammonium carbamate. This is an exothermic reaction, and heat is recovered by a boiler which produces steam. The first reactor achieves 78% conversion of the carbon dioxide to urea, since the ammonium carbamate slowly decomposes into urea and water. This reaction is slightly endothermic, and this liquid is subsequently purified. The second reactor receives the gas from the first reactor and recycle solution from the decomposition and concentration sections. Conversion of CO_2 to urea is approximately 60% at a pressure of 50 bar. The solution is then purified in the same process as was used for the liquid from the first reactor. Figure 10 shows a typical urea production process. The reaction follows the equation below. About 98% pure CO_2 is needed to produce ammonium carbamate.[191]

$$\boldsymbol{2NH_3 + CO_2 \rightleftharpoons NH_2COONH_4}\ (\boldsymbol{ammonium\ carbamate})$$

$$\boldsymbol{NH_2COONH_4 \rightleftharpoons H_2O + NH_2CONH_2}\ (\boldsymbol{urea})$$

Because the urea production process is usually integrated with the ammonia production process, and urea synthesis relies on by-product CO_2 from ammonia production,[192] there is often potential for the utilisation of non-captive CO_2 in the production process. However, in the future, more green ammonia will be produced which relies on green hydrogen. Since the production of green hydrogen delivers no by-product CO_2, CO_2 will have to be sourced elsewhere and can be external. The synthesis of urea would still follow Figure 10, but using green ammonia and CO_2 that was captured elsewhere.

There are various initiatives that aim to scale up the production of green ammonia, most notably a 20,000 tonne per year plant in the Netherlands by Proton Ventures, Yara, and Siemens,[193] and pilot plants in Japan and the UK.[194] However, there are no known examples where green ammonia is used to produce urea with externally captured CO_2 and thus produces intermediate ammonium carbamate.

---

[190] BASF, 2019. *Ammonium carbamate by BASF.* http://www.monomers.basf.com/cm/internet/en/content/Produkte/Technische_Salze/Ammoniumcarbamat

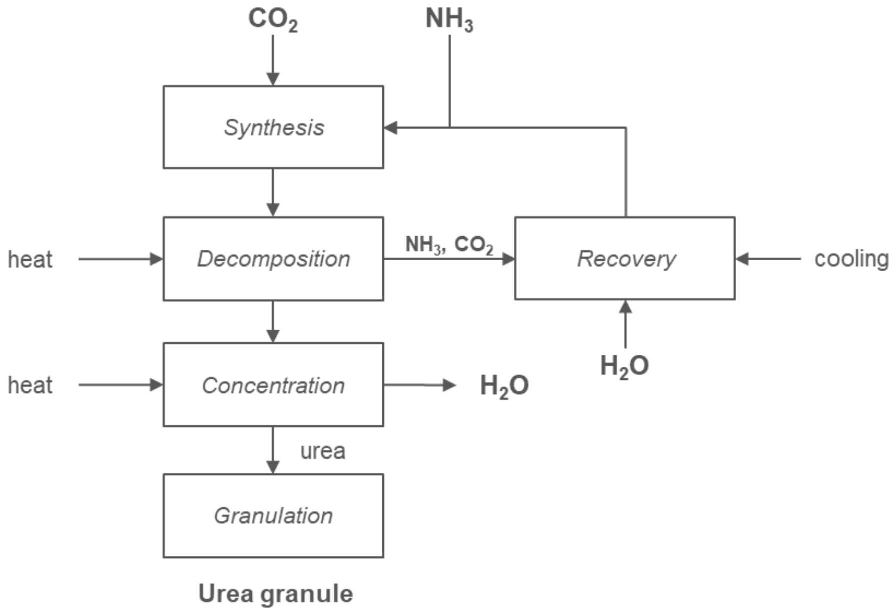
[191] Kolay, 2007. Manures and Fertilizers. https://books.google.nl/books?id=S0o0IDMJORYC&pg=PA60&lpg=PA60&dq=co2+purity+urea+ammonium+carbamate+concentration&source=bl&ots=O0B29eR74G&sig=ACfU3U3CcZflslmWyau1vdjgeiEf_v9oEg&hl=nl&sa=X&ved=2ahUKEwjq2_Ch0I7hAhUPM-wKHdWMAocQ6AEwCXoECAYQAQ#v=onepage&q&f=false

[192] Ammonia is produced by synthesizing N_2 from an air separation unit with hydrogen in the Haber-Bosch process. To get the hydrogen, steam methane reforming is commonly used with natural gas as a feed. This yields carbon monoxide and hydrogen. The carbon monoxide is shifted to produce hydrogen and CO_2, which is removed from the process. Subsequently, the nitrogen can be catalytically reacted with hydrogen to produce ammonia.

[193] Brown, 2018. *Green ammonia demonstration plant in The Netherlands*. https://ammoniaindustry.com/green-ammonia-demonstration-plant-in-the-netherlands/

[194] Brown, 2018*. Green ammonia pilot plants now running, in Oxford and Fukushima*. https://ammoniaindustry.com/green-ammonia-pilot-plants-now-running-in-oxford-and-fukushima/

Figure 10. Schematic of typical urea synthesis process



Source: Navigant, adopted from New Zealand Institute of Chemistry[195]

Current technology status

The individual components of this technology have been demonstrated, i.e., the production of green ammonia, using green hydrogen and the Haber-Bosch process, and the capture, compression, and transport of CO_2. However, together these technologies have not yet been demonstrated. Since the production of green ammonia is currently at TRL 8, where demonstration pilots are scaling up, this technology is also considered TRL 8.

Energy intensity per unit of product

Producing urea from imported green ammonia and externally captured CO_2 is equally energy intensive than the traditional process. Urea plants are usually net consumers of steam and electricity, and often import steam from the ammonia process which is exothermic.[196] For the urea synthesis, heat energy is needed in various steps of the process. About 3.3 GJ of high-pressure steam is needed, and 0.14 GJ of low-pressure steam. In addition, around 81 kWh (0.3 GJ) of power is needed per tonne of urea. However, we argue that the CO_2 utilisation process does not require more or less energy compared to the reference process based on CO_2 from ammonia production and does not lead to a higher or lower level of emissions. There is, therefore, no additional energy demand attributed to producing green urea. Since in this situation ammonia is shipped to the urea plant, which is already at elevated pressure, less compression is needed to produce the urea. The heat that is released in the synthesis of ammonium carbamate will be used further in the synthesis of urea.

Ammonium carbamate utilises 0.56 tonnes of CO_2 per tonne product produced.[197] About 1.3 tonnes of ammonium carbamate is needed for 1 tonne of urea, i.e., 0.73 tonnes of CO_2 are utilised per tonne of urea. In addition, the weight fraction of hydrogen in urea is 6.6%, meaning that for one tonne of green urea 66 kg

---

[195] New Zealand Institute of Chemistry, 2017. *Ammonia and Urea Production*. https://nzic.org.nz/app/uploads/2017/10/1A.pdf

[196] Noelker & Ruether, 2011. *Low Energy Consumption Ammonia Production: Baseline Energy Consumption, Options for Energy Optimization*. https://www.thyssenkrupp-industrial-solutions.com/media/products_services/fertilizer_plants/ammonium_sulphate_plants/low_energy_consumption_ammonia_production_2011_paper.pdf

[197] CarbonNext, 2017. Report on fully integrated and intensified value chain concepts for process selection http://carbonnext.eu/Deliverables/_/D2.1%20Value%20Chains%2031%2010%202017.pdf

of hydrogen-related emissions are avoided. Assuming an emissions factor of 8.1 tCO_2/tonne,[198] this would avoid another 0.54 tonnes of CO_2 emissions. Compared to the reference process where grey ammonia is used; the actual avoided emissions would be only those 0.54 tonnes of CO_2 primarily coming from the hydrogen-related emissions avoided since the other emissions captured from the traditional ammonia production process were already reused.[199]

4.3.3.2 Commercial

Market application

Since ammonium carbamate is an intermediate product, its largest share of the produced volume is not marketed but produced from ammonia and used directly in the production of urea. However, there are also other uses for the product, such as an ingredient in aluminium phosphide pesticide or the denitrification of exhaust emissions. For this reason, BASF is known to market this product in the Benelux area.[200,201] We will focus on the use of ammonium carbamate in the production of urea.

According to the International Fertilizer Association the global demand for urea stood at 174 mil tonnes in the year 2016 and is projected to increase by 1.5% per year to 187 mil tonnes in 2021, with major growth markets in Latin America, Africa, and South Asia.[202] Supply of urea will continue to outpace demand. According to The World Bank, Singapore consumes on average around 30 tonnes of fertiliser per hectare of arable land.[203] Multiplied by the 730 hectares of arable land in Singapore,[204] the potential local urea market is estimated at around 22,000 tonnes. However, since urea is a globally traded commodity, demand would not be confined to Singapore alone.

Status quo

As of 2019, Singapore does not produce any urea or ammonia locally. To engage in this CO_2 utilisation process, either production or imports of green ammonia are necessary. In the absence of a urea synthesis facility, Singapore could export CO_2 for use in green urea production elsewhere in the region.

Future growth potential to 2030

As the demand for agricultural products grows globally, so will the demand for fertiliser. The demand for urea is expected to grow at a pace of 1.5% per year towards 2021. Extrapolating this trend towards 2030 would indicate access to a global market of 214 mil tonnes. The production of green urea, however, will likely have a competitive edge in that its use emits significantly less GHG emissions and thereby has a certain marketing value.

---

[198] Rostrup-Nielsen & Rostrup-Nielsen, 2007. *Large-scale Hydrogen Production.* https://www.topsoe.com/sites/default/files/topsoe_large_scale_hydrogen_produc.pdf

[199] Note that for the abatement and cost analysis, only the production up to the point of ammonium carbamate was considered, though with investment costs related to a urea synthesis plant.

[200] BASF, 2019. *Ammonium carbamate by BASF.* http://www.monomers.basf.com/cm/internet/en/content/Produkte/Technische_Salze/Ammoniumcarbamat

[201] Brenntag, 2019. *Ammonium carbamate crystals by BASF: Product information page*. http://www.brenntag.nl/prd/product/ammoniumcarbamateammoniumcarbamaaten.php

[202] International Fertilizer Association, 2017. *Fertilizer Outlook 2017 – 2021.* https://www.fertilizer.org/images/Library_Downloads/2017_IFA_Annual_Conference_Marrakech_PIT_AG_Fertilizer_Outlook.pdf

[203] World Bank, 2019. *World Bank Development Indicators*: *Fertilizer consumption (kilograms per hectare of arable land).* https://data.worldbank.org/indicator/AG.CON.FERT.ZS?locations=SG

[204] Nation Master, 2019. *Singapore Agriculture Stats.* https://www.nationmaster.com/country-info/profiles/Singapore/Agriculture

Product value

Urea is marketed at a price of around US$260/tonne for urea shipped to the Black Sea region and is usually aligned with the other index price of urea shipped to China.[205,206]

Ammonium carbamate utilises 0.56 tonnes of CO_2 per tonne product produced.[207] The degradation of ammonium carbamate into urea makes that 1.3 tonnes of ammonium carbamate is needed for one tonne of urea, i.e., 0.73 tonnes of CO_2 are utilised per tonne of urea. In addition, the weight fraction of hydrogen in urea is 6.6%, meaning that for 1 tonne of urea, 66 kg of hydrogen-related emissions are avoided. Assuming an emission factor of 8.1 tCO_2/tonne,[208] this would avoid another 0.54 tonnes of CO_2 emissions. At a CO_2 price of US$11/tonne, the 0.73 plus 0.54 tonnes CO_2 represent a green premium for green urea of US$14/tonne urea, increasing its market value by around 5%. However, conventional urea production also incorporates CO_2 in the first step, namely captive CO_2 from ammonia production, which cannot be counted towards a green premium. Taking only the avoided CO_2 emissions from hydrogen production, 0.54 tonnes, leaves a green premium of US$6/tonne urea.

Investment and operating cost

For a world-class plant of 1.5 mil tonnes per year the associated CAPEX is in the order of $1.2 billion. In addition, there are non-energy-related OPEX of US$285 million per year and an average gas demand of 30 PJ per year, based on an Australian case study.[209] However, a typical plant is quoted to produce around 1,500 tonnes of urea per day,[210] i.e., around 0.55 mil tonnes per year. OPEX for urea production would increase due to the requirement for green hydrogen. Since 0.57 tonnes of ammonia are needed per tonne of urea and green ammonia costs are around US$1,070/tonne,[211] this adds another US$256 million per year to the OPEX for a 0.55 mil tonne per year plant.[212] A summary of the production costs is provided in Table 18.

Table 18. CAPEX and OPEX estimates for producing green urea in reference scenario

Cost parameter	Value 2025	Value 2050	Approach or source
OPEX	US$469/tonne	US$362/tonne	At an annual production of 0.55 million tonne green urea, feedstock-related OPEX (green ammonia) are around US$256 million per year in 2025 and US$197 million in 2050. This is based on feedstock costs for green ammonia of US$1.1/kg and US$0.8/kg in 2025 and 2050, respectively. Energy costs were assumed at zero since the process is highly exothermic. All costs are listed in the Annex.
CAPEX	US$100/tonne	US$100/tonne	CAPEX investment related to the construction of a typical urea plant of 0.55 million tonne are in the order of US$467 million. Annualised, this yields a CAPEX-related cost of around US$55 million per year and US$100/tonne urea.
Total	**US$569/tonne**	**US$462/tonne**	**Expressed in US$ (2019) per tonne of green urea.**

---

[205] Index Mundi, 2019. *Urea Commodity Prices.* https://www.indexmundi.com/commodities/?commodity=urea

[206] CRU Fertilizers, 2013. *Outlook for the Asian Ammonia & Urea Markets.* https://www.fertilizer.org/images/Library_Downloads/2013_ifa_bali_Ju_slides.pdf

[207] CarbonNext, 2017. Report on fully integrated and intensified value chain concepts for process selection http://carbonnext.eu/Deliverables/_/D2.1%20Value%20Chains%2031%2010%202017.pdf

[208] Rostrup-Nielsen & Rostrup-Nielsen, 2007. *Large-scale Hydrogen Production.* https://www.topsoe.com/sites/default/files/topsoe_large_scale_hydrogen_produc.pdf

[209] Duncan Seddon Associates, 2013. *Ammonia Production Costs and Gas Prices.* http://www.duncanseddon.com/docs/pdf/ammonia-production-costs.pdf

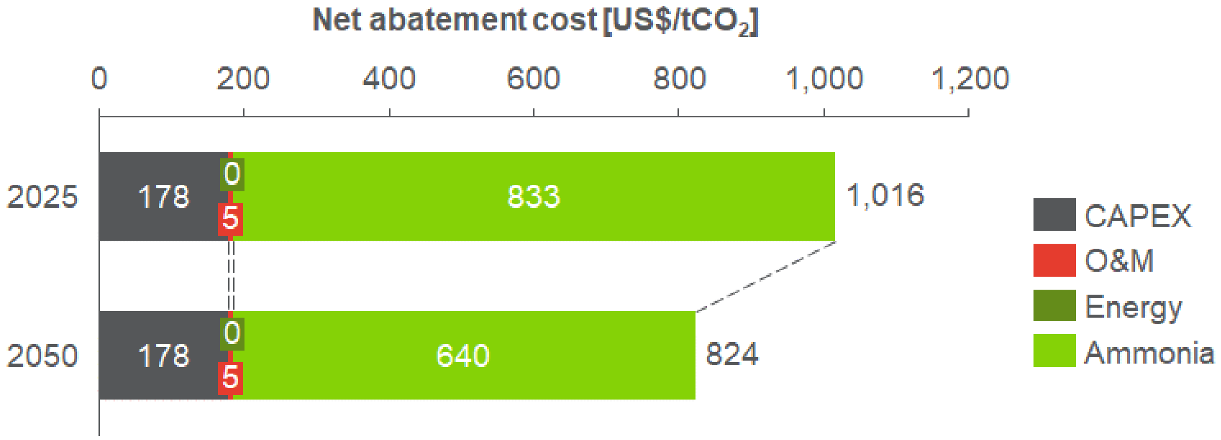
[210] European Fertilizer Manufacturers Association, 2000. *Production of Urea and Urea Ammonium Nitrate.* http://www.productstewardship.eu/fileadmin/user_upload/user_upload_prodstew/documents/Booklet_nr_5_Production_of_Urea_and_Urea_Ammonium_Nitrate.pdf

[211] U.S. Department of Energy, 2016. *Renewable Energy to Fuels Through Utilization of Energy-Dense Liquids (REFUEL).* https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=e070d735-6ab4-446a-adc9-da275c569ef4

[212] This is assuming that the original source calculates the non-energy related OPEX with an ammonia cost of ~$450/tonne.

Source: references indicated, Navigant analysis

Figure 11. Net abatement cost breakdown reference scenario – ammonium carbamate (green urea)



Source: Navigant analysis

4.3.3.3 Operational

Scalability to match emissions profile or local demand

Ammonia and urea plants generally try to utilise economies of scale. While smaller scale plants face profitability challenges, there are known examples of <100,000 tonnes per year facilities that are commercially operating, indicating that this is possible.[213]

Locations for deployment

Due to Singapore's land constraints, locations for deployment will be limited. In the Netherlands (Sluiskil), Yara opened a new urea production facility in 2018 which will produce 660,000 tonnes of urea per year.[214] Together with the granulation facility, the plants occupy an area of 100 by 500 meters.

Benefits and opportunities

By producing green urea in a typical size urea plant, Singapore could potentially sequester hundreds of kilo tonnes CO_2 per year into ammonium carbamate. Unfortunately, urea has a low level of permanency and once used, the CO_2 embedded with urea is re-emitted into the atmosphere in about a weeks' time.[215]

Barriers and required support

The synthesis of green urea relies on the production of green hydrogen. Depending on the willingness to pay for green urea, this requirement could lead to the process not being cost-competitive. Another constraint is Singapore's limited land availability to develop new large infrastructure.

---

[213] Brown, 2018. *The capital intensity of small-scale ammonia plants*. https://ammoniaindustry.com/the-capital-intensity-of-small-scale-ammonia-plants/

[214] Petrochem, 2019. *YARA*. https://www.petrochem.nl/fotograaf/yara/

[215] Brown, 2016. *Urea production is not carbon sequestration*. https://ammoniaindustry.com/urea-production-is-not-carbon-sequestration/

4.3.3.4 Circular

By-products, if any, and their potential use case

The urea process results in a stream of wastewater that contains small amounts of CO_2, ammonia and urea since urea synthesis is limited by equilibrium. However, the majority of these substances are typically recycled back into the production process or the ammonia from the wastewater is re-used as a feedstock to produce other chemicals like ammonium nitrate. Environmental legislation generally dictates how much of these substances is discharged into the environment.[216]

4.3.4 Synthetic methanol

Category	Summary
Technological	*Many pathways exist to synthesise methanol from CO_2, most of which require hydrogen, with the most mature technology at TRL7-9.*
Commercial	*Methanol is a growth market, especially in the Asia Pacific region. One of the main growth applications is in fuel blends. BAU projection of local production costs show synthetic methanol to be much more expansive than cited in wider literature, predominantly because of high electricity prices.*
Operational	*A typical synthetic methanol plant would abate 0,03% of present-day industrial CO_2 emissions. The volumes of hydrogen required for such a plant likely will need to be imported. Overcoming cost barriers is crucial for deployment at scale.*
Circular	*Oxygen is a by-product that could be reused.*

4.3.4.1 Technological

Technology outline and TRL

Methanol synthesis from CO_2 receives more attention recently because of the central role methanol can play as a chemical feedstock, fuel, and energy carrier for hydrogen. Currently, methanol is produced from syngas derived from natural gas. Syngas can also be produced from coal gasification which is the second-most common route; it is widely applied in China.[217] Biomass gasification is also being explored for syngas synthesis, but the process is not well established and still needs improvements. [218]

At present eight different pathways are being explored that utilise CO_2 to produce methanol, see Table 19.[219] Of all the available pathways, the most advanced route converts CO_2 and H_2 to a CO and H_2O mixture using a reverse water gas shift reaction. In the next step, water is removed, and more hydrogen is injected into the mixture. Subsequently methanol is synthesised using a catalyst. The reaction takes place at high temperatures and pressure.[220] The reaction requires a relatively pure stream of CO_2 and is intolerant towards major impurities which may interact with the catalyst (e.g., sulphur compounds like H_2S (should be

---

[216] Haas et al., 2016. *Snamprogetti Urea Production and Purification*. http://fse.studenttheses.ub.rug.nl/15512/1/CE_BC_2016_UreaGroupReport.pdf

[217] World Coal Association, "Development of Coal Gasification Technology in China", https://www.worldcoal.org/development-coal-gasification-technology-china

[218] Jo Howes et al., Innovation Needs Assessment for Biomass Heat, 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699669/BE2_Innovation_Needs_Final_report_Jan18.pdf

[219] The University of Sheffield, *The Next Generation of Carbon for the Process Industry, Deliverable 2.1: Report on Fully Integrated and Intensified Value Chain Concepts for Process Selection*, 2017. http://carbonnext.eu/Deliverables/_/D2.1%20Value%20Chains%2031%2010%202017.pdf

[220] Tom Berg et al., *Recovery and Utilization of Gaseous Industrial Effluents in the Chemical sector*, European Commission, 2018.

less than 0.1 ppm), reactive gases including O_2, tar and soot). [221,222] The technology is currently at TRL 7-9.[219]

Table 19. CO_2 to methanol production pathways

CCU pathway	TRL	Comment
Production of CO and water from CO_2 and H_2 mixture. In the next step water is removed and more H_2 is injected. This follows methanol synthesis using a catalyst.	7-9	The technology is currently post demonstration but is 2-3 times more expensive compared to conventional methanol production.[219]
Dry methane reforming (DMR) to produce syngas, followed by water gas shift reaction to adjust the H_2:CO ratio. This follows water removal, compression and subsequent methanol synthesis using a catalyst. DMR is a highly endothermic reaction. [225,223]	6-7	The development of right catalyst for CO_2 reforming of methane is a challenge. The challenges of carbon deposition on the catalyst and production of secondary gas-phase products have been a major hindrance towards commercialisation of the process [224, 225] Noble metals do not have carbon deposition issues, but are very expensive.
Combined steam and CO_2 reforming of methane. It follows similar steps as dry methane reforming.	5-7	The technology is at demonstration scale. Chiyoda Corporation is currently researching the technology. They refer to the process as CO_2 reforming technology.[226]
Direct catalytic hydrogenation of CO_2 to methanol. In this process formic acid is formed as an intermediate which undergoes dehydration to make methanol.	5	Research focuses on finding a catalyst which allows the reaction to proceed at temperatures that would avoid the formation of undesirable by-products.[227, 228, 219] First large-scale demonstration project has started in China.[229]
Electro-catalytic reduction of CO_2 to methanol. The process uses water electrolysis in an inverse methanol fuel cell. Electricity is used to provide the energy necessary to perform reverse combustion of methanol.	1-3	The technology is currently being tested at lab scale with efforts directed towards developing electrodes and cells that allow for direct conversion of CO_2 to methanol (without the need for separate H_2 production).[219]
High temperature electrolysis of CO_2 or steam in a solid oxide cell (SOC) to produce syngas. Syngas can then be converted to methanol using compression and ensuing catalytic synthesis.	3-5	SOC are currently operated only at lab scale (TRL 3-5). The technology is costly because of electricity and the capital cost of the electrolyser. This technology may have significant potential in the future because it offers storage of large amounts of electrical energy as chemical energy which is considerably easier. [219]
Photoelectrochemical CO_2 utilisation: using light energy instead of electrical energy for the reduction of CO_2 to methanol.	1-3	The technology is at lab scale and needs less expensive materials for electrodes and a better understanding of electrocatalysis at semiconductor interfaces. [230]

---

[221] Chemicals Technology, "George Olah CO_2 to Renewable Methanol Plant, Reykjanes", https://www.chemicals-technology.com/projects/george-olah-renewable-methanol-plant-iceland/

[222] Sacha Alberici et al., *Assessing the Potential of CO_2 Utilization in the UK*, 2017. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/665580/SISUK17099AssessingCO2_utilisationUK_ReportFinal_260517v2.pdf

[223] Recently, tri-reforming of methane has received a lot of attention. It is a synergetic combination of CO_2 reforming, steam reforming and partial oxidation of methane in a single reactor to produce syngas. The process is still in the research phase. https://www.researchgate.net/publication/282507090_Tri-reforming_of_methane_for_the_production_of_syngas_Review_on_the_process_catalysts_and_kinetic_mechanism

[224] Lei Shi et al., An introduction of CO_2 Conversion by Dry Reforming with Methane and New Route of Low-temperature Methanol Synthesis, "Accounts of Chemical Research", no. 46 (2013), https://pubs.acs.org/doi/10.1021/ar300217j

[225] Sepehr Hamzehlouia et al., Microwave Heating-Assisted Catalytic Dry Reforming of Methane to Syngas, "Scientific Reports", no. 8940 (2018), https://www.nature.com/articles/s41598-018-27381-6

[226] Chiyoda Corporation, CO_2 Reforming Process, https://www.chiyodacorp.com/en/service/gtl/co2-reforming/

[227] Sumpan Gesmanee & Wanida Koo-amornpattana, Catalytic Hydrogenation of CO_2 for Methanol Production in Fixed-bed Reactor Using Cu-Zn Supported on Gamma-Al_2O_3, "Energy Procedia", no. 138 (2017), https://doi.org/10.1016/j.egypro.2017.10.211

[228] Lisheng Guo et al., Recent Advances in Direct Catalytic Hydrogenation of Carbon dioxide to Valuable C_2+ Hydrocarbons, "Journal of Materials Chemistry A", no. 46 (2018), https://pubs.rsc.org/en/content/articlelanding/2018/ta/c8ta05377d#!divAbstract

[229] http://www.cas.cn/zkyzs/2018/07/158/yxdt/201807/t20180710_4657687.shtml

[230] Jeffery Greenblatt et al., The Technical and Energetic Challenges of Separating (Photo)Electrochemical Carbon Dioxide Reduction Products, "Joule", no. 2 (2018), https://doi.org/10.1016/j.joule.2018.01.014

CCU pathway	TRL	Comment
CO_2 reduction to methane followed by partial oxidation to methanol.	1-4	There are challenges with regards to the controlled oxidation of methane to methanol. Over-oxidation may lead to different products that impact the performance of catalysts. This lack in selectivity originates from high C–H bond energy in methane molecule compared to the low C–H bond energy of the partially oxidized products which results in further oxidation. Therefore, there is a thermodynamic limit to this process. The process also requires high energy for catalyst activation (with temperatures of around 600ºC) in addition to the energy needed in the first step for methane formation. Commercialisation of this route seems to be challenging.[219, 231]

Source: University of Sheffield[219]

Mitsui Chemicals Inc. started the world's first CO_2 to methanol pilot plant of 100 t/year in 2009, close to its Osaka production complex. The plant uses industrial by-product H_2 and utilises exhaust CO_2 from ethylene production.[219] The company reports that securing a more stable supply of H_2 is a major challenge for further development on synthetic methanol. They are exploring the option of biomass-derived hydrogen to overcome this problem, among others.

Currently, Carbon Recycling International (CRI) operates the only commercial CO_2 to methanol plant in Svartsengi, near Grindavik, Iceland, called the George Olah Renewable Methanol Plant. Production began in late 2011 and was completed in 2012. [232] The estimated investment costs were US$8 million and the plant produced 5 million litres or 4 kilo tonnes of synthetic methanol per year and is spread over a land area of 66 hectares.[221] The company has the ambition to scale up the production to 50 million litres or 40 kilo tonnes per year and the expected costs of a commercial plant of such scale is €50 million or US$57 million.[222] The CO_2 for methanol synthesis is captured from the flue gas stream of an adjacent geothermal power plant. The flue gas comes from geothermal steam emissions. The plant also supplies power for the electrolysis of water to produce hydrogen. A 5 MW electrolyser is used for electrolysis.[233] All the process energy needs are supplied by the Icelandic grid which is fully renewable. The electricity in Iceland is generated using hydro and geothermal energy.

Energy intensity per unit of product

To produce CCU-based methanol, CO_2 can be derived from a non-sustainable fossil source such as an industrial site or a power plant. The process utilises 2.75 tCO_2 per tonne of methanol and 0.25 tH_2 per tonne of methanol. The process energy needs for the CCU pathway are estimated to be 5.4 GJ per tonne of methanol. We assume that this energy is an equal split of electrical and thermal energy for compression and distillation. The process-related emissions are estimated to be 0.45 tCO_2 per tonne of methanol. If current hydrogen streams from Singapore are used for methanol production, then feedstock-related emissions would be around 2 tCO_2 per tonne of methanol. In this case, the net abatement effect for CO_2 based methanol would be around 10%, or 0.3 tCO_2 per tonne of methanol in absolute terms.

However, the synthesis of methanol can be made to be more efficient in terms of CO_2 use by recycling CO to increase methanol yield. In this scheme, less CO_2 would be needed to produce one tonne of methanol, leading to a negative abatement effect of around -80% (-1.1 tCO_2 per tonne of methanol). The negative abatement results primarily from the use of fossil-derived feedstock and the fact that less CO_2 feed is used

---

[231] Kimberly T. Dinh et al., Viewpoint on the Partial Oxidation of Methane to Methanol Using Cu- and Fe-Exchanged Zeolites, "ACS Catalysis," no. 8 (2018), 10.1021/acscatal.8b01180

[232] Carbon Recycling International, World's Largest CO_2 Methanol plant, http://www.carbonrecycling.is/george-olah

[233] DECHEMA, *Low Carbon Energy and Feedstock for the European Chemical Industry*, 2017. https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry.pdf, p62 and further

due to CO recycling. This sensitivity analysis does not account for additional energy needed for recycling CO for methanol synthesis

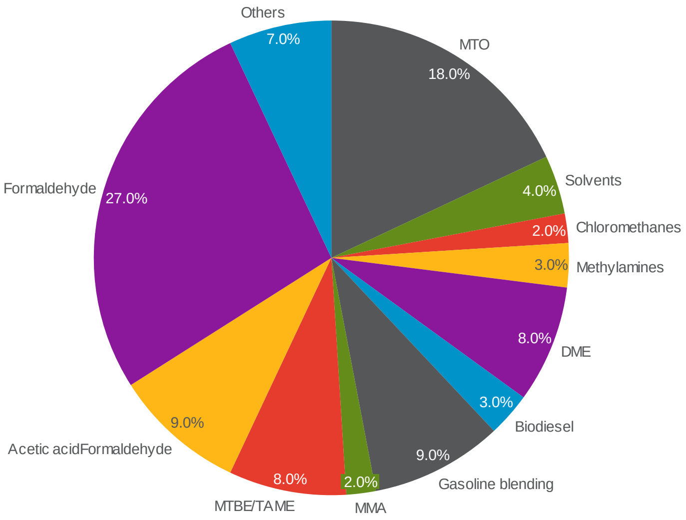
For synthetic methanol to be considered renewable, the required H_2 should be produced using renewable electricity. This energy is mainly based on electricity needs for water electrolysis for hydrogen production. If green hydrogen imports become a possibility in future, then the abatement effect (assuming that the emissions associated with green hydrogen imports are negligible) would be 2.3-0.95 tCO_2 per tonne of methanol depending on whether CO is recycled. Moreover, with synthetic methanol the conventional methanol production would be substituted that would save additional emissions of around 0.52 tCO_2.[233]

4.3.4.2 ***Commercial***

Market application

Global production capacity for methanol stands at 110 mil tonnes (138 billion litres) in 2015, whereas the global methanol demand reached 75 mil tonnes (91 billion litres) the same year.[234] This methanol is used either as a chemical feedstock or as transportation fuel. In the chemical segment, the primary use of methanol is in the production of formaldehyde (27%) followed by MTO (methanol to olefins) (18%), acetic acid (9%), and dimethyl ether (DME) (8%). Methanol is also used as a blending agent in gasoline (9%) and as a key component in transesterification process for biodiesel production (3%). In addition, methanol is used as an anti-knocking agent in the form of methyl tert-butyl ether (MTBE) (8%). Figure 12 provides an overview of methanol demand by end use in 2015.

Figure 12. Global methanol demand by end use in 2015



Source: Adapted from IHS[235]

Asia Pacific is the fastest growing market for methanol both in terms of volume and value with China being the main market in the region.[236] Almost half of the global capacity and demand of methanol comes from China. Currently there is no methanol production in Singapore. Global Industry Analysts, Inc. reports that the global methanol market is expected to reach 139 mil tonnes by 2024, which results in a CAGR of 7% between 2015 and 2024.This growth is largely driven by emerging new uses of methanol such as MTO and

---

[234] Methanol Institute, The Methanol Industry, https://www.methanol.org/the-methanol-industry/

[235] IHS, Methanol, 2016. http://www.methanol.org/wp-content/uploads/2016/07/Marc-Alvarado-Global-Methanol-February-2016-IMPCA-for-upload-to-website.pdf

[236] Mordor Intelligence, Methanol Market Size, Share, Growth, Trends and Forecast, (2019-2024), 2018. https://www.mordorintelligence.com/industry-reports/methanol-market

as a marine fuel. Applying the same growth rates towards 2030 result in annual methanol demand of 207 mil tonnes.

Status quo

At an industrial scale, methanol is predominantly produced from steam methane reforming of natural gas. The resulting syngas is converted to methanol using pressure and a catalyst.

Future growth potential to 2030

The focus of this study is on methanol use as a transportation fuel. Over 30% of the global demand for methanol is currently used for transportation. For road transport, methanol and its derivatives are recognised as important transport fuels globally. China leads the methanol use in the transport sector, methanol accounts for 7% of the country's total transport fuel consumption.[237] Various methanol blends ranging from 5% (M5) to 100% (M100) are already being used in China. High concentration methanol blends such as M85, which only include 15% gasoline, are used in special vehicles called Flexible Fuel Vehicles. On the other hand, existing EU regulations effectively restrict methanol blending to 3%.[238] In the US, ethanol is mainly used as an oxygenate fuel in gasoline,[239] so methanol demand is not substantial. Gasoline demand in Singapore is around 20 kbpd,[240] which translates into 0.9 mil tonne per year. From July 2019 onwards, methanol blending is restricted to 3%.[241] However, actual use data is not available on Singapore methanol blending rates so demand for methanol is not identified. For methanol demand in transport sector, we applied similar growth rates as are projected for the overall methanol market, i.e., 7%. This is because the fuels contribute significantly towards projected methanol demand. Using these growth rates, the methanol demand as transport fuel turns out to be 60 million tonnes by 2030.

The interest in methanol use for the shipping sector is also growing due to regulatory changes introduced by IMO under MARPOL convention. These regulations will require the sector to move from heavy fuel oil (HFO) to low sulphur alternatives such as low sulphur fuel oil (LSFO) or invest in scrubbers for onboard abatement of sulphur emissions. Alternatives that are being discussed include LNG and methanol. Methanol is sulphur free and its use in the marine sector reduces air pollution and related human health issues.

This development can also be observed locally. Singapore witnessed the announcement of Asia's first trial of methanol as a marine fuel in January 2019. Following an engine bench testing phase, this pilot would equip a harbour craft vessel with a methanol engine for a 6-month sea trial.[242]

The extent to which methanol can be deployed in the marine sector depends on its cost-competitiveness with other low sulphur fuel options (marine gas oil (MGO) and LSFO), the possibility of using existing bunkering infrastructure, and engine modification and vessel retrofit costs.[243] Renewable alternatives such as synthetic methanol are cost-prohibitive and it appears that renewable and low carbon fuels will most likely be less competitive against low sulphur fossil fuels in the shipping sector. However, IMO's recent decarbonisation target[244] of 50% CO_2 emissions reduction by 2050 compared to 2008 levels provides an

---

[237] Methanol Institute, Energy, https://www.methanol.org/energy/

[238] DOR, Methanol as a Fuel Alternative, 2017, http://www.methanol.org/wp-content/uploads/2017/06/Dor-Methanol-Economy-June-2017.pdf

[239] Alternative Fuels Data Centre, Ethanol Blends, https://afdc.energy.gov/fuels/ethanol_blends.html

[240] Index Mundi, Motor Gasoline Consumption by Country, 2019, https://www.indexmundi.com/energy/?product=gasoline&graph=consumption&display=rank

[241] The Straits Times, Singapore to introduce limits on additives in petrol and diesel from July 1, 2019: NEA, https://www.straitstimes.com/singapore/environment/singapore-to-introduce-limits-on-additives-in-petrol-and-diesel-from-july-1

[242] Safety4Sea, Singapore conducts Asia's first trial of methanol as marine fuel, January 2019, https://safety4sea.com/singapore-conducts-asias-first-trial-of-methanol-as-a-marine-fuel/

[243] Methanol Institute, Methanol as a Marine Fuel Report, 2018. http://www.methanol.org/wp-content/uploads/2018/03/FCBI-Methanol-Marine-Fuel-Report-Final-English.pdf

[244] Climate Institute, The IMO's GHG Strategy: A Step toward Meeting the 2° target?, http://climate.org/the-imos-ghg-strategy-a-step-toward-meeting-the-2-target/

opportunity for the deployment of renewable fuels. It remains unclear if this target is stringent enough to trigger the necessary shift towards the renewable fuels in the marine sector.

The direct use of methanol in the aviation sector is not considered feasible because of its low energy density.

Market value

The value of CO_2-derived methanol would either exceed or fall below the market value of conventional methanol depending upon its CO_2 abatement effect. Total CO_2 abatement from CO_2 derived methanol is estimated to be -1.1 to 0.3 tCO_2 per tonne of methanol. This abatement is derived under the assumption that production of hydrogen is done using steam methane reforming. If green hydrogen is used, then corresponding feedstock emissions would be zero. The market price for conventional methanol in Asia Pacific is US$345 per tonne.[245] The market value for CO_2-derived methanol would be negligible or absent in the case of using conventional fossil hydrogen and around US$25 per tonne of methanol or 7% in the case of using green hydrogen assuming a carbon tax of US$11/$tCO_2$ by 2030.

Investment and operating costs

The costs of producing synthetic methanol heavily depend on the electricity costs and full load hours of the electrolyser producing hydrogen feedstock. Table 20 includes a list of assumptions and the methodology to calculate total costs per tonne of methanol for 2025 and 2050. These production costs can be compared to a literature reference range of US$330-US$534 per tonne against full load hours of 7,000/year and against renewable electricity production costs of US$11 and US$34 per MWh, respectively.[233] The costs projected here are much higher. This is because this BAU projection assumes higher electricity costs to produce renewable hydrogen (at least threefold by 2025 and twofold by 2050) and includes the costs associated with transporting the hydrogen to Singapore).

Table 20. CAPEX and OPEX estimates for producing synthetic methanol in reference scenario

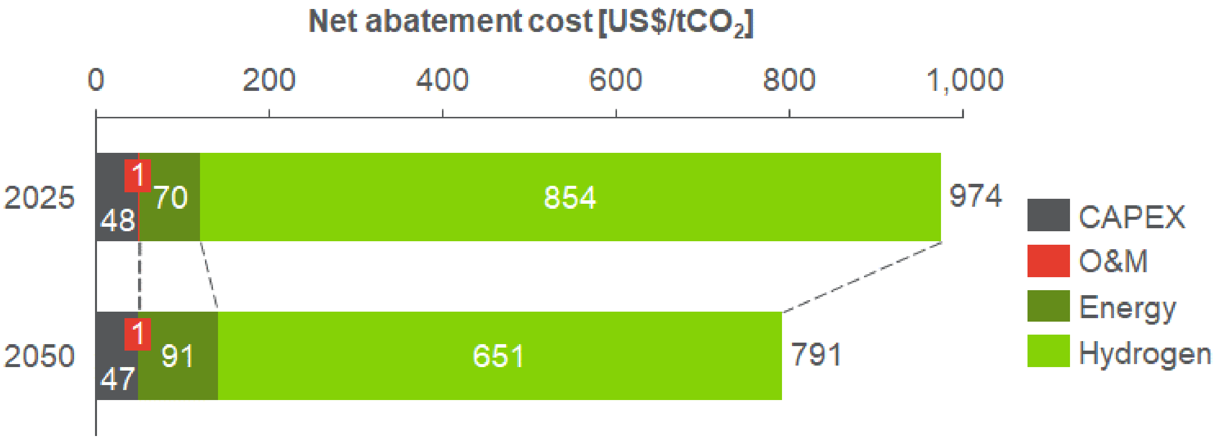
Cost parameter	Value 2025	Value 2050	Approach or source
OPEX	US$2,130/tonne	US$1,725/tonne	Calculated using 0.25 tH_2 and 5.4 GJ per tonne of synthetic methanol split evenly over thermal and electrical inputs. Hydrogen feedstock is assumed to be imported at additional cost. Cost associated with CO_2 capture and concentration are excluded.
CAPEX	US$110/tonne	US$110/tonne	Calculated based on CRI reference case of 4 kilo tonnes annual output capacity and $8 million investment. This is then scaled to tenfold capacity using the 0.67 power law.
Total	**US$2,240/tonne**	**US$1,835/tonne**	**Expressed in US$ (2019) per tonne of methanol**

Source: references indicated, Navigant analysis

---

[245] Methanex, Methanex Posts Regional Contract Methanol Prices for North America, Europe and Asia, https://www.methanex.com/our-business/pricing

Figure 13. Net abatement cost breakdown reference scenario – synthetic methanol



Source: Navigant analysis

4.3.4.3 Operational

Scalability to match emissions profile

At present, there is no local production of methanol in Singapore. But Singapore could setup synthetic methanol facilities in the future and export methanol in the region where there is huge potential for methanol both in the chemicals and fuels sector. Total methanol production capacity is 110 mil tonnes globally and there are approximately 90 production facilities. This means that a typical methanol production facility has a capacity of 1.2 mil tonnes per year on average. Such facilities could be installed in Singapore if the right resources and infrastructure are available. However, the typical size of a conventional plant may not be a good proxy for the size of a synthetic methanol plant. Another source indicates that the standard size of a commercial synthetic methanol plant would be 50 million litres or 40 kilo tonnes.[221] If we assume such a typical plant size, the amount of CO_2 required per year is about 110 kilo tonnes or 0.06% of present-day industrial emissions.

Locations for deployment

Assuming that most of the hydrogen would be imported, the facilities could be located close to hydrogen distribution infrastructure to limit distribution cost and ensure stability of supply. In addition, a relatively pure stream of CO_2 is required. Connecting to a CO_2 source should be done when quality compatibility is guaranteed. If local renewable energy potential would be sourced for synthetic methanol production, it could also be economical to establish the setup close to such a location. The amount of hydrogen and high FLH to ensure economic production would likely require a dedicated, utility scale renewable electricity generation site for use in water electrolysis and to keep distribution losses as low as reasonably practical. No further information on land area requirements was identified.

Benefits and opportunities

A key benefit of methanol use is the reduction of air pollution in urban areas when methanol is blended with gasoline or when it substitutes diesel in the form of DME.[246] Synthetic methanol can enable compliance with environmental standards set by IMO for the international marine sector and contribute to air pollution reduction.

---

[246] Methanol Institute, *Methanol Gasoline Blends: Alternative Fuel for Today's Automobiles and Cleaner Burning Octane for Today's Oil Refinery*, 2016, http://www.methanol.org/wp-content/uploads/2016/06/Blenders-Product-Bulletin-Final.pdf

Barriers and required support

Synthetic methanol currently faces challenges before it can compete with other fuels in the market. It is costly in this BAU projection and its business case depends on the steady supply of low-cost green hydrogen and an effective carbon tax or other supporting legislation mechanisms in the location of deployment. Also, there are existing/other low carbon fuels that could compete with methanol in transport subsectors, such as hydrogen and all-electric vehicles and vessels. Creating an overview of the distribution of average ride distance per transport mode and establishing the most economic low carbon alternative within that distribution may help identify in what transport applications in Singapore methanol will have merit and can help inform policymakers.

In various global markets, restrictions exist towards methanol blending which limits its demand potential. These restrictions are applied in part because methanol blending in gasoline alters the vapour pressure of gasoline. This requires refiners to adjust their processes which increases costs. Because of this, fuel suppliers may oppose changes in methanol blending limits. Engine manufacturers are usually reluctant to provide warranty for high methanol blends also. In the latest version of World-Wide Fuel Charter (WWFC5) the worldwide automobile industry has proposed a ban on methanol blending in gasoline. The use of methanol is strongly opposed due to its corrosive nature as it can severely impact the metallic components of fuel systems.[247] Prescribing minimum blend rates could help to provide stability in such specifications and offer suppliers and manufacturers with clear design inputs.

4.3.4.4 Circular

By-products and their potential use case

The George Olah CO_2 to methanol plant only produces oxygen as a by-product which is generated as a result of water electrolysis.[221] The production process does not produce any other toxic wastes or by-products.[232] The oxygen stream is very pure and can be used in medical, metallurgy, and other industrial sectors.[248] Oxygen in these volumes may prove valuable when oxyfuel combustion is used to create a relatively pure stream of CO_2 in for instance (combined heat and) power plants.

4.3.5 Synthetic kerosene

Category	Summary
Technological	*Multiple routes to produce synthetic kerosene exist and are relatively mature (TRL5-7). Increasing efficiency and scaling up are the next challenges. The abatement effect is critically dependent on the emissions factor of hydrogen as feedstock.*
Commercial	*Jet fuel is a growing market and sustainable alternatives are receiving more attention. In our BAU projection, synthetic kerosene stays more expensive compared to literature ranges, mostly due to higher assumed costs of energy and feedstock.*
Operational	*Synthetic kerosene has the potential to abate around 2 mil tonnes of CO_2. This would entail considerable infrastructure development. To achieve such scale, support is needed to overcome the cost barrier between synthetic kerosene and other fuels.*
Circular	*Like all other CCU fuels, synthetic kerosene will be used for combustion . A circular scheme would require CO_2 to be sourced directly from the air or from biogenic industrial processes such as bio-refineries.*

---

[247] European Automobile Manufacturers Association (ACEA), *ACEA Position Paper on Methanol as a Gasoline Blending Component*, 2015.

[248] OxygenWorldWide, Everyday Uses of Oxygen, https://www.oxygenworldwide.com/news/articles-and-information/597-everyday-uses-of-oxygen.html

4.3.5.1 Technological

Technology outline and TRL

There are two main routes to produce synthetic kerosene (most commonly used as a sustainable aviation fuel (SAF)); either by using biomass as feedstock or by using (electricity-based) hydrogen and industrial or atmospheric CO_2. Within these routes, CCU technologies are needed for the use of captured CO_2 which can be divided into two main categories, both using CCU-derived syngas: technologies using Fischer-Tropsch to convert syngas into linear hydrocarbon waxes that are hydrotreated and processed further into kerosene and alcohol-to-jet routes such as the LanzaTech - Virgin Atlantic process, which utilises anaerobic bacteria to produce ethanol from syngas. This ethanol is converted to kerosene by oligomerisation and dehydration/hydrogenation. Both routes are reported to have TRLs in the range of 5-7.[249,250] An alternative way to create syngas from CO_2 is by using an electrolyser directly, see Box 4.

Box 4. Syngas is an important feedstock for liquid CCU fuels. The production process sees important technological breakthroughs.

Most liquid hydrocarbons such as diesel, kerosene, or gasoline can be produced from syngas, a mixture of CO and H_2, using Fischer-Tropsch (FT) synthesis. Producing syngas from CO_2 (and water or hydrogen) can be done in many ways; using bacteria such as in the LanzaTech process, using reverse Water-Gas Shift (rWGS), or using electrolysis. Usually these routes involve multiple steps. Technological advancements in any of these technologies mostly evolve around increasing efficiency, for instance through developing better performing catalysts.

Sunfire, a Germany-based technology developer, announced their successful test run of the SUNFIRE-SYNLINK process.[251] This co-electrolysis system produces syngas from CO_2 and water in a single step, using waste heat and renewable power. Sunfire estimates an overall efficiency of up to 80% might be reached and are currently working with a FT technology provider and a direct air capture technology provider to design a two-step process to go from electricity, water, and CO_2 to liquid hydrocarbons or what they refer to as e-Crude.

Today, rather than sourcing CO_2 and converting this to syngas, the LanzaTech-Virgin Atlantic process is applied directly to effluent CO. The partnership between LanzaTech and Virgin Atlantic resulted in the production of 1,500 gallons of jet fuel in 2017.[252] This fuel was produced from waste CO from a steel mill. Carbon in this waste gas is captured via fermentation to ethanol, which is then recovered to produce kerosene.

The catalysts used for Fischer-Tropsch (FT) synthesis are typically cobalt-, iron-, and ruthenium-based. Nickel is also an active catalyst but is generally not used due to its preference to produce methane (methanation). Commercial FT processes typically use iron as the catalyst due to its lower cost and its suitability for use with lower hydrogen to carbon monoxide ratios.[253] These catalysts are reported to be sensitive to acid halides, H_2S and ammonia impurities in the feed gas. This means that these impurities should be removed or limited for any potential CO_2 feed stream.

Energy intensity per unit of product

The thermal energy intensity per unit of product is reported to be 3.5 GJ per tonne of kerosene for a reverse Water-Gas Shift (rWGS) process to produce syngas from CO_2 and the FT based process,[249] excluding feedstock production. The hydrogen demand per tonne of kerosene in this process is 0.43 tH_2, and the process utilises 3.11 tCO_2 per tonne of kerosene. For the LanzaTech process, less hydrogen is required (0.33 tH_2) but this process requires additional nutrients.[250] Due to lack of further quantification, this pathway is not considered further in this study. If we assume the present-day emission factor for industrial heat and no additional emissions for hydrogen feedstock, some 2.7 tCO_2 would be saved per tonne of kerosene,

---

[249] Dechema, Low carbon energy and feedstock for the European chemical industry, 2017

[250] CarbonNext, Report on fully integrated and intensified value chain concepts for process selection, 2017

[251] Sunfire, https://www.sunfire.de/en/products-and-technology/sunfire-hylink

[252] http://www.lanzatech.com/low-carbon-fuel-project-achieves-breakthrough-lanzatech-produces-jet-fuel-waste-gases-virgin-atlantic/, accessed February 2019

[253] Ecofys a Navigant company, Recovery and utilization of Gaseous Industrial Effluents in the chemical sector, https://ec.europa.eu/docsroom/documents/32306

equal to a net abatement effect of 87%. However, if the present-day hydrogen emissions factor for hydrogen[254] would be used, this would turn negative to -0.78 tCO_2 per tonne of kerosene or a net abatement effect of -25%.

As shown above, the abatement effect of deploying synthetic kerosene is determined primarily by the carbon footprint of energy and feedstock inputs required for the production process. Therefore, abundant renewable energy, including hydrogen, is often cited as a prerequisite for these synthetic routes to materially contribute to abatement.[255,256]

4.3.5.2 Commercial

Market application

Within the transport sector, aviation is one of the most difficult to decarbonise due to high energy density required of fuels and safety-related regulations. Because of this, direct application of electricity is not expected to happen soon for long-haul flights.[257] Using hydrogen as a fuel comes with similar challenges. Therefore, SAF are widely believed to have a large role to play in aviation in the near-term, compared to electrification and hydrogen.[258,259] The challenge to the uptake of these fuels is production cost and, in the case of bio-based fuels, availability of sustainable biomass. Today, virtually all jet fuel is produced from fossil hydrocarbons[260] and resulting GHG emissions are rising. Aviation is growing rapidly, and, with increasing consumer affluence, this is not projected to stop soon. IEA projects a growth of passenger-kilometres at a rate of 3.6% per year to 2060 globally in its reference scenario.[261] The growth in demand is partly offset by efficiency measures, rendering an overall growth in GHG emissions from fuel demand of 1.6%, which can be considered a close proxy for fuel demand.

---

[254] 8.1 tCO_2 per tonne of hydrogen, taken from Rostrup-Nielsen, Large-scale Hydrogen Production, 2007, https://www.topsoe.com/sites/default/files/topsoe_large_scale_hydrogen_produc.pdf

[255] SAM, Novel carbon capture and utilisation technologies, Scientific Opinion 4/2018

[256] Bains et al., CO2 Capture from the industry sector, Progress in Energy and Combustion Science 63 (2017) 146-172

[257] Roland Berger, Aircraft electrical propulsion, 2017

[258] T&E, Roadmap to decarbonizing European Aviation, 2018

[259] IEA ETP 2017

[260] De Jong, S., Green Horizons, PhD Thesis, 2018

[261] IEA ETP, 2017

Status quo

Fossil kerosene is an oil distillate. It is a mixture of different hydrocarbons determined by their boiling temperature (150-275 °C). After distilling crude oil into different fractions, the distribution of carbon chains is manipulated by further processing. These conversion steps can include catalytic cracking, reforming, or hydro-processing. Contaminants such as aromatics need to be removed using solvents.

Future growth potential to 2030

Future theoretical maximum potential for deploying synthetic kerosene is determined here by the current local annual production level (approximately 11 mil tonne per year)[262] and the annual growth rate described above. The economic potential (lower than the maximum potential) for SAF, and in particular, synthetic kerosene, to meet this projected demand will be largely driven by cost and regulation which is difficult to estimate. Historically, the selling prices of bio-based jet fuels are higher than fossil kerosene.[263] Synthetic kerosene costs are expected to be even higher. For example, in a recent European aviation roadmap, the projected difference in price between synthetic kerosene and conventional is up to a factor of six by 2020.[264] Biofuels are produced at costs closer to a factor of two or three difference with conventional jet fuel.[265] Based on these cost differences, it is safe to assume biofuels are first in the merit order of replacing conventional kerosene in the near term. Towards 2050, besides legislation, the cost difference between SAF and conventional fuels, limited availability of biofuels, or a combination of both will determine the share of synthetic kerosene in meeting aviation fuel demand.

Local deployment of biofuels for aviation is ongoing today. In 2017, Singapore Airlines launched biofuel powered flights with biofuels produced by AltAir Fuels from used cooking oil, supplied by SkyNRG in cooperation with North American Fuel Corporation (NAFCO), a wholly owned subsidiary for China Aviation Oil (Singapore), and EPIC Fuels.[266]

The Carbon Offsetting and Reduction Scheme for International Aviation that is introduced by International Civil Aviation Organisation is a step in the right direction for facilitating low carbon fuels in aviation. The first phase starts in 2021 and participation of countries is kept voluntary until 2026.[267] There is a possibility to purchase offsets for compliance which may reduce the impact of this scheme towards real emissions reduction for the sector. Synthetic fuels such as synthetic kerosene could play a role, but their deployment depends on their cost-competitiveness and stringency of GHG reduction targets moving forward. Biofuels provide an alternative but are limited in supply even in aggressive climate scenarios. IEA in its Beyond 2 Degree Scenario (B2DS) foresees a major role for biofuels in aviation but the extent of deployment remains constrained by sustainable biomass availability.[268] Synthetic kerosene may therefore have a role to play even under such scenarios.

Product value

For reference, synthetic kerosene costs should be compared to around US$650 per tonne of conventional jet fuel today.[269] Using World Bank's commodity forecast for oil[270] we assume here that this price will remain flat until 2030. Assuming a carbon price of US$11/t$CO_2$ by 2025 as a proxy for a green premium and

---

[262] Index Mundi, Jet fuel consumption by country, https://www.indexmundi.com/energy/?product=jet-fuel&graph=consumption&display=rank, accessed February 2018, extrapolated to 2019

[263] IRENA, Biofuels for Aviation, 2017

[264] Cerulogy, "What role is there for electrofuel technologies in European transport's low carbon future?", Transport & Environment, 2018

[265] See for instance the range 1012-2080 US$ per tonne for forest residue based fuels as cited in IRENA, Biofuels for Aviation, 2017

[266] Channel News Asia, Singapore Airlines launches biofuel-powered flights, May 2017. https://www.channelnewsasia.com/news/singapore/singapore-airlines-launches-biofuel-powered-flights-8813364, accessed February 2018

[267] ICAO, Frequently Asked Questions: What is CORSIA and How Does it Work? https://www.icao.int/environmental-protection/pages/a39_corsia_faq2.aspx

[268] International Energy Agency, Energy Technology Perspectives 2017, 2017.

[269] Iata Fuel Monitor, https://www.iata.org/publications/economics/fuel-monitor/Pages/index.aspx, accessed February 2018

[270] World Bank, Commodities Price Forecast, 2017

assuming all energy and feedstock inputs were low carbon could create a premium of around 5% to conventional fuel prices.

Investment and operating costs

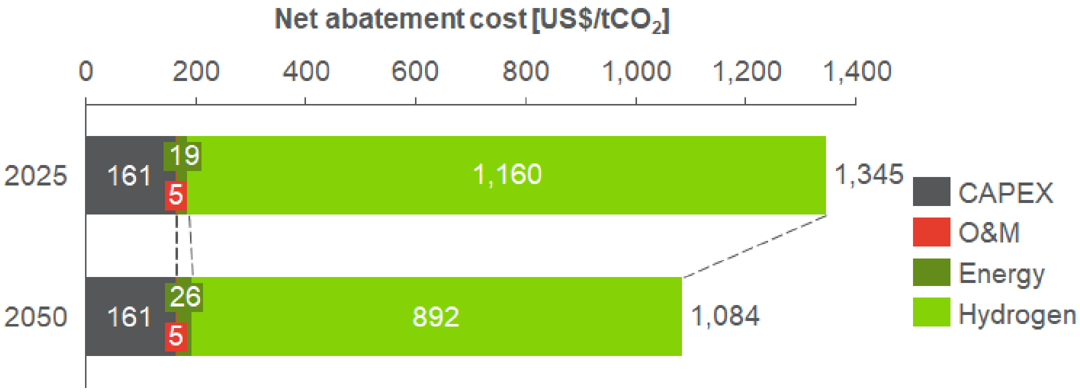
We use the following assumptions to determine total costs for producing 1 tonne of synthetic kerosene. These costs can be compared to US$3,400 per tonne in the near term and US$2,300 per tonne by 2050.[264] In this reference study, electrolysis-based hydrogen and FT synthesis was assumed at an electricity price US$4.45ct/kWh by 2050, i.e., slightly lower than what is assumed in the reference scenario. We also include the costs associated with transportation of required hydrogen to Singapore.

Table 21. CAPEX and OPEX estimates for producing synthetic kerosene in reference scenario

Cost parameter	Value 2025	Value 2050	Approach or source
OPEX	US$3,448/tonne	US$2,688/tonne	Calculated using 0.43 tH_2 and 972 kWh thermal energy per tonne of synthetic kerosene, see energy intensity section above. Electrical energy demand is negligible. Cost associated with CO_2 capture and concentration are excluded..
CAPEX	US$470/tonne	US$470/tonne	Calculated assuming FT investment cost of US$110,000/bbl[271] and assuming 55% of those investment costs are for gasification which is not needed in this pathway since syngas is produced directly from CO_2 and external hydrogen feed. This is scaled using a scaling factor of 0.67 to represent Malaysia's Bintulu GTL plant capacity of 14.7 kbpd.[272] To turn CO_2 to CO we assume rWGS.
Total	**US$4,918/tonne**	**US$3,158/tonne**	**Expressed in US$ (2019) per tonne of kerosene**

Source: references indicated, Navigant analysis

Figure 14. Net abatement cost breakdown reference scenario – synthetic kerosene



Source: Navigant analysis

4.3.5.3 Operational

Scalability

---

[271] De Klerk, A., Gas-to- liquids conversion, 2012

[272] Energy Trend Insider, Inside Shell's Bintulu GTL Plant, 2010, http://www.energytrendsinsider.com/2010/11/14/inside-shells-bintulu-gtl-plant/

Replacing today's total annual kerosene production of 11 mil tonne[273] in Singapore with solely synthetic kerosene is a sizeable operation. If FT were to be used in combination with rWGS, this would require 4.7 mil tonne of H_2 or almost 26 times the total annual hydrogen production today. If this hydrogen were to be produced using renewables, due to local land area constraints, this will likely be done abroad, preferably in regions with high solar irradiance to reduce production costs. For Singapore, a hydrogen import infrastructure through either shipping or the international pipeline will then be required that does not exist at this scale in the world today. The water required for electrolysis will have to be sourced sustainably, also if production happens abroad. This means it should not negatively impact local water supply, or source water from vulnerable areas.

The amount of CO_2 required for producing 11 mil tonnes in such a process is 34 Mt/year, or almost 90% of today's industrial emissions. Excluding combustion of the fuel and assuming carbon-free feedstock, this will result in an abatement of 32 mil tonne CO_2 per year. The difference of 2 mil tonne results from the energy required for rWGS.

If we assume a plant of a capacity similar to Shell's Bintulu plant in Malaysia[278], 296 kilo tonnes of hydrogen would be needed (twice the amount produced locally today) and would require 2.1 mil tonne CO_2. The abatement in the case of carbon-free hydrogen would be around 2 mil tonne CO_2.

Locations for deployment

The large CO_2 and hydrogen volumes required make it important for such a plant to be near hydrogen import infrastructure and connected to a CO_2 pipeline grid. An operation at this scale should source CO_2 from numerous different industrial sources to ensure relative security and stability of supply and quality. A smart connection to potential CO_2 export meant for CCS or larger CCU applications outside of Singapore could ensure additional grid balance as well as economies of scale. In the Netherlands, such a CO_2 smart grid concept to integrate and balance CCU and CCS is currently being developed.[274]

When such volumes of hydrogen become available in Singapore, and when the infrastructure exists to deal with these volumes, annual GHG emissions may change considerably. For example, dispatch power could be fuelled by hydrogen directly, lowering the CO_2 emissions from the power sector significantly. A merit curve showing the best abatement options available in the Singapore using these potential volumes of hydrogen can potentially inform the amount of hydrogen and CO_2 that would be available for producing synthetic kerosene.

Land requirement

Scaling down linearly an estimated[275] 230 hectares for an electrolyser and FT facility producing 72 kbpd to Bintulu's capacity of 14.7 kbpd as used in this analysis, we would need 47 hectares.

Benefits and opportunities

Besides abatement of GHG emissions, two other benefits are the increased energy security for countries or regions and the storage potential that production of kerosene may offer. Both benefits are relevant mostly in the scenario where the required energy is renewable and produced locally. The increasing share of intermittent renewables in the electricity grid mix may threaten grid stability and calls for energy storage solutions. Converting electricity to fuel enables storage of this electricity in times of oversupply. This can reduce costs of synthetic fuels as electricity in oversupply will be cheap.

The size of this system makes it comparable to the infrastructure required for carbon capture for export to storage capacity abroad. Both solutions could work together to achieve economies of scale. However, in our analysis, we estimate total abatement potential of one reference plant to be around 2 mil tonne CO_2 by

---

[273] Extrapolated from https://www.indexmundi.com/energy/?product=jet-fuel&graph=consumption&display=rank using growth projections IEA ETP reference scenario

[274] BLOC, CO_2 Smart Grid, https://www.bloc.nl/bloc-works/co2-smart-grid/, accessed February 2019

[275] Kalavasta, Carbon neutral aviation with current engine technology, 2018 p47-48

2025, at a total estimated investment of US$323 mil. The total abatement costs are in the order of US$1,344 per tonne CO_2 excluding the costs for capture and concentration of CO_2. This should be compared against other, perhaps more direct, abatement measures that could be taken to decarbonise Singapore's industry.

The size of the hydrogen infrastructure makes it interesting to investigate other applications for hydrogen as mentioned above. Such a multi-purpose hydrogen infrastructure could lower the costs of many more abatement solutions that require hydrogen, including many that are reported in this study.

Barriers and required support

The relative high costs that result from importing relatively expensive hydrogen and using novel kerosene synthesis technology are a key barrier to the uptake of synthetic kerosene at the scale as described here. At these costs, it will be difficult to compete against conventional fuels or even biofuels in the short term. To overcome this, carbon tax on conventional fuels may level the playing field. Other legislative measures could entail a prescribed minimal blend of SAF in the jet fuel that is bunkered in Singapore, similar to a 10% biofuels (ethanol) blend for gasoline as a 2020 target in the European Union.[276] Such legislation may help to kick-start a synthetic kerosene industry.

The alternative route to create a more balanced playing field is to lower overall costs of producing synthetic kerosene. This could be done in a direct manner by, for instance, supporting renewable energy production and decreasing the price of energy and feedstock required. Producing synthetic kerosene is not yet mature and could benefit from specific R&D support; key research areas include increasing the efficiency of electrolysers and increasing selectivity of the production process towards the desired hydrocarbon range.

Another important barrier to overcome to ensure global adoption of synthetic kerosene is certification. The produced jet fuels need to be approved/certified by international standardisation agencies to ensure they meet relevant fuel standards. Currently, five technologies are certified by ASTM to supply commercial aviation.[277] Two of these involve FT synthesis, but only fossil capacity is in place at the moment. It is worth investigating if these certifications allow for the synthetic synthesis routes as treated here.

Finally, and critical for adoption, is the question who can claim carbon reduction in a scheme that produces synthetic kerosene from locally produced CO_2. Any industrial plant will have the clear incentive to claim all CO_2 that does not leave their chimney as their own carbon reduction. On the other hand, any airline operator would like to claim the carbon emission reductions associated with flying on synthetic kerosene. Double counting of carbon reduction in both the industrial and the aviation sector should be avoided to ensure climate targets are being met, as allowing double counting results in poor climate outcomes.[278] A potential climate policy designed to support the uptake of synthetic kerosene will need to perform a balancing act: to provide an incentive for both airline and industrial plant to partake in a scheme to deploy synthetic kerosene, whilst ensuring the associated carbon reduction credit is only allocated once. To date, no government-issued guidelines exist that explicitly aim to avoid double counting specific to CCU-derived fuels. Regulation does exist that prevents double-counting of CCU projects implicitly, such as the Monitor and Reporting Regulation of the EU-ETS, that states that "the transfer of inherent or pure CO_2 shall only be allowed for the purpose of long-term geological storage".[279] The Paris Agreement calls for clear provisions to prevent double counting of emission reductions by Parties, as well as public and private authorized entities (Art. 4.13; Art. 6.2,6.5),[280] but this is a general concern, not particular to CCU-derived fuels. Agora Energiewende, a German think tank, published an overview of sustainability aspects in the production of

---

[276] European Commission, Biofuels, https://ec.europa.eu/energy/en/topics/renewable-energy/biofuels, accessed February 2019

[277] SkyNRG, Technology section, http://skynrg.com/technology-section/

[278] See Christensen and Petrenko, CO_2-Based Synthetic Fuel: Assessment of Potential European Capacity and Environmental Performance, 2017 and specifically p29 for a good discussion on the potential adverse impact of double counting.

[279] Commission Regulation (EU) No 601/2012 of 21 June 2012 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and Council.

[280] Climate Focus Client Brief on the Paris Agreement, v2.0 January 2016

synthetic fuels, where they propose only CO_2 captured from the air or sustainable biogenic sources create a closed CO_2 cycle and if this cannot be achieved, all CO_2 emissions are to be counted.[281]

4.3.5.4 Circular

By-products

The FT process is flexible in that it can result in a broad range of hydrocarbons. It can be made selective, by changing process conditions such as temperature, pressure, feedstock ratio and catalyst. A lower temperature regime can create linear waxes, from which hydrocarbons in the desired range can be produced via hydrocracking. Depending on the selectivity of hydrocracking, hydrocarbons outside of the desired range may be produced, such as diesel. This synthetic diesel could serve other transport markets, such as shipping or long-haul road transport.

One of the challenges for the rWGS is selectivity to CO. Many investigated catalysts yield methane as a dominant product.[282] In general, CO_2 hydrogenation can result in a range of hydrocarbon by-products and research into catalysis that boosts selectivity is ongoing. The methane could find other purposes in the production scheme as fuel, but this is costly and methane production should be minimised.

Potential to fit in circular production scheme

The production and consumption of synthetic kerosene in general can only fit a circular scheme if the utilised carbon is of atmospheric or biogenic origin.[283] This holds true for all CCU-derived fuels, as their use is typically for combustion. A circular scheme will need to close this cycle. Therefore, besides direct air capture, only industrial sources using biomass could serve as a long-term source for this pathway. In the interim, synthetic kerosene does contribute to leaving fossil carbon in the ground, as it displaces conventional kerosene.

4.3.6 Formaldehyde

Category	Summary
Technological	*Low maturity (TRL1-3) synthesis routes exist to produce formaldehyde from CO_2.*
Commercial	*Formaldehyde is used for a wide range of application out of which resins is the most important one. It is a growth market especially in the Asia Pacific region. Due to the low TRL, CCU-derived formaldehyde costs are difficult to estimate.*
Operational	*For this technology to materialise, R&D support is required. Research focuses on catalyst development.*
Circular	*A waste-to-value scheme is suggested relating to the removal of formaldehyde from wastewater streams.*

4.3.6.1 Technological

Technology outline and TRL

Formaldehyde can potentially be synthesised from CO_2 in at least two ways. The first route is through hydrogenation of CO_2 to create formic acid as an intermediate, followed by reduction to formaldehyde. The second route is through the use of an advanced catalysed reduction reported by French scientists,[284] where up to 74% selectivity under atmospheric conditions was achieved using a polyhydride ruthenium complex.

---

[281] Agora Verkehrswende and Agora Energiewende (2018): The Future Cost of Electricity-Based Synthetic Fuels: Conclusions Drawn by Agora Verkehrswende and Agora Energiewende.

[282] Liu et al., Hydrogenation of Carbon Dioxide to Value-Added Chemicals by Heterogeneous Catalysis and Plasma Catalysis, Catalysts 2019, 9, 275; doi:10.3390/catal9030275

[283] Styring et al., Carbon Dioxide Utilisation: Closing the Carbon Cycle, Elsevier, 2014

[284] Bontemps et al., Ruthenium-catalyzed reduction of carbon dioxide to formaldehyde, J. Am. Chem. Soc. 2014, 136, 4419−4425, DOI: dx.doi.org/10.1021/ja500708w

A final hydrolysis step to amine and formalin solutions demonstrates the concept of synthesising formaldehyde from CO_2 in the lab. Both routes are reported[285] to be at TRL 1-3.

$$2CO_2 + 2H_2 \rightleftharpoons 2CH_2O + O_2$$

As most of the research revolves around selecting and testing catalysts, it may be premature to explore how such a process would precisely dictate required purity or concentration of CO_2 feedstock gas. In general, it can be said that any process requiring one or more catalysts could be sensitive to catalyst deactivating mechanisms such as poisoning or sintering due to unwanted impurities in the feedstock gas stream.

Energy intensity per unit of product
Based on stoichiometry above, the synthesis of formaldehyde through hydrogenation of CO_2 is exothermic and would yield 6.12 GJ per tonne of formaldehyde, excluding the energy embedded in hydrogen. Based on the average difference between minimal theoretical energy and actual industrial energy demand for exothermic processed, we estimate the total energy required to be around 0.25 GJ per tonne of formaldehyde.[286] This average difference may cover energy penalties such as associated with purification, reactant recycling and compression.

4.3.6.2 Commercial

Market application
Formaldehyde is used as a chemical building block for many more complex compounds such as resins, disinfectants, plastics, alcohols, and solvents. An estimated 26-30 mil tonne of formaldehyde currently is produced globally.[287,288] Of these applications, resins account for more than half of the total market.[289] Reportedly, there is increasing attention for utilising formaldehyde as a precursor to fuels as a liquid hydrogen carrier, but this application is in its infancy.[290]

Status quo
Today, over 35% of methanol is used to produce formaldehyde, making it the most important derivative of methanol.[290] From methanol, formaldehyde can be produced by partial oxidation and dehydrogenation with air and steam in the presence of silver or by oxidation in excess air and in the presence of a modified iron, molybdenum, or vanadium oxide catalyst.

These processes differ in temperature requirements. The first route requires temperatures in the range of 600°C-720°C, depending on the specifics of the process. The second route, also known as the Formox process, requires only 250°C-400 °C. The Formox process however requires higher capital investment.[289]

Future growth potential to 2030
The market for formaldehyde is growing at an estimated 4.8% CAGR towards 2026.[287] If we extrapolate these growth figures, by 2030 the global formaldehyde market could be 43.9 mil tonnes. This growth is expected to materialise to a large extent in the Asia Pacific and resins remain the most important segment

---

[285] CarbonNext, Report on fully integrated and intensified value chain concepts for process selection, 2017

[286] See Annex A.1.1 for a detailed description on how the difference (Δ) is established

[287] Transparency Market Research, Global Formaldehyde Market is expected to reach 36.6 million tons towards the end of 2026, accessed February 2018.

[288] Bahmanpour, et al., Hydrogenation of carbon monoxide into formaldehyde in liquid media. ACS Sustainable Chemistry & Engineering, 4(7), 3970-3977, 2016,https://doi.org/10.1021/acssuschemeng.6b00837

[289] Ullmann's Encyclopedia of industrial chemistry; Formaldehyde. DOI: 10.1002/14356007.a11_619

[290] Heim, Konnert, Prechtl, Future perspectives for formaldehyde: pathways for reductive synthesis and energy storage, Green Chem. 2017, 19, 234. DOI: 10.1039/c6gc03093a

of applications for formaldehyde. Today, the formaldehyde production capacity in Asia Pacific already accounts for more than half of global production capacity.[291]

Because the CO_2-derived formaldehyde production process is still in the laboratory stage, this demand forecast for 2030 is likely to be met completely by incumbent, fossil-based production. As an alternative, CO_2-derived formaldehyde could also be produced via CCU-based methanol.

Product value

Market prices or cost of production of formaldehyde range from US$210-370 per tonne.[292,293] In the future, if a CO_2-derived formaldehyde would enter, it could benefit from a green premium. Taking CO_2 price as a proxy and assuming US$11/t$CO_2$, with a utilisation factor of 1.47 tCO_2 per tonne of product this premium could add around 6% to present-day's market value.

Investment and operating costs

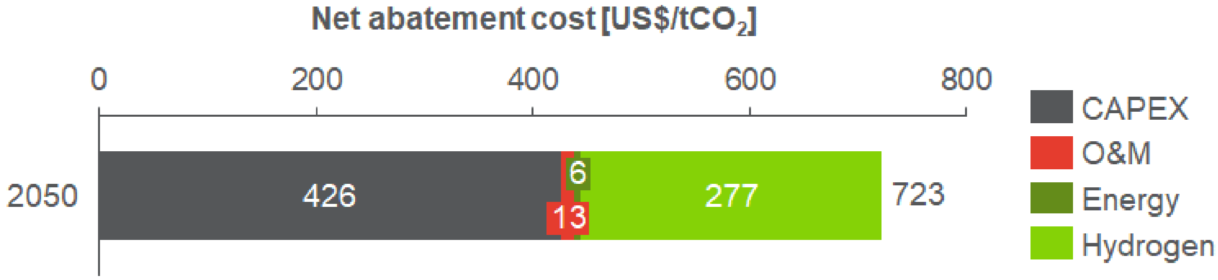
Given its low technology maturity and with limited literature available, we estimated the costs of a hypothetical industrial scale production of formaldehyde based on its projected energy and feedstock needs as well as its investment costs required based on the OPEX cost. The resulting cost estimate should be considered a high-level approximation to actual costs if the technology were to materialise.

Table 22. CAPEX and OPEX estimates for producing formaldehyde in reference scenario

Cost parameter	Value 2025	Value 2050	Approach or source
OPEX	US$554/tonne	US$430/tonne	Calculated using 0.07 tH_2 per tonne and 0.25 GJ energy per tonne, assumed to be split equally across electricity and heat. Cost associated with CO_2 capture and concentration are excluded..
CAPEX	US$796/tonne	US$618/tonne	Assumed ratio of 60/40 CAPEX/OPEX on a per tonne of product basis, based on analogue chemical plant.
Total	**US$1,350/tonne**	**US$1,048/tonne**	**Expressed in US$ (2019) per tonne of formaldehyde**

Source: references indicated, Navigant analysis

Figure 15. Net abatement cost breakdown reference scenario – formaldehyde



Source: Navigant analysis

4.3.6.3 Operational

Scalability to match emissions profile

---

[291] Merchant Research & Consulting ltd, Formaldehyde: 2019 World Market Outlook and Forecast up to 2028, 2019

[292] CEIC, China market price organic chemical material: formaldehyde, September 2018

[293] Dynea, operational cost, https://www.dynea.com/technology-sales/silver-catalysed-formaldehyde-plant/operational-cost/, accessed February 2019

A typical formaldehyde production plant today has a capacity of 100 kilo tonnes per year.**[294]** In the scenario that such a capacity plant is built that produces CO_2-derived formaldehyde, this would consume 147 kilo tonnes of CO_2 per year, or some 0.4% of today's industrial CO_2 emissions in Singapore. This process would need 7 kilo tonnes of hydrogen per year.

Locations for deployment

The typical plant capacity results in volumes for CO_2 and hydrogen required that may warrant a pipeline or connection to a larger H_2 grid. As such, it seems logical to place such a plant at or near an industrial cluster where these gases are or will become available.

No information on land area requirements is available due to the low maturity of the technology.

Benefits and opportunities

With a reported 8.4 wt% H_2 in aqueous media,[290] formaldehyde is cited to exhibit potential as a hydrogen storage medium or perhaps as a battery. The energy required for one cycle of charging and discharging as well as the long-term stability of this system is considered favourable against other hydrogen carriers often suggested in similar storage roles, such as methanol. In such a function, formaldehyde could function as a hydrogen battery in for example hydrogen fuel cell technology. Further research is needed for these applications.

Barriers and required support

The CCU process to produce formaldehyde is in its infancy. Therefore, government support at this stage could focus on propelling R&D in maturing both the CCU pathway and relevant applications such as a storage mechanism in hydrogen fuel cell. Current research is focussed on developing catalysts that support borylation of CO_2 to increase reaction efficiencies at low temperatures. To illustrate this, in 2016, scientist proved[290,295] a similar concept, as the French scientist Bontemps et al. showed using copper and cobalt phosphine complexes are active for the borylation of CO_2. This process showed a range of selectivity of bisboryl acetal and methoxy borane out of which formaldehyde can be synthesised.

4.3.6.4 Circular

By-products

One of the challenges for this pathway is the selectivity of the hydrogenation step, similar to the rWGS as required for synthetic kerosene. Many investigated catalysts yield methane as a dominant product.[296] In general, CO_2 hydrogenation can result in a range of hydrocarbon by-products and research into catalysis that boosts selectivity is ongoing.

Potential to fit in circular production scheme

Formaldehyde is a common contaminant found in wastewater. Formaldehyde removal from wastewater is discussed in a recent paper[290] as it has a potential co-benefit of yielding hydrogen. Catalytic decomposition of formaldehyde in wastewater yields an 85% pure stream of hydrogen while removing formaldehyde to levels as low as 10-40 ppm. This waste-to-value application thus removes formaldehyde and produces, besides hydrogen, (high purity) CO_2—a pathway in the opposite direction as discussed in our study. A circular scheme can be envisaged where this hydrogen and CO_2 are used to again yield formaldehyde, thereby closing the production loop. Research is needed to verify that the scales and volumes of wastewater removal products available in Singapore and formaldehyde production could match.

---

[294] Hydrocarbon processing, Dynea announces successful commissioning & start-up of new formaldehyde plant, 2018, accessed February 2019

[295] Aloisi et al., Dalton Transaction 37, 2016. DOI: 10.1039/C6DT02135B

[296] Liu et al., Hydrogenation of Carbon Dioxide to Value-Added Chemicals by Heterogeneous Catalysis and Plasma Catalysis, Catalysts 2019, 9, 275; doi:10.3390/catal9030275

4.3.7 Acetic acid

Category	Summary
Technological	*Low maturity (TRL2-4) synthesis routes exist to produce acetic acid from CO_2.*
Commercial	*Acetic acid is used for a wide range of application out of which adhesives and textiles are sizeable. Due to the low TRL, CCU-derived acetic acid costs are difficult to estimate.*
Operational	*For this technology to materialise, R&D support is requiring at this stage. Research focuses on developing and selecting genetically modified microorganisms that boost acetic acid yield.*
Circular	*Recycling schemes are developed to extract and recycle acetic acid from dilute wastewater streams and LCD displays.*

4.3.7.1 Technological

Technology outline

Gas fermentation of CO_2 and H_2 by anaerobic digestion produces acetic acid. The metabolic process uses acetogenic bacteria (acetogenic bacterium Clostridium sp.) in the absence of air (oxygen) to produce mainly acetate or acetic acid from CO_2 and H_2.[297] Acetogens are characterised by the Wood–Ljungdahl pathway of CO_2 reduction with acetyl-CoA synthase as the key enzyme and is considered the worlds first biochemical pathway. Before the fermentation process, the gas mixture is first compressed and is the sole source of energy and carbon in the fermentation process.[298]

$$2\,CO_2 + 3H_2 \rightleftharpoons CH_3COOH + 2\,OH$$

Another pathway that is being explored is the synthesis of acetic acid from methane and CO_2.[299,300] No pilot plants exist and the technology is still at lab scale where appropriate catalyst development for high acetic acid selectivity remains a challenge.[297]

Current technology status

LanzaTech is currently developing this technology together with Malaysian company Petronas. The consortium had indicated plans back in 2012 to start a demo plant in Malaysia if pilot work proved successful.[301] LanzaTech is also looking into industrial conversion of acetic acid to lipids which can then be converted to liquid fuels such as diesel and gasoline. The second step of industrial conversion of acetic acid to lipids does not take place in the same bioreactor. No further updates could be identified on the progress with regards to the installation of a demonstration facility. The technology is reported to be at TRL 2–4.[297]

Energy intensity per unit of product

The CCU process utilises 1.47 tCO_2 and 0.1 tH_2 per tonne of acetic acid. Some process energy is needed for gas compression before it is fed into a reactor for fermentation. The data on energy needs could not be identified from publicly available sources, so we estimated the process energy needs based on Gibbs free

---

[297] The University of Sheffield, The Next Generation of Carbon for the Process Industry, Deliverable 2.1: Report on Fully Integrated and Intensified Value Chain Concepts for Process Selection, 2017. http://carbonnext.eu/Deliverables/_/D2.1%20Value%20Chains%2031%2010%202017.pdf

[298] LanzaTech, WTE Workshop Presentation, 2017, ://www.energy.gov/sites/prod/files/2017/07/f35/BETO_2017WTE-Workshop_SeanSimpson-LanzaTech.pdf

[299] George W. Roberts & James J. Spivey, Synthesis of Acetic Acid via Carboxylation of Methane, 1998, https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.highlight/abstract/358

[300] Wei Huang et al., Direct Synthesis of Acetic Acid from CH4 and CO2 in the Presence of O2 over a V2O5-PdCl2/Al2O3 Catalyst, "Journal of Natural Gas Chemistry", no. 13 (2004), http://www.jenergychem.org/fileup/PDF/2004-02-0113.pdf

[301] Green Car Congress, LanzaTech Exploring Lipids Production as Part of its CO_2 to Acetic Acid Plans; Pathways to Renewable Fuels, 2012, https://www.greencarcongress.com/2012/10/lanzatech-20121017.html

energy of the reaction. The Gibbs free energy of the reaction is -84 kJ/mol or -1.35 GJ per tonne. For an exothermic reaction the difference between theoretical minimum and energy demand of the process is around 6.4 GJ/tonne.[302] The real process energy would be 5 GJ/tonne. Assuming that compression takes place using electricity, the process emissions would be 0.542 tCO_2 per tonne of acetic acid. With existing hydrogen production in Singapore, feedstock production would emit 0.8 tCO_2 per tonne of acetic acid. The CCU pathway would, therefore, abate 0.128 tCO_2 per tonne of acetic acid. This represents a net abatement effect of 8%.

The net abatement effect would increase to 63%, or 0.928 tCO_2 per tonne of acetic acid, if green hydrogen is used for the process, where we assume an emissions factor of zero. This is more relevant under a scenario when there is a possibility to import significant volumes of green hydrogen into Singapore.

4.3.7.2 Commercial

Market application

Acetic acid is a key building block in the production of major chemicals such as vinyl acetate monomer (VAM), purified terephthalic acid (PTA), acetic anhydride and acetate esters. These chemicals are further used in different sectors such as textiles, adhesives, and pesticides. VAM had the highest consumption of acetic acid in 2017[303] and is projected to be the leading growth market for acetic acid till 2022.[304]

VAM is used to make resins for adhesives, paints, and coatings. It has applications in construction, packaging, and the furniture industry. The product is also applied in photovoltaic modules which further augment the growth of acetic acid.[305] PTA supplies polyester coatings which are used in automotive, appliances, and metal works. PTA is also used in textile industry either alone or in blends with natural and other synthetic fibres. Acetate esters are mainly used as industrial solvents whereas acetic anhydride is used to make cellulose acetate used for cigarette filters and textile applications. It is also used as a raw material for aspirin and other pharmaceuticals.[304,305]

Status quo

Today, acetic acid is produced from the carbonylation of methanol and is responsible for 9% of global methanol demand in 2015.[306] There are two related processes for carbonylation of methanol. The first is the Monsanto process and the second the Cativa process. The Monsanto process uses a rhodium catalyst whereas the Cativa process uses iridium catalyst. The Monsanto process was the main process until 1996 when BP Chemicals introduced the Cativa process. The Cativa process is proven to be more efficient, requires less amounts of water, and generates very low impurity content. This also means that the downstream purification step is less expensive. The Cativa process has largely replaced the Monsanto process globally.[307] Bio-based acetic acid is also introduced as an alternative to petroleum-based products. This bio-based acetic acid is produced by the fermentation of biomass feedstock such as agricultural crops

---

[302] See Annex A.1.1 for a detailed description on how the difference (Δ) is established.

[303] Mordorintelligence, Acetic Acid Market - Segmented by Application, End-user Industry, and Geography - Growth, Trends, and Forecast (2019 - 2024), 2018, https://www.mordorintelligence.com/industry-reports/global-acetic-acid-market-industry

[304] Business Wire, Global Acetic Acid Market 2018-2022| Increasing Demand for Methanol to Drive Growth, 2018, https://www.businesswire.com/news/home/20181003005834/en/Global-Acetic-Acid-Market-2018-2022-Increasing-Demand

[305] MarketWatch, Acetic Acid Market Analysis by Major Regions, Consumption, Production, Suppliers, Key Players 2024, 2018, https://www.marketwatch.com/press-release/acetic-acid-market-analysis-by-major-regions-consumption-production-suppliers-key-players-2024-2018-12-11

[306] IHS, Methanol, 2016. http://www.methanol.org/wp-content/uploads/2016/07/Marc-Alvarado-Global-Methanol-February-2016-IMPCA-for-upload-to-website.pdf

[307] Guicho Valves, Acetic acid – Manufacturing process for Acetic acid, http://guichon-valves.com/faqs/acetic-acid-manufacturing-process-for-acetic-acid/

and lignocellulosic materials.[308] The manufacturers are actively investing to develop bio-based pathways.[309] It is anticipated that bio-based pathways would play a considerable role before CCU pathways can penetrate the market.

Future growth potential to 2030

Global demand of acetic acid is approximately 15 mil tonnes.[310] Acetic acid is projected to grow at a CAGR of 4% till 2023.[303] Extrapolating to 2030 gives global acetic acid demand of 23 million tonnes. In Singapore a production plant from Celanese has a capacity of around 0.6 million tonnes, roughly 4% of the global demand.[311,312] Assuming that production follows demand, the production in Singapore could reach 0.9 million tonnes by 2030. Asia Pacific is anticipated to be the main market for growth due to its rapid expansion in the textile sector.[310]

Product value

The market price for acetic acid could range between US$600–US$800.[313] Since CO_2-derived acetic acid abates emissions its market value would be higher. The premium for carbon abatement (using green hydrogen) could be US$14/t$CO_2$, assuming a carbon tax of US$11/t$CO_2$ by 2030. The product value of CO_2-derived acetic acid would increase by around 1.5%.

Investment and operating costs

Having a low technology maturity, there are no cost assumptions identified from LanzaTech directly or in wider literature, thus, the study focusses on estimated energy and feedstock needs to estimate operating costs and scale the resulting relative costs to estimate investment costs. The resulting cost estimate should be considered a high-level approximation to actual costs for a high-grade version of acetic acid if the technology were to materialise.

Table 23. CAPEX and OPEX estimates for producing acetic acid in reference scenario

Cost parameter	Value 2025	Value 2050	Approach or source
OPEX	US$1,053/tonne	US$927/tonne	Calculated using 0.1 tH_2 per tonne and 5 GJ electricity per tonne as explained under Energy intensity per unit of product. Cost associated with CO_2 capture and concentration are excluded..
CAPEX	US$1,511/tonne	US$1,331/tonne	Assumed ratio of 60/40 CAPEX/OPEX on a per tonne of product basis, based on analogue chemical plant abatement costs.
Total	**US$2,564/tonne**	**US$2,259/tonne**	**Expressed in US$ (2019) per tonne of acetic acid**

Source: references indicated, Navigant analysis

Figure 16. Net abatement cost breakdown reference scenario – acetic acid

---

[308] Fact.Mr, Bio Based Acetic Acid Market Forecast, Trend Analysis & Competition Tracking - Global Review 2018 to 2028, 2018, https://www.factmr.com/report/1189/bio-based-acetic-acid-market

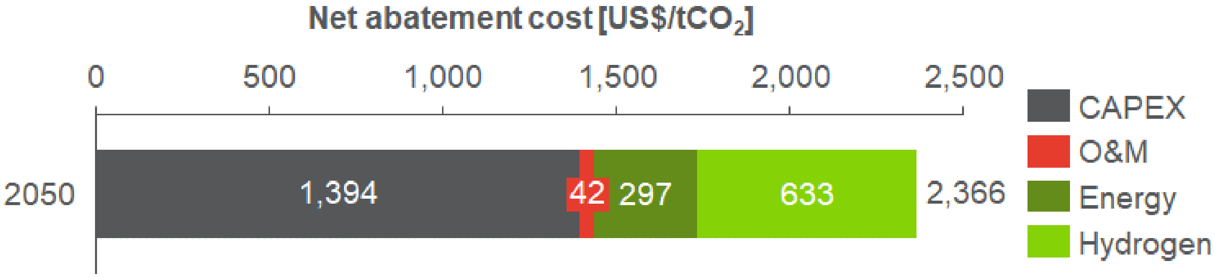
[309] Global Market Insights, Bio-based Acetic acid Market to Witness Remarkable Gains Over 2017-2024, U.S. to Drive the Regional Industry Trends, 2017, https://gminsights.wordpress.com/2017/07/14/acetic-acid-market/

[310] PRNewswire, Global Acetic Acid Market - Segmented by Application, and Geography - Trends and Forecasts (2015-2020) - Report linker Review, 2015, https://www.prnewswire.com/news-releases/global-acetic-acid-market---segmented-by-application-and-geography---trends-and-forecasts-2015-2020---reportlinker-review-300145381.html

[311] ICIS, Plant status: Celanese's Singapore acetic acid plant shut unexpectedly, 2018, https://www.icis.com/explore/resources/news/2018/12/03/10289551/plant-status-celanese-s-singapore-acetic-acid-plant-shut-unexpectedly/

[312] Chemicals Technology, Celanese Integrated Acetyls Complex, Jurong Island, https://www.chemicals-technology.com/projects/celanese/

[313] ICIS, OUTLOOK '19: US Acetic Acid Headed Toward Record New Year, 2019, https://www.icis.com/explore/resources/news/2019/01/08/10301264/outlook-19-us-acetic-acid-headed-toward-record-new-year/



Source: Navigant analysis

4.3.7.3 Operational

Scalability to match emissions profile

Currently, local production of acetic acid is around 0.6 mil tonnes. If CO_2-derived acetic acid fully substitutes the current production it could sequester around 0.88 mil tonnes of CO_2, or around 2.3% of today's industrial CO_2 emissions in Singapore . Around 60 kilo tonnes of hydrogen would be needed which accounts for more than 40% of Singapore's existing production volumes. The availability of enough volumes of hydrogen could be a challenge. Import options for green hydrogen should be explored in the future to benefit from scaled deployment of the CCU pathway.

In general, it can be said that any process requiring one or more catalysts could be sensitive to catalyst deactivating mechanisms such as poisoning or sintering due to unwanted impurities in the feedstock gas stream. Hence, it is likely the technology to synthesise acetic acid from CO_2 will need high purity CO_2.

Locations for deployment

The typical plant capacity results in volumes for CO_2 and hydrogen that may warrant a pipeline or connection to a larger H_2 grid. As such, it seems logical to place such a plant at or near an industrial cluster where these gases are or will become available.

No information on land area requirements is available due to the low maturity of the technology.

Benefits and opportunities

Acetate/acetic acid is usually the main metabolic product of acetogenic bacteria; however, a large range of over 30 different products can be selected, from alcohols to fatty acids, although with a varying degree of selectivity. Ethanol and 2,3-butanediol have the highest selectivity, but even fatty acid precursors to jet fuel with lower selectivity are being explored.[297] This flexibility potentially creates opportunity to respond and scale to price fluctuations in petrochemical markets. In theory, the reactor can be used at varying operating conditions, feedstock and microbes can be tweaked to be more selective towards certain outputs.

Barriers and required support

The technology is in early stages of development and would need further research. The development and selection of the right genetically engineered microorganism for conversion to the desired end-product is the focus of most research.[297] The separation of acetic acid from water via conventional distillation is difficult because of the proximity of boiling points. The separation requires advanced distillation methods that add to the cost.[314] A study finds that the separation and purification of acetic acid from the fermentation broth can account for over 30% of the processing costs for further downstream processing to make high-value

---

[314] Federico Galli et al., Simulation of the Water-Acetic Acid Separation via Distillation
Using Different Entrainers: an Economic Comparison, "CHEMICAL ENGINEERING TRANSACTIONS", no. 57 (2017), https://doi.org/10.3303/CET1757194

products.[315] Therefore, the costs of separation could pose a hindrance towards commercialisation and scaled production if no regulatory or policy incentives are introduced. More sophisticated separation and purification techniques are currently being explored. Besides this, research focuses on improving fermentation conditions and developing suitable bioreactors, partly to reduce land area requirements.[316] The market for acetic acid is likely to continue to expand in the region and there is considerable production capacity in Singapore already. Therefore, the industry may explore the potential low carbon alternative routes for acetic acid synthesis.

4.3.7.4 Circular

By-products

Although acetate/acetic acid is the main metabolic product of acetogenic bacteria, other hydrocarbon by-products can be formed. Genetically engineering acetogenic species that can efficiently ferment CO_2/H_2 to valuable desired products remains a challenge in this area. The fermentation process also generates sludge containing cell mass from enzymes and water that need to be further processed.

Potential to fit in circular production scheme

Dilute acetic acid wastewater streams are produced in large quantities by synthetic organic chemical industries.[317] Technologies are being developed to recover and concentrate this acid, and to ultimately repurpose the product. Acetic acid as applied in LCD display panels can also be removed and recycled using sub/supercritical water treatments.[318]

4.3.8 Propylene glycol

Category	Summary
Technological	*Low maturity (TRL 2) as only the underlying technology concept has been conceived. No evidence found that the technology has been demonstrated at lab scale.*
Commercial	*Propylene glycol is used for a wide range of applications, where resins are an important final product in terms of volumes. Due to the low TRL, CCU-derived propylene glycol costs are difficult to estimate.*
Operational	*For this technology to materialise, R&D support is required at this stage.*
Circular	*Oxygen is produced as a by-product, at high concentration, for which numerous (niche) applications exist.*

4.3.8.1 Technological

Technology outline

A pathway to produce propylene glycol exists which uses CO_2 as a feedstock.[319] The electrochemical reduction of CO_2 results in propylene glycol production. The reaction equation is as follows:

$$3\,CO_2 + 4\,H_2 \rightleftharpoons HO(CH_2)_3OH + 2O_2$$

---

[315] Nanditha Murali et al., Biochemical Production and Separation of Carboxylic Acids for Biorefinery Applications, "Fermentation", no. 3 (2017), https://doi.org/10.3390/fermentation3020022

[316] CO2Chem, Roadmap for the future of CO2Chem and CCU, 2012

[317] EPA. In-process recycling of acetic Acid from dilute aqueous waste streams, 1994

[318] Wang et al., Recycling acetic acid from polarizing film of waste liquid crystal display panels by sub/supercritical water treatments, Environ Sci Technol. (2015) doi: 10.1021/acs.est.5b00104.

[319] The University of Sheffield, The Next Generation of Carbon for the Process Industry, Deliverable 2.1: Report on Fully Integrated and Intensified Value Chain Concepts for Process Selection, 2017. http://carbonnext.eu/Deliverables/_/D2.1%20Value%20Chains%2031%2010%202017.pdf

There is literature available on the electrochemical reduction of CO_2 to ethylene glycol production;[320] however, sources that cover CO_2 based propylene glycol production were not identified.

Current technology status

The technology is reported to be at TRL 3–7.[219] However, the wide range in TRL is not justified. The technology is still in the research phase and from the literature, no evidence could be identified that shows demonstration of the concept. In theory it is possible to produce propylene glycol through electrochemical reduction, so we have assumed a TRL of 2.[321]

Energy intensity per unit of product

Propylene glycol production requires 1.74 tonne CO_2 and 0.11 tonne H_2 per tonne of product. The process energy needs could not be identified from literature and were therefore estimated using Gibbs free energy as a proxy for process cost. The Gibbs free energy of the reaction is calculated to be -880 kJ/mol or -11.6 GJ per tonne of propylene glycol. The energy consumption of a real-world exothermal process is an estimated 6.4 GJ per tonne higher,[322] indicating that the process would need 5.2 GJ per tonne of propylene glycol. Assuming this is electrical energy since it is an electrochemical reduction process, we arrive at process emissions of 0.55 tonne CO_2 for 2025 when grid electricity is used. With assumed hydrogen emission factor of 8.1 tCO_2 per tonne H_2 in Singapore, the net abatement effect of CO_2 based propylene glycol would be 0.29 tCO_2 per tonne of propylene glycol. This represents the case where fossil fuel-derived hydrogen is used instead of renewable hydrogen for the CCU pathway.

In the event renewable hydrogen would be imported into Singapore in the future and with the assumption that the emissions from this hydrogen are negligible, the net abatement effect of the technology would increase to 1.19 tCO_2 per tonne of propylene glycol.

4.3.8.2 Commercial

Market application

Propylene glycol also known as propane-1,2-diol is available in two grades, (i) industrial grade and (ii) pharmaceutical grade. Industrial grade propylene glycol is used to make unsaturated polyester resins (which is the largest downstream application in terms of volumes),[323] coolants, heat transfer liquids, de-icers for aircraft, paint and coatings, grinding aids in cement industry, and intermediate for other chemical products like ethers, surfactants, and plasticisers.[323,324] Pharmaceutical grade propylene glycol finds its applications in food and beverages, pharmaceuticals, cosmetics, and personal care. In the food and beverages industry it is used as a solvent, flavour enhancer, anti-freeze agent, and as a stabiliser in food products. It is also used as a solvent, emulsifier, and stabiliser in pharmaceutical applications.[323]

Status quo

Propylene glycol is conventionally produced from propylene oxide via hydration. The hydration of propylene oxide takes place either by catalytic or non-catalytic process. The catalytic process takes place at relatively

---

[320] Toshiba has setup a technology that uses photo-electrochemical processing for converting CO_2 to ethylene glycol. The company has developed a molecular catalyst which is an imidazolium salt that is absorbed on to a metal surface that suppresses hydrogen production and enables direct conversion of CO_2 in an aqueous solution to ethylene glycol.

https://phys.org/news/2016-10-toshiba-photo-electrochemical-efficiency-co2-ethylene.html

[321] The TRL of 3–7 is reported by (The University of Sheffield, 2017) which we used for developing our long list. The reference implicitly assumes similar technological maturity as it does for ethylene glycol. However, upon further evaluation as part of our deep dive we come up short in finding sufficient evidence to justify the indicated TRL range. No case study was found which shows that the technology is being tested even at lab scale, so we associate a TRL of 2 as per the standard TRL descriptions provided in Annex A.1.2.

[322] See Annex A.1.1 for a detailed description on how the difference (Δ) is established.

[323] Market Research Future, Propylene Glycol Market Research Report – Forecast to 2023, 2019, https://www.marketresearchfuture.com/reports/propylene-glycol-market-5957

[324] Shell Chemicals, Datasheet MPG-Industrial PO & Derivatives, 2016, https://www.shell.com/business-customers/chemicals/our-products/propylene-glycols.html

low temperatures whereas the non-catalytic process takes place at 200 °C and 12 bar pressure. The amount of water is controlled to facilitate propylene glycol production. The reaction mixture also includes dipropylene glycol, tripropylene glycol, and small amounts of polypropylene glycols. The water from the reaction mixture is removed and different glycols are separated using the distillation process.

Bio-based propylene glycol is produced by the hydrogenolysis of glycerine. Glycerine, which is a by-product of biodiesel production, can also be used for propylene glycol synthesis.[325] Archer Daniels Midland has a bio-based propylene glycol facility that started its operations in 2011.[326] The plant produces 100 kilo tonnes of propylene glycol from biomass like soy bean and canola. These sources are first used to make biodiesel which produces glycerine as a by-product. The glycerine is then converted into industrial grade propylene glycol. The company also manufactures propylene glycol from sorbitol which is a corn-derived sugar alcohol.[327] Michigan State University developed a process which converts a sugar alcohol to propylene glycol. The process claims to reduce the quantities of undesirable products such as lactic acid, ethylene glycol, etc.[328] A French company, Metabolic Explorer, has a patent for propylene glycol production. The process produces propylene glycol via fermentation. With these bio-based routes close to deployment, it is worth investigating if the performance of a CO_2-derived product remains attractive in terms of GHG emissions against other environmental metrics.

Future growth potential to 2030

The largest production capacity (more than 50%) is centred in Asia Pacific followed by North America and Europe.[329] Towards 2030 most of the new plants will be mainly targeted within the Asia Pacific region. Asia Pacific is also projected to the fastest growing region in terms of demand followed by North America. The demand in Europe, Middle East, and Latin America is projected to show moderate growth in the coming years.[323] Currently, the global production of propylene glycol is around 2.9 million tonnes[330] and is expected to grow at a CAGR of 4.6%[331] by 2025. Assuming similar growth rates towards 2030 we arrive at propylene glycol demand of 4.7 million tonnes.

The CCU pathway for the production of propylene glycol is in its infancy and in the coming years it is not expected to considerably penetrate the market. The bio-based routes are more advanced and are already substituting the incumbent product. There is also growing consumer preference for bio-based products which is in part driven by regulations that restrict the use of petroleum derived products especially in the developed regions.[323] The bio-based propylene glycol market is project is to grow at a CAGR of around 8% towards 2021.[332]

---

[325] Kumar Chatterjee et al., Glycerol to Propylene Glycol, 2011. https://repository.upenn.edu/cgi/viewcontent.cgi?article=1025&context=cbe_sdr

[326] Archer Daniels Midland (ADM), ADM Announces Industry-First Bio-based Propylene Glycol USP, 2011, https://www.adm.com/news/news-releases/adm-announces-industry-first-biobased-propylene-glycol-usp

[327] Archer Daniels Midland (ADM, Manufacturing Facility, https://www.adm.com/products-services/industrials/propylene-glycol/manufacturing-facility

[328] Michigan State University (MSU) Technologies, High Yield Glycerol to Propylene Glycol Conversion Process, http://msut.technologypublisher.com/technology/5720

[329] Market Research & Consulting ltd., Propylene Glycol (PG): 2019 World Market Outlook and Forecast up to 2028, 2019, https://mcgroup.co.uk/researches/propylene-glycol-pg

[330] PRWeb, Global PG Production to Go Beyond 2.56 Mln Tonnes in 2017, According to In-demand Report by Merchant Research & Consulting, 2014, https://www.prweb.com/releases/2014/03/prweb11679702.htm

[331] PRNewswire, Global Glycols Market Analysis By Product, By Application, By Region, And Segment Forecasts, 2014 - 2025 - Research and Markets, 2017, https://www.prnewswire.com/news-releases/global-glycols-market-analysis-by-product-by-application-by-region-and-segment-forecasts-2014---2025---research-and-markets-300453307.html

[332] PRNewswire, Global Bio-based Propylene Glycol Market 2017-2021 - Market to Grow at a CAGR of 8.27%, 2017, https://www.prnewswire.com/news-releases/global-bio-based-propylene-glycol-market-2017-2021---market-to-grow-at-a-cagr-of-827-300523865.html

Product value

Global market value for propylene glycol stands at US$4.14 billion.[333] The current market price per tonne is around US$1,400.[334] The product value of propylene glycol via CCU route could be higher due to its enhanced environmental performance. If we use a future carbon tax as a proxy for this premium value, by 2030, the product value for CO_2 based propylene glycol (utilising green hydrogen) would be 1.4% higher than the fossil-derived product, considering a carbon tax of US$11/t CO_2.

Investment and operating costs

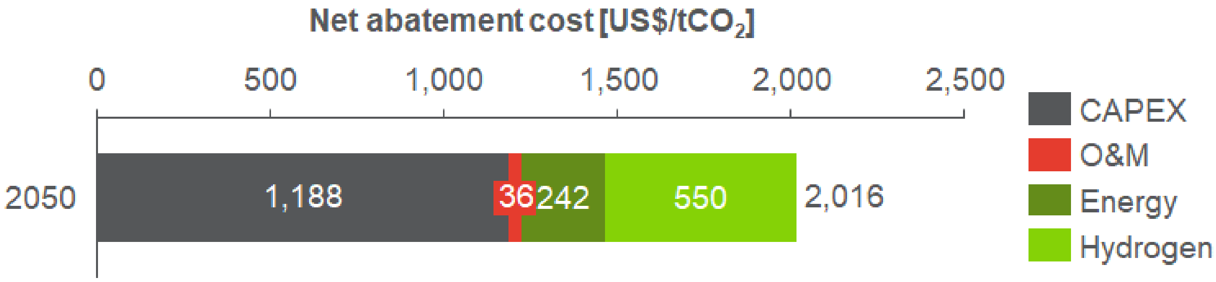
Having a low technology maturity, we estimate the production costs at a hypothetical industrial scale plant. There are no cost assumptions identified from literature, which is why we focus on estimated energy and feedstock needs to estimate operating costs and scale the resulting relative costs to estimate investment costs. The resulting cost estimate should be considered a high-level approximation to actual costs if the technology were to materialise.

Table 24. CAPEX and OPEX estimates for producing propylene glycol in reference scenario

Cost parameter	Value 2025	Value 2050	Approach or source
OPEX	US$1,142/tonne	US$1,000/tonne	Calculated using 0.11 tH_2 per tonne and 5.2 GJ energy per tonne as explained under Energy intensity per unit of product.
CAPEX	US$1,640/tonne	US$1,436/tonne	Assumed ratio of 60/40 CAPEX/OPEX per tonne of product, based on analogue chemical plant abatement costs.
Total	**US$2,782/tonne**	**US$2,436/tonne**	**Expressed in US$ (2019) per tonne of propylene glycol**

Source: references indicated, Navigant analysis

Figure 17. Net abatement cost breakdown reference scenario – propylene glycol



Source: Navigant analysis

4.3.8.3 Operational

Scalability to match local demand

Production of propylene glycol takes place in Singapore. Shell has a production facility of 80 kilo tonnes per year.[335] Most of the chemical products that are produced in Singapore are exported.[336] Propylene glycol can also be exported in the region where the demand is expected to grow in the coming decade.[329] We

---

[333] Zion Market Research, Propylene Glycol Market by Grade (Industrial Grade and Pharmaceutical Grade) and by End-Use Industry, 2019, https://www.zionmarketresearch.com/report/propylene-glycol-market

[334] ICIS, "Asia MPG under pressure as demand remains tepid", July 09, 2018, https://www.icis.com/explore/resources/news/2018/07/09/10239193/asia-mpg-under-pressure-as-demand-remains-tepid/

[335] Shell, Shell Chemicals in Singapore, https://www.shell.com/business-customers/chemicals/factsheets-speeches-and-articles/factsheets/shell-chemicals-singapore.html

[336] Singapore Chemical Industry Council Limited (SCIC), Asia Petrochemical Industry Conference 2018, 2018, http://cpmaindia.com/pdf/apic-country-2018/apic2018-singapore-report.pdf

consider Shell's site as representative of a typical propylene glycol production plant today. If a CO_2-derived propylene glycol plant is built at such capacity, it would consume 139 kilo tonnes of CO_2 or 0.4% of the emissions from all point sources in Singapore. This facility would also need around 8.8 kilo tonnes of hydrogen each year.

Locations for deployment

The conventional plants are usually located close to ethylene or propylene crackers where oxides are converted into numerous chemical derivatives including glycols, polyols, ether solvents, etc. It remains unclear what CO_2 purity levels are needed for the electrochemical process used in propylene glycol production. In general, it can be said that any process requiring one or more catalysts could be sensitive to catalyst deactivating mechanisms such as poisoning or sintering due to unwanted impurities in the feedstock gas stream. Hence, it is likely the technology to synthesise propylene glycol from CO_2 will need high purity CO_2.

No information on land area requirements is available due to the low maturity of the technology.

Benefits and opportunities

Due to the relatively longer lifetime of products using or including propylene glycol, CO_2 is stored for longer durations. This is a climate benefit besides the displacement of fossil feedstock.

Barriers and required support

For the technology to mature, support is likely required to further the ongoing R&D efforts. There are no demonstration or pilot plants and the technology described here still is in the conceptual phase. Hence, more research is needed to further develop, pilot, and scale the technology. At a later stage, other measures could be considered to help market penetration of the technology. With resins as the largest application in terms of industrial grade volumes, CO_2-derived propylene glycol could be supported by building standards or certifications stimulating the use of low-carbon materials. This is would, however, not impact the deployment of this technology in the coming decade due to the relatively low development stage of the technology.

The market for propylene glycol is likely to continue to expand in the region and there is production capacity in Singapore at present. Therefore, industry may explore the potential low carbon alternative routes for propylene glycol synthesis.

4.3.8.4 Circular

By-products and their potential use case

In general, CO_2 hydrogenation can result in a range of hydrocarbon by-products that could lead to separation problems. Catalysts with high selectivity for the desired product are aimed to increase the conversion efficiency of the process. [219]

4.3.9 Oxalic acid

Category	Summary
Technological	*A low maturity (TRL3-4) electrochemical synthesis route exists to produce oxalic acid from CO_2.*
Commercial	*Oxalic acid is used for a wide range of applications, where pharmaceuticals are an important final product in terms of volumes. Due to the low TRL, CCU-derived oxalic acid costs are difficult to estimate.*
Operational	*For this technology to materialise, R&D support is required at this stage.*
Circular	*A sacrificial metal anode is used in this process, which is likely suited to be recycled given Singapore's strong track record of recycling metals.*

4.3.9.1 Technological

Technology outline and TRL

Oxalic acid ($C_2H_2O_4$, often written as HOOCCOOH) can be produced through electrochemical reduction of CO_2 using a copper-complex as a catalyst. This process, currently at TRL 3-4, slowly yields an oxalate that needs to be removed to recycle the anode and affects the cathode adversely.[337] Recent papers call for improved methods for removal of this oxalate.[338] The process is at lab scale and noncontinuous. A reactor design is required for future scale up with a focus on continuous feeding of metal to the anode site, replacing sacrificial anodes.

$$2CO_2 + H_2 \rightleftharpoons HOOCCOOH$$

Energy intensity per unit of production

The process is exothermic and requires one mole of hydrogen per two moles of CO_2 as feedstock, or 0.022 tH_2 per tonne of oxalic acid. Using the average Δ between theoretical energy need and industrial energy need for exothermic processes as detailed in Annex A.1.1, we see energy demand stays negative. Therefore, in further calculations, we consider this process as not to require further process energy.

4.3.9.2 Commercial

Market application

Applications of oxalic acid range from its use in metal treatment, textile treatment, bleaching agent, and other chemical uses, for instance as a synthetic intermediate. The use of oxalic acid is distributed roughly equally across these applications according to an older literature source.[339] In metal treatment, it is used for cleaning purposes like rust removal and in protective coatings. In the textile industry, oxalic acid is used for dying purposes and as stripping agent to remove colours. It is further used as bleaching agent for leather, cork, and wood, as well as in waxes. In chemicals, oxalic acid is used as a precursor to certain esters and slats. It is also used as a dehydrating agent and for the concentration and isolation of rare earth elements. There are also applications for oxalic acid in pharmaceuticals such as antibiotics and as a miticide. The applications in pharmaceuticals is an especially fast-growing market. Reuters reported that the pharmaceutical segment accounted for the largest share of the global market for oxalic acid in 2016, seemingly exceeding the other four segments mentioned above.[342]

Status quo

Oxalic acid can be produced from a range of industrial processes. The three most important routes are from carbohydrates, olefins, and CO. The first utilises nitric acid, the latter uses an alcohol in the presence of a catalyst. The first route, based on carbohydrates, can utilise biomass such as sugar/molasses, arguably a sustainable feedstock. This process requires nitric acid and produces nitrogen oxide and CO_2; this incumbent process is therefore not necessarily a directly competing sustainable production route for oxalic acid.

---

[337] CarbonNext, Report on fully integrated and intensified value chain concepts for process selection, 2017

[338] Angamuthu et al., Electrocatalytic CO_2 conversion to oxalate by a copper complex, Science 327 (5963), 313-315, DOI: 10.1126/science.1177981

[339] Riemenschneider, W., & Tanifuji, M, Oxalic Acid. Ullmann's Encyclopedia of Industrial Chemistry, 2000. doi:10.1002/14356007.a18_247

Future growth potential

Today, an estimated 500 kilo tonnes are produced globally.[340,341] Production capacity in China alone is reported to exceed 300 kilo tonnes, with an export of 50 kilo tonnes in 2009.[341] The expected CAGR towards 2025 is 4%, globally.[342]

Product value

Average wholesale market prices range from around US$1,000-1,400 per tonne.[342,343] Around 0.5 tonne of CO_2 can be stored in the product, and roughly 0.2 tonne is emitted in producing oxalic acid from hydrogen and electrolysis, assuming present-day EFs.**[344]** If the net abatement effect were to be included in this value, at US$11/t$CO_2$ the value of CCU-derived oxalic acid would increase by US$3-4 per tonne of product or around 0.3%. This market signal is likely not going to be a differentiating factor.

Investment and operating costs

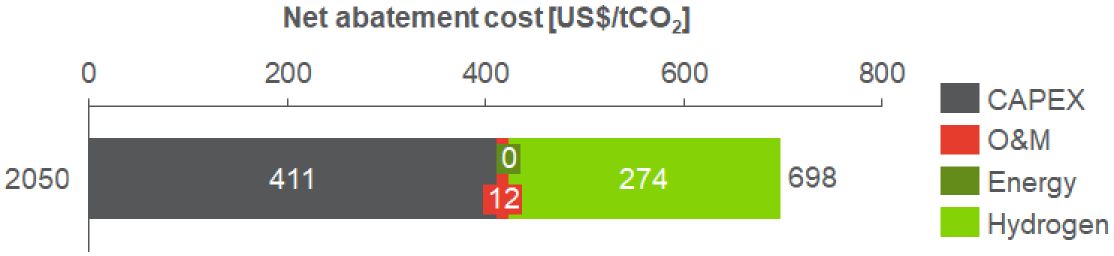
Given its low technology maturity and with limited literature available, we estimate production costs of a hypothetical industrial scale production of oxalic acid based on its projected energy and feedstock needs as well as its investment costs required based on the OPEX cost. This ignores the cost of the sacrificial anode that may present a cost barrier if the recycling rates are not further optimised. Reported yields are up to 85%, but deposition of the metallic oxalate leads to fouling of the cathode resulting in a continuous decrease in current efficiency.[337] The resulting cost estimate should be considered a high-level approximation to actual costs if the technology were to materialise.

Table 25. CAPEX and OPEX estimates for producing oxalic acid in reference scenario

Cost parameter	Value 2025	Value 2050	Approach or source
OPEX	US$183/tonne	US$140/tonne	Calculated using 0.02 tH_2 per tonne of oxalic acid and no additional energy requirements. This is a simplification as it ignores anode and electrolyte inputs that are flagged as significant at this stage of development.
CAPEX	US$262/tonne	US$201/tonne	Assumed ratio of 60/40 CAPEX/OPEX per tonne of product, based on analogue chemical plant.
Total	**US$444/tonne**	**US$342/tonne**	**Expressed in US$ (2019) per tonne of oxalic acid**

Source: references indicated, Navigant analysis

Figure 18. Net abatement cost breakdown reference scenario – oxalic acid



Source: Navigant analysis

---

[340] Global Industry Analysts, Inc., Oxalic Acid – A global strategic business report, 2008. Growth forecast extrapolated to 2019.

[341] Business Wire, Research and Markets: China's oxalic acid industry, 2010-2012, 2011, Growth forecast extrapolated to 2019.

[342] Reuters, Global Oxalic Acid Market Projected to grow at a CAGR of 4% during 2018-2025, 2018

[343] Pharmacompass, Oxalic Acid, https://www.pharmacompass.com/price/oxalic-acid, accessed February 2019

4.3.9.3 Operational

Scalability to match emissions profile

A typical, relatively large incumbent oxalic acid production plant has an annual production capacity of around 70 kilo tonnes.[341] Working with the abatement potential reflecting today's emission factors of various inputs, a CCU-based production plant of similar capacity would need around 34 kilo tonnes of CO_2 and abate 22 kilo tonnes, when taking into account associated emissions for hydrogen production. With a reducing emissions factor for hydrogen over time due to efficiency or (drop-in) production from renewables, this abatement effect will be closer to the original consumption of 34 kilo tonnes of CO_2. This upper bound level of abatement for a single typical plant has the potential to reduce Singapore industrial emissions by about 0.1% based on today's emissions profile. This is an optimistic estimate, as other material inputs such as anode material or electrolyte are not likely to be recovered 100%, adding to the overall production footprint of the final product.

Locations for deployment

We assume such a plant would require a high purity of CO_2 and hydrogen. The volumes required may warrant a direct pipeline connection, but this should be weighed against the option of using mobile pressurised/liquefaction tanks from industrial gas producers. The latter setup could ensure a stable supply of feedstock and is less restrictive on the exact plant location.

No information on land area requirements is available due to the low maturity of the technology.

Benefits and opportunities

The annual production volumes as indicated imply that there is limited potential for economies of scale compared to other technologies considered in this study, including CCS. The process studied here is relatively immature which makes it unlikely for this application to serve as a stepping stone towards other applications of CO_2.

Barriers and required support

When we compare current market price levels (US$1,000-1,400 per tonne) with total production costs, as estimated in Table 25, this process may prove economical even compared to the incumbent production processes that currently exists. If this is the case, regardless of the abatement potential being relatively small, it could still prove to be an interesting business case for Singapore to explore further. A next step would be to support further R&D efforts into scaling this technology. Reported areas for development are to increase the recyclability of the anode, reactor design improvements, improving catalyst performance, and reducing the precipitation of oxalate on the electrodes.[337,338]

4.3.9.4 Circular

By-products and potential fit to circular scheme

The formation of oxalate is highly selective and relatively rapid, no by-products were mentioned. However, this process describes requires sacrificial anodes that need to be recycled using conventional hydrometallurgical processes. This is not expected to reach a 100% efficiency; in other words, this will generate waste material. With 98%-99%,[345] the recycling rate for metals in Singapore is very high. It could be explored if these waste stream may be added to existing infrastructure and value chains. These waste metals could be fed to Singapore's existing electric arc furnaces for recycling but the cost of using Electric Arc Furnaces may prove to be a cost barrier.

---

[345] NEA, Waste management statistics and overall recycling measures, 2017. https://www.nea.gov.sg/our-services/waste-management/waste-statistics-and-overall-recycling

4.3.10 Supercritical CO_2

Category	Summary
Technological	*Supercritical CO_2 can be widely applied as a "green" solvent in the chemical industry and as a medium to produce polymers, such as fluoropolymers. The production of supercritical CO_2 itself is a highly mature process, although more research is needed to increase the scope of applications. Energy use is fairly high, at around 89 kWh per tonne of CO_2 converted to supercritical CO_2.*
Commercial	*Markets for potential applications of supercritical CO_2 is growing rapidly, such as fluoropolymers, at a rate of around 6%. The cost of CO_2 in bulk can be as low as US$15/tonne supercritical CO_2, whereas production costs at small scale exceed US$20/tonne, with limited CAPEX investments for a multi-stage compressor.*
Operational	*The potential CO_2 utilisation of processes running on supercritical CO_2 is negligible, since the scale of usage per year in plants usually does not exceed the hundreds of tonnes per year. This CO_2 is also not permanently locked away in products and will be re-emitted at some point in the "product" lifetime.*
Circular	*The use of supercritical CO_2 as an alternative organic solvent avoids the production of environmentally hazardous volatile organic compounds (VOCs), and thereby contributes to the reduction of waste.*

4.3.10.1 Technological

Supercritical CO_2 has a wide range of applications, such as extraction and purification in the food industry, in chemical reactions (e.g., alkylations, hydroformylations, and hydrogenation), polymer production and processing, semiconductor processing, and powder production. For this study, we consider the use of supercritical CO_2 as an organic solvent in the chemical industry, since this is considered the most relevant application for Singapore's chemical industry.

Technology outline and TRL

Many reactions, extractions, separations, and other operations in the chemical industry involve the use of organic solvents. Organic solvents are often difficult to handle and dispose and can represent an environmental hazard due to atmospheric and land toxicity. Conventional organic solvents are often regulated as volatile organic compounds (VOCs). Some organic solvents are under restriction due to their ozone-layer-depletion potential. Because CO_2 is not considered a VOC, supercritical CO_2 can be an attractive alternative to conventional organic solvents. Additionally, traditional organic solvents can cause N_2O emission in some applications such as anaesthetic, manufacture of electronics and as a propellant. These applications are not within the scope of this assessment, but if supercritical CO_2 were used as a substitute it would also displace N_2O emissions, which have stronger effect on global warming compared to CO_2. The greenhouse gas abatement effect within the scope of this assessment is when CO_2 is captured from an industrial process and reused as a solvent there is no additional CO_2 entering the atmosphere.

Supercritical CO_2 is a good solvent for many non-polar and low molecular weight compounds. On the other hand, it is not a very good solvent for high-molecular-weight compounds and most polar compounds. Very high process pressure may be required to solvate polar, inorganic, or high-molecular-weight material in CO_2. To increase the solubility of such compounds in supercritical CO_2, small amounts of polar or non-polar co-solvents may be added.

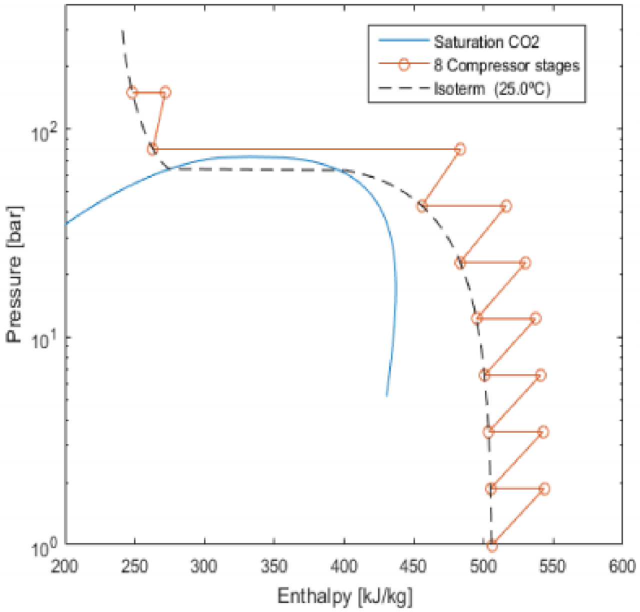
The conventional way to produce supercritical CO_2 is using an eight-stage compressor process, which is illustrated in Figure 19. The compressor uses intercoolers to remove the waste heat from compression, which has a typical compression ratio of around two. After the CO_2 reaches supercritical level it behaves like a fluid and can be pumped for its final stages of compression. Alternatively, one could also refrigerate the CO_2 and pump it to its critical level. Research finds that the energy demand between the various compression processes is the same if all processes are optimised.[346]

---

[346] Jackson & Brodal, 2018. *A comparison of the energy consumption for CO_2 compression process alternatives.* https://iopscience.iop.org/article/10.1088/1755-1315/167/1/012031/pdf

The production of supercritical CO_2 has been done for many decades and is a mature process. However, the use of supercritical CO_2 as an alternative organic solvent is less developed and is facing challenges in reaching commercial scale, due to high energy costs (see section on Barriers and political support).

Figure 19. Illustration of a conventional eight-stage compressor process in a pressure-enthalpy diagram; for reference, the critical pressure of CO_2 is at 74 bar



Source: Jackson & Brodal[346]

Energy intensity per unit of production

If the number of compression cycles are optimised, energy demand to reach critical pressure is around 0.32 GJ or 89 kWh_e/tCO_2.[346] This is the energy demand at room temperature. However, due to compression, the temperature of CO_2 increases. This temperature is decreased using intercoolers. Since the critical temperature of CO_2 is slightly above room temperature, it is expected that the use of the intercooler can be slightly decreased to arrive at supercritical CO_2. However, due to the variety of its applications in chemical reactions and therefore also the variety of requirements in pressure, no further distinction in energy demand was made here. It should be considered that for some applications, such as the production of styrene-based polymers, the supercritical CO_2 medium should be at 345 bar, although the energy requirement increases significantly slower above the supercritical pressure.

4.3.10.2 Commercial

Market application

Chemical reactions

Supercritical CO_2 has been tested in a variety of industrially important reactions such as alkylation, hydroformylation, oxidation, disproportionation, esterification, and hydrogenation—as an alternative reaction medium.[347] The incentives to use supercritical CO_2 as reaction medium can include replacement of the conventional organic solvent with a green solvent, improved chemistry such as reactivity and selectivity, new chemistry, and improved separation and recovery of products/catalysts. Relatively high

---

[347] Mayadevi, 2012. *Reactions in supercritical carbon dioxide.* https://pdfs.semanticscholar.org/941b/1a241161167681b1d83344be55bcb263c95c.pdf

rates of molecular diffusion and heat transfer are possible with a homogenous, supercritical-CO_2 reaction medium.

Limitations to the use of supercritical CO_2 as a reaction medium include poor solubility of polar and high-molecular-weight species, no observed improvement in reaction chemistry in some cases, and higher capital investment cost due to higher operating pressures. For reactions not limited by reactant-gas concentrations or other mass-transfer limitations, there is no improvement in reactivity observed when using a homogeneous, supercritical CO_2 medium.

Polymer production and processing

Applications of supercritical CO_2 in polymers include polymerisation, polymer composite production, polymer blending, particle production, and microcellular foaming. Several applications, particularly those involving low pressures, have been successfully commercialised.

At moderate pressure, very few polymers, except for certain amorphous fluoropolymers and silicones, show any significant solubility in CO_2. Very high pressure is typically needed to dissolve polymers in supercritical CO_2. Its solvent power is weaker than that of *n*-alkanes. However, high degrees of swelling of the polymer by CO_2 can occur at significantly lower pressure. Although many polymers have very low solubility in CO_2, the solubility of CO_2 in polymers is typically high. This has led to the use of CO_2 as a plasticiser. One example of this application area is to produce fluoropolymers using supercritical CO_2 as the reaction medium that was developed by scientists at the University of North Carolina, Chapel Hill.

Research is also ongoing at many universities in the production of microcellular foams using supercritical CO_2.

Status quo

Applications using supercritical CO_2 in their uses in chemical reactions and polymer processing often indicate a fundamentally different production process. The use of supercritical CO_2 will likely not be done because of climate change mitigation, but rather will be a way to improve production or develop new materials. Environmental regulations can also provide a push since supercritical CO_2 is a cleaner organic solvent. Processes based on supercritical CO_2 therefore have the potential to replace existing thermoplastic production.

Future growth potential

Depending on which polymers and chemical reactions are chosen as potential end-use applications of supercritical CO_2, the market demand could be higher or lower. The suitability of supercritical CO_2 for the end-uses can vary and scientific research may be in its infancy stages for some polymerisation routes. To estimate the potential market demand in Singapore, only fluoropolymers are chosen.[348] The market for fluoropolymers is expected to grow by 5.8% in the coming years to reach a value of US$230 million by 2020 in Asia Pacific alone.[349]

Product value

The price of bulk CO_2 is typically agreed through business to business negotiations and is not generally available for the public or published in indices. However, ammonia producers in the US experienced a range in prices of around US$3-15 per tonne for bulk gaseous/supercritical CO_2, which varied significantly by location within the US.[350]

Investment and operating costs

---

[348] Bell, 2009. *Supercritical CO_2: A Green Solvent*. https://ihsmarkit.com/pdf/RP269_toc_173828110917062932.pdf

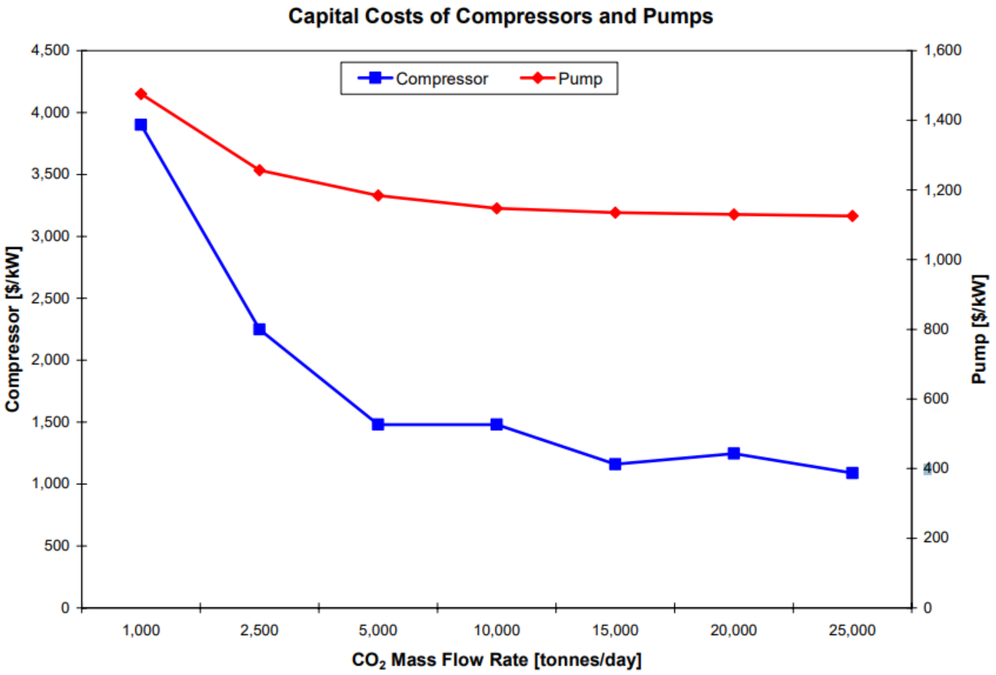
[349] Acmite, 2012. *Global Fluoropolymer Market*. https://www.acmite.com/market-reports/chemicals/global-fluoropolymer-market.html

[350] SRI Consulting, 2010. *Chemical Economics Handbook 2010;* https://hub.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide/2-co2-market#fnr_p02_001

The only noteworthy costs related to the production of supercritical CO_2 for chemical reactions is the investment cost of compressing equipment such as the compressor and intercooler, and OPEX related to power consumption.

The investment costs related to the compressor depends on the CO_2 mass flow rate (Figure 20). For applications in chemical reactions, the supercritical CO_2 is only used as a medium and will as such not be compressed at the mega tonne per year scale. Investment costs optimistically will be around US$4,000/kW.[351] In polymerisation reactions, the weight ratio of CO_2 compared to the solvent is between 10% and 25%. For the 1,100 tonnes per year plant as stated above, and a 70%–80% polymerisation yield,[352] around 250–400 tonnes of CO_2 per year would be needed. Taking the energy intensity of 89 kWh/tCO_2 and load hours of around 8,000 per year, yields a capacity of 3 kW–5 kW and thus an investment of US$12,000–20,000 for a compressor dealing with such relatively low amounts of CO_2.

Figure 20. Capital costs of compressors and pumps as a function of CO_2 mass flow rate



Source: McCollum & Ogden [351]

Table 26. CAPEX and OPEX estimates for producing supercritical CO_2 in reference scenario

Cost parameter	Value 2025	Value 2050	Approach or source
OPEX	US$14/tonne	US$18/tonne	With an electricity usage of 89 kWh/tonne, the OPEX of supercritical CO_2 production is around US$14/tonne in 2025 and US$18/tonne in 2050.
CAPEX	US$6/tonne	US$6/tonne	Based on an investment of US$16,000 for a compressor producing 325 tonnes of supercritical CO_2 per year, annualised CAPEX is around US$1,900 per year and US$6 per tonne.

---

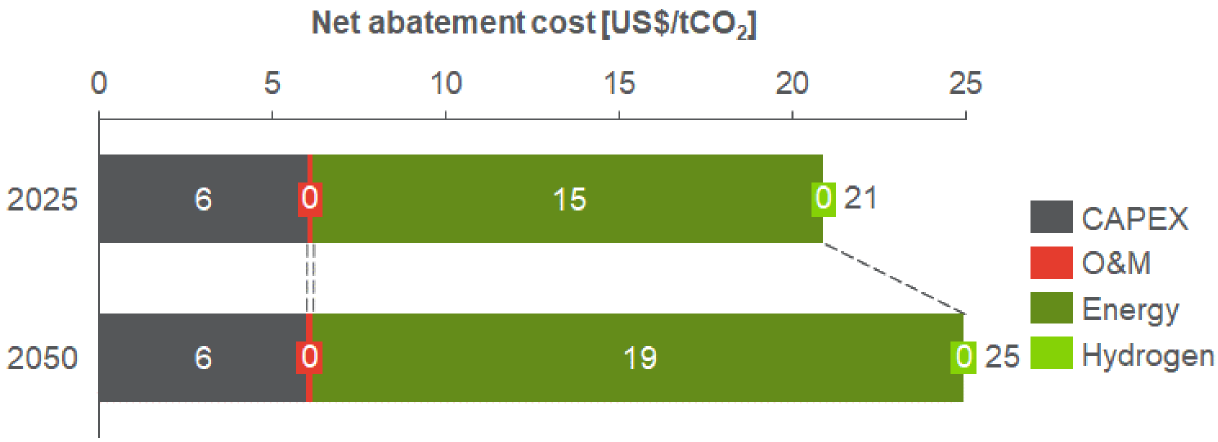
[351] McCollum & Ogden, 2006. *Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity*. http://www.canadiancleanpowercoalition.com/pdf/CTS1%20-%202006_UCD-ITS-RR-06-14%5B1%5D.pdf

[352] Du et al., 2009. *Fluoropolymer synthesis in supercritical carbon dioxide.* http://desimone-group.chem.unc.edu/wp-content/uploads/2010/02/2009_fluoropolymer_synthesis_in_supercritical_carbon_dioxide.pdf

Total	**US$20/tonne**	**US$24/tonne**	**Expressed in US$ (2019) per tonne of supercritical CO_2. Costs of the CO_2 feed itself is not included, this relates to the conversion of normal CO_2 to supercritical CO_2.**

Source: Navigant analysis

Figure 21. Net abatement cost breakdown reference scenario – supercritical CO_2



Source: Navigant analysis

4.3.10.3 Operational

Scalability to match emissions profile

A typical application using supercritical CO_2 for polymer production would use an amount in the order of 300 tonnes supercritical CO_2. If one such plant was introduced in Singapore, the effect on the mitigation of industry and energy-related emissions would be negligible.

Locations for deployment

The technology can be applied where alkylation, hydroformylation, oxidation, disproportionation, esterification, and hydrogenation reactions take place. It can also be applied in processes that involve polymerisation, polymer composite production, polymer blending, particle production, and microcellular foaming. Hence, the potential locations for deployment in Singapore near plants which produce (fluoro)polymers.

Benefits and opportunities

Unlike many organic solvents, supercritical CO_2 is non-flammable. It is inert, non-toxic, has a relatively low cost, and has moderate critical constants. Its solvation strength can be fine-tuned by adjusting the density of the fluid. CO_2 leaves a lower amount of residue in products compared to conventional solvents, and it is available in relatively pure form and in large quantities.

Benefits of carrying out reactions in supercritical CO_2 are high reaction rates, improved selectivity, and elimination of mass-transfer problems.[353] CO_2 critical temperature (T_c; 32.1°C) is also near ambient, making it an attractive solvent for temperature-sensitive materials. CO_2 critical pressure is 73.8 bar (P_c; 1,070 psi).

Barriers and required support

---

[353] Mayadevi, 2012. *Reactions in supercritical carbon dioxide.* https://pdfs.semanticscholar.org/941b/1a241161167681b1d83344be55bcb263c95c.pdf

Research on the use of supercritical CO_2 as an organic solvent has lately focussed on the development of soluble complex catalysts and its modifications for enhancing solubility. Another area of focus is the heterogenisation of homogenous catalysts, the use of metal oxide catalysts in heterogeneous phase and on the continuous operation of the reaction process. The application of supercritical CO_2 as an organic solvent in chemical reactions has not yet commercialised, which is mainly attributable to the high energy costs related to the compression of CO_2 when a side stream of this pressure is not available within an industrial process.

4.3.10.4 Circular

By-products and potential fit to circular scheme

The use of supercritical CO_2 as an alternative organic solvent avoids the production of environmentally hazardous VOCs, and thereby contributes to the reduction of waste.

4.4 Comparing technologies

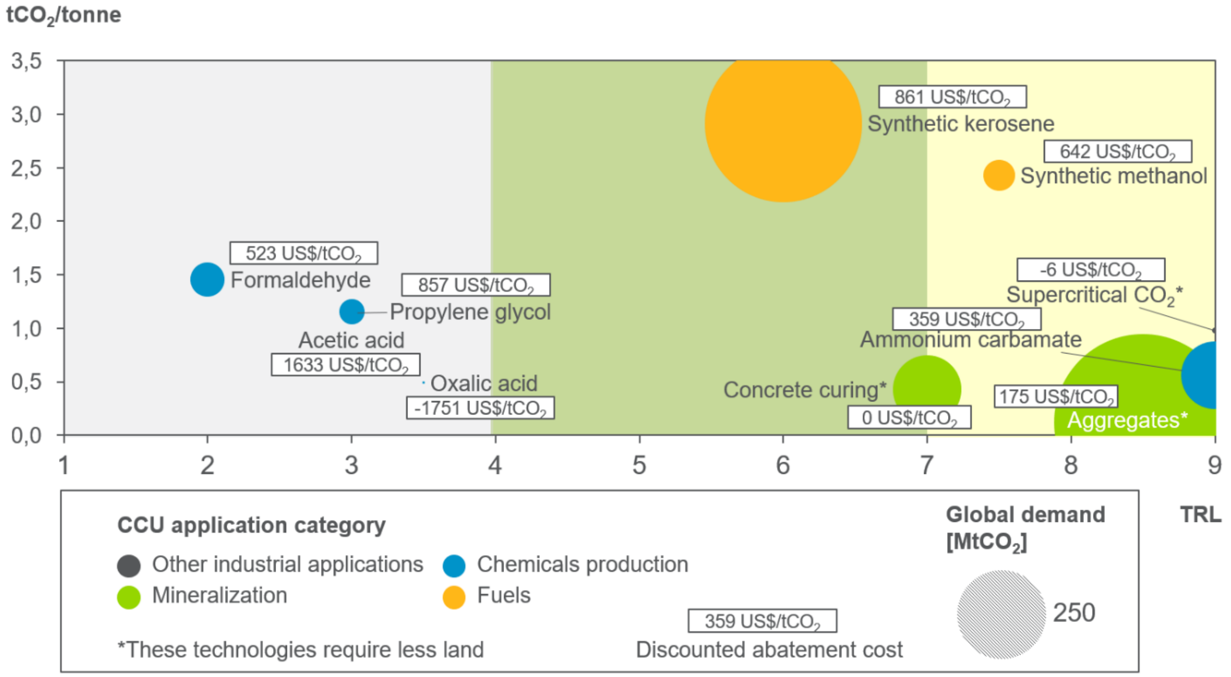
In this section, we compare technology maturity, abatement effect, and abatement potential for typical reference plants, as well as the associated costs to yield insight in cost-effectiveness and relative scale. This comparison is done under BAU (reference) scenario assumptions. The considerations to map CO_2 sources to CO_2 sinks in Singapore are evaluated and the section concludes with potential CCU-related R&D investment areas.

4.4.1 Technology heat map

The shortlisted technologies differ in their relative abatement potential; in other words, how much CO_2 is abated per tonne of resulting product. This is a measure for the abatement effectiveness. Combined with the total hypothetical global CO_2 demand resulting from global demand for the CO_2-derived product and the maturity of the technology expressed in TRL, a heat map can explore overall abatement potential across these dimensions. Figure 22 shows this heat map, comparing all shortlisted technologies. The heat map also shows the discounted abatement costs in white data labels. This reflects net abatement costs discounted for the market value of the resulting product. Section 4.4.5 explores this effect of lowering abatement cost through the selling of CCU products.

The ideal CCU technology for Singapore is a relatively mature technology that consumes a lot of CO_2 per tonne, produces a product which is in high demand and does all this without requiring too much additional land. Technologies that fulfil these requirements are represented as large bubbles, as close as possible to the upper-right corner of the heat map. Fuels, ammonium carbamate, and perhaps concrete curing come closest and thus seem promising—despite not meeting all requirements. Less mature technologies should not be ruled out to contribute significantly towards Singapore's GHG abatement strategy towards 2050.

Figure 22. Deep dive technologies heat map

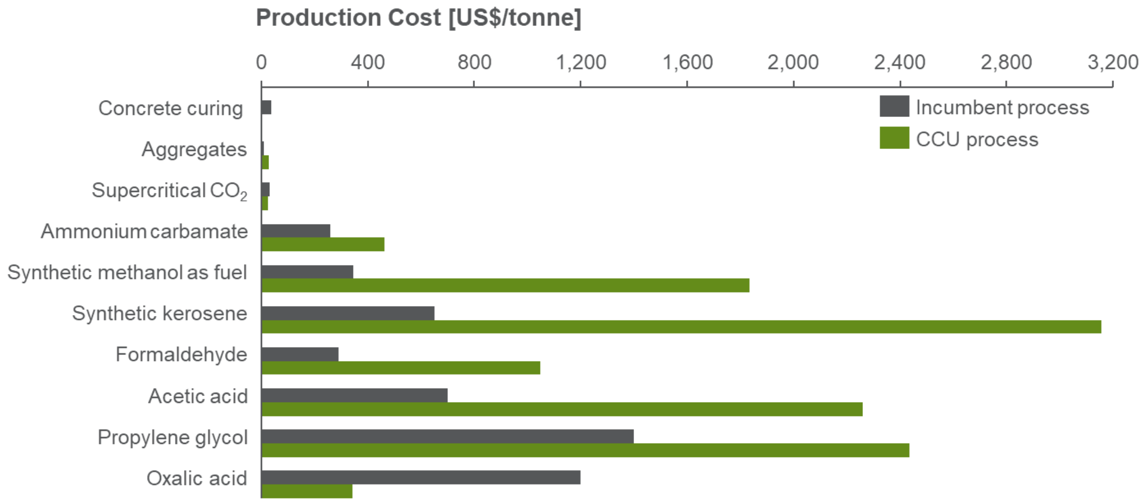


Source: Navigant analysis

4.4.2 Additional production costs

The production costs using the technologies described in the previous deep dives are mostly more expensive than their incumbent counterparts. This section shows this comparison for all technologies to allow a direct view of what this economic gap looks like under the reference scenario. In establishing incumbent production costs, we equate production costs to market price, ignoring profit margins. Hence, this comparison is indicative only. Market price data is part of the deep dive analysis, and data is referenced from the market value subsections for each technology in the earlier section.

Figure 23. Comparison of production costs between conventional process and CCU process



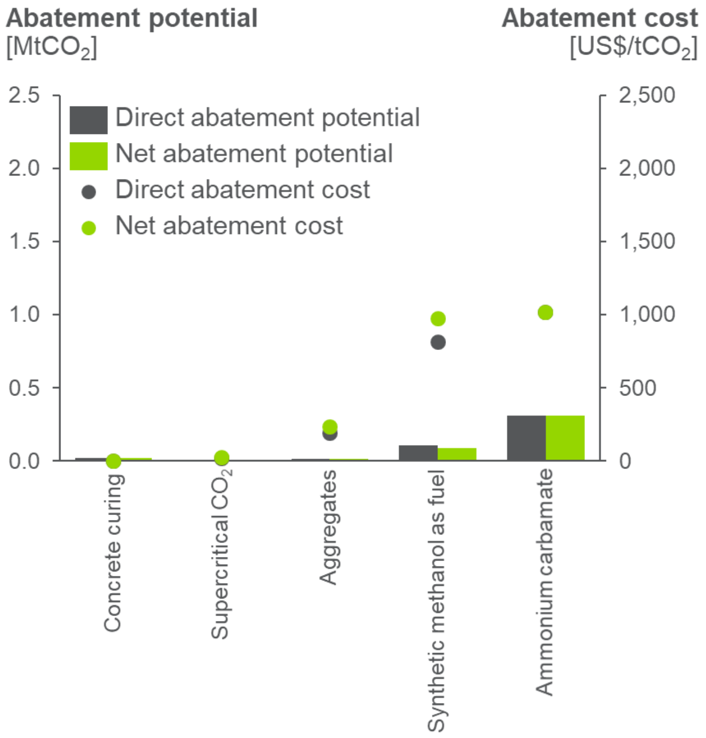
Source: Navigant analysis, reference scenario

4.4.3 Abatement potential and costs

The deep dives in the previous section detail the cost of producing one tonne of product, split to CAPEX and OPEX. These costs are derived assuming a typical (reference) plant size. With knowledge of the abatement effect of these technologies, we can compare abatement potential and costs. This section compares the abatement potential and costs of all 10 shortlisted technologies for the BAU or reference scenario as employed throughout the deep dive analyses, using the approach as further detailed in Annex A.1.4. We do this for target years 2025 and 2050. The year 2025 is used as a milestone for near-term implementation by 2030. For both years we show two cases. One case indicates the direct abatement effect, e.g., how much CO_2 is consumed, without considering how much CO_2 is emitted in the production process. The other case indicates the net abatement, which accounts for CO_2 emissions from the production process as well. The abatement cost depicted in the figures in this section do not account for the value of the resulting product. These numbers are depicted separately in Figure 22 and discussed further in Section 4.4.5.

Target year 2025

Figure 24. Abatement potential and cost for 2025 in the Reference scenario



Source: Navigant analysis. Five technologies deployed at the scale of one reference plant per technology.

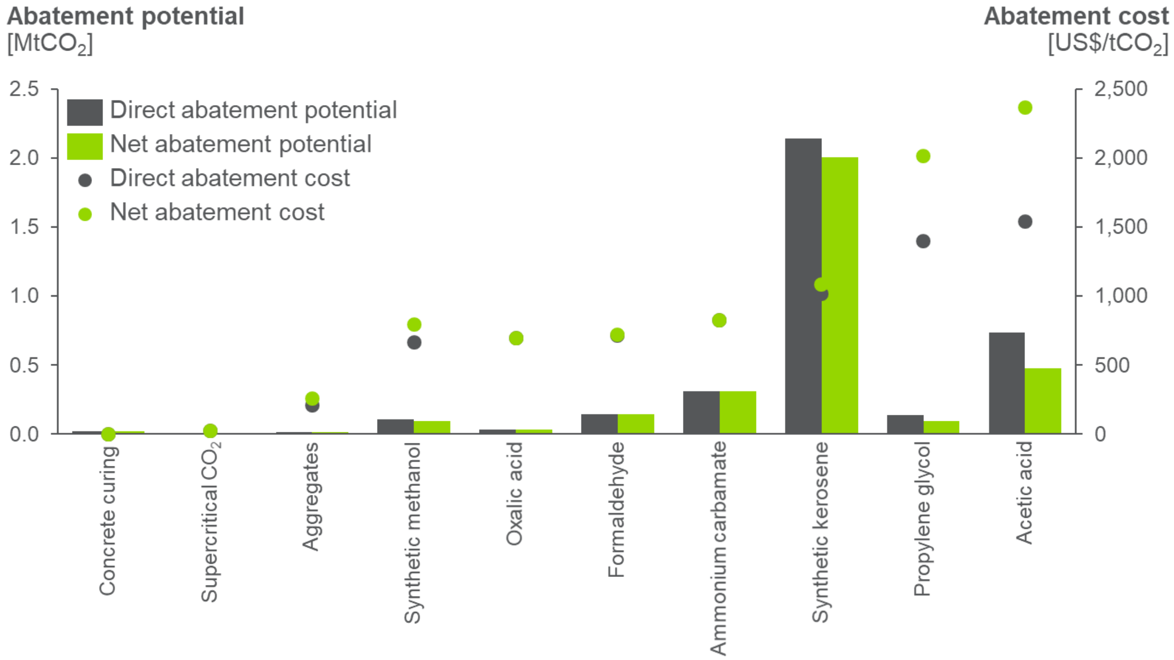
By 2025, 5 out of 10 shortlisted technologies have a reasonable chance of developing to full maturity and, therefore, of being deployed in the form of one single plant in Singapore. This is reflected in the figure above. The figure shows the effect of an overall increase in abatement potential at marginally lower cost if only the direct abatement is considered, and the CO_2 emissions associated with energy and feedstock inputs are ignored.

Based on this figure, by 2025, producing ammonium carbamate or synthetic methanol has the largest abatement potential, but at relatively high marginal costs. Concrete curing and, to a lesser extent, producing aggregates, are much cheaper to produce and hence have much lower abatement costs. And the same time, their abatement potential is smaller. This is due to a combination of a smaller reference plant size and, more importantly, due to a lower amount of CO_2 utilised per tonne of product.

Target year 2050

This order of abatement potentials and costs continues towards 2050 in our reference scenario. By then, the other five shortlisted technologies may have fully matured and are thus included in the figure for this target year as depicted below. Perhaps the most striking is the large potential for synthetic kerosene in the 2050. This abatement potential reflects the scale of a hypothetical synthetic kerosene plant, and in the case of the net abatement, it shows the high abatement efficiency in synthesising kerosene from low carbon hydrogen and CO_2. In accordance with the definition for net abatement as employed throughout this study, this potential does not account for the emissions associated with fuel combustion.

Figure 25. Abatement potential and costs for 2050 in the Reference scenario



Source: Navigant analysis. Ten technologies deployed at the scale of one reference plant per technology.

Even by 2050, the technologies to produce chemicals and fuels are expensive when considered purely as an abatement measure. In the reference scenario, should a carbon tax in the order of $50/tCO_2$ be levied by 2050, the CCU technologies are not significantly closer to a viable economic business case. In this context the technologies in the Figure 25 are treated merely as abatement measures. However, products with value are created, which may further offset the marginal costs of abatement. This is illustrated by the example of synthetic kerosene. Producing kerosene abates 2.7 tCO_2 per tonne of kerosene,[354] which translates to 0.37 tonne of kerosene produced per tonne of CO_2 abated. Hence, at an average price of US$650 per tonne of jet fuel,[269] US$240 is made per abated tonne of CO_2. Lowering the synthetic kerosene marginal (net) abatement costs from US$1,345 to US$1,105. Taking an avoided CO_2 tax into account, the marginal costs may be further reduced to US$1,045. Section 4.4.5 takes a closer look at this effect by providing an integrated assessment of net abatement cost per CCU technology.

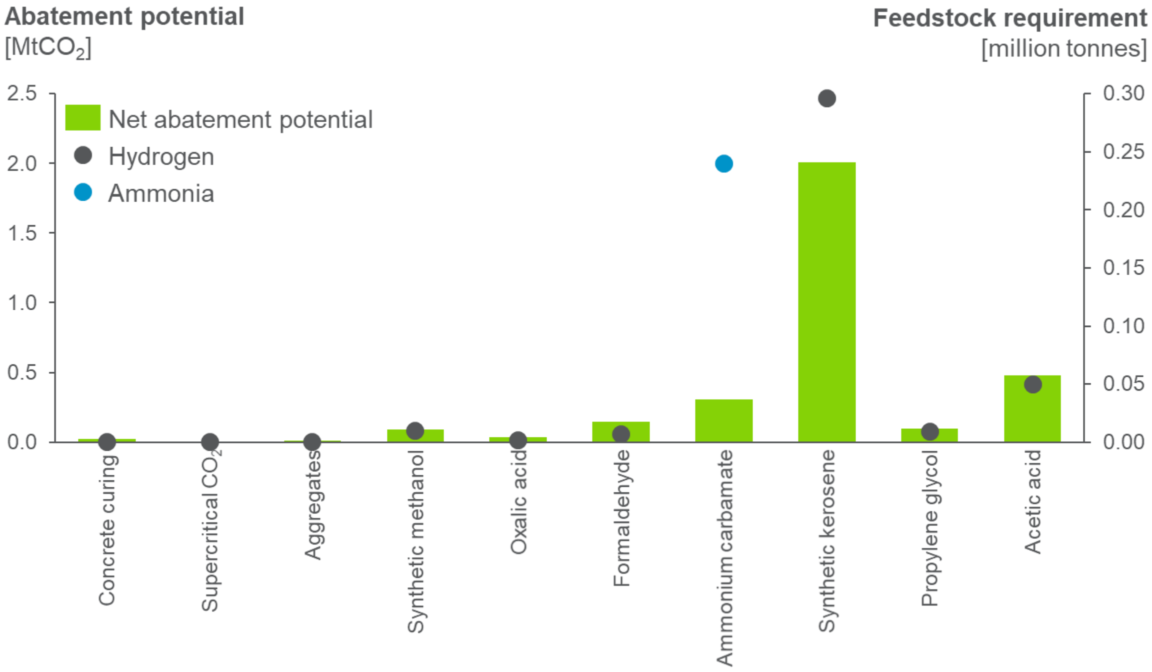
4.4.4 Feedstock requirements

Considerable amounts of feedstock are required for most CCU technologies. We depict the necessary quantities per reference plant and compare these to the net abatement potential in Figure 26. There is a correlation between the amount of feedstock required and the net abatement potential of a reference plant. This is to be expected; pathways with significant abatement potential require substantial input of hydrogen or ammonia. It is important to explore the future availability and costs of these hydrogen related low-carbon commodities. To provide a sense of scale, current publicly known production of hydrogen in Singapore is around 0.15 million tonnes per year (Section 2.1.3).

---

[354] CO_2 utilisation factor is 3.11 tCO_2 per tonne of kerosene, 87% abatement effect under our assumptions, see section 4.3.5.1.

Figure 26. Abatement potential for 2050 versus feedstock requirements in million tonnes



Source: Navigant analysis, reference scenario. Ten technologies deployed at the scale of one reference plant per technology.

4.4.5 Integrated net abatement cost assessment

Up to this point in the study, net abatement costs for CCU technologies have been assessed excluding the costs of CO_2 capture and excluding the discounting effect of selling the resulting product on the market. This section explores how net abatement costs could look when these capture costs and product value are accounted for.

The abatement potential for each CCU technology was estimated based on the CO_2 utilisation rate of a typical reference plant. The establishment of one plant for each of the 10 CCU technologies in 2050, will require 3.2 million tonnes CO_2 as feedstock. The combined net abatement potential of 3.2 million tonnes of CO_2 from all analysed CCU pathways is scalable. For example, a synthetic kerosene plant larger than a reference plant capacity of 0.7 million tonnes of kerosene can be established to utilise a larger amount of CO_2. Figure 7 of Section 3.1.3 shows the capture costs for all of Singapore's industrial and energy point sources combined, with a weighted average capture cost of around US$85. Assuming the lowest cost capture opportunities first, this picture could be updated to show a weighted average capture cost of US$46. This cost is shown in Figure 27.

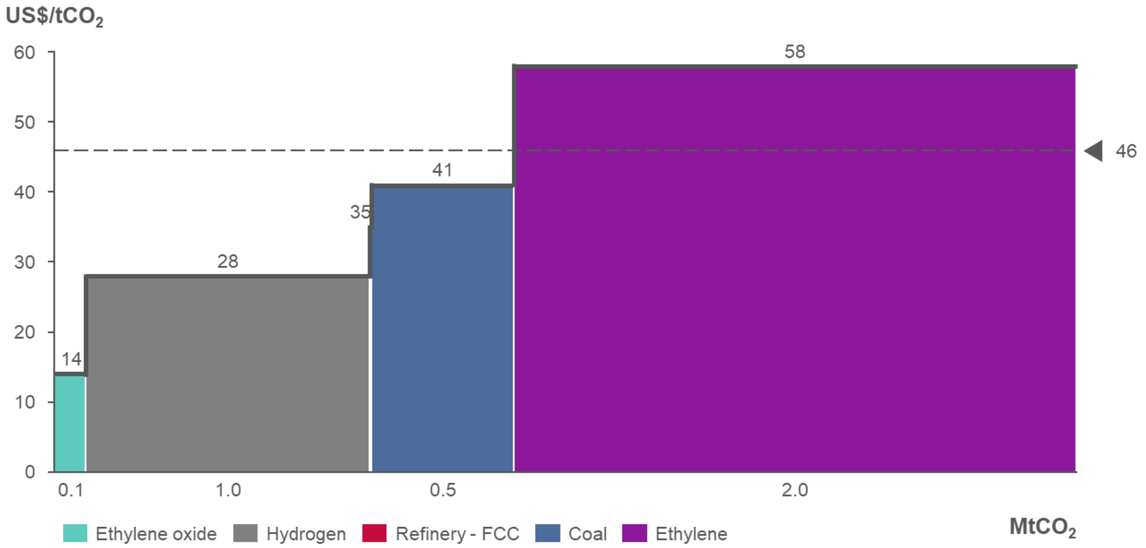
Total net abatement costs will be lowered when accounting for the fact that resulting products have a value. We analysed the impact of accounting for product value on the cost of abatement for the reference scenario in target year 2050. Projecting product value towards 2050 comes with increased additional uncertainty. No further product value developments have been considered and hence the resulting analysis and figure should be taken as indicative only. Figure 28 shows that when product value is considered, net abatement costs reduce substantially (18%-329% reduction), but does not drop below US$ 200/tCO_2 in most cases.[355]

Table 27. Product value for selected technologies.

Product	Product value (US$/tonne)	Reference
Concrete	36	Building and Construction Authority of Singapore[142]
Aggregates	9	Straits Times[173]
Urea	260	Index Mundi,[205] CRU fertilizers[206]
Methanol	345	Methanex[245]
Kerosene	650	Iata Fuel Monitor[269]
Formaldehyde	290	CEIC,[292] Dynea[293]
Acetic acid	700	ICIS[313]
Propylene glycol	1,400	ICIS[334]
Oxalic acid	1,200	Business Wire,[341] Pharmacompass[343]
Supercritical CO_2	15	SRI Consulting[350]

Under the reference scenario and using all assumptions made to arrive at production costs, most shortlisted CCU technologies have high costs associated with them. Production costs, and with that abatement costs, will need to come down further for them to become economically viable. In the next chapter we will explore this further using scenario analysis.

Figure 27. CO_2 capture costs, weighted average costs and emissions from lowest cost point sources of CO_2 in Singapore, adding up to 3.6 million tonnes of CO_2

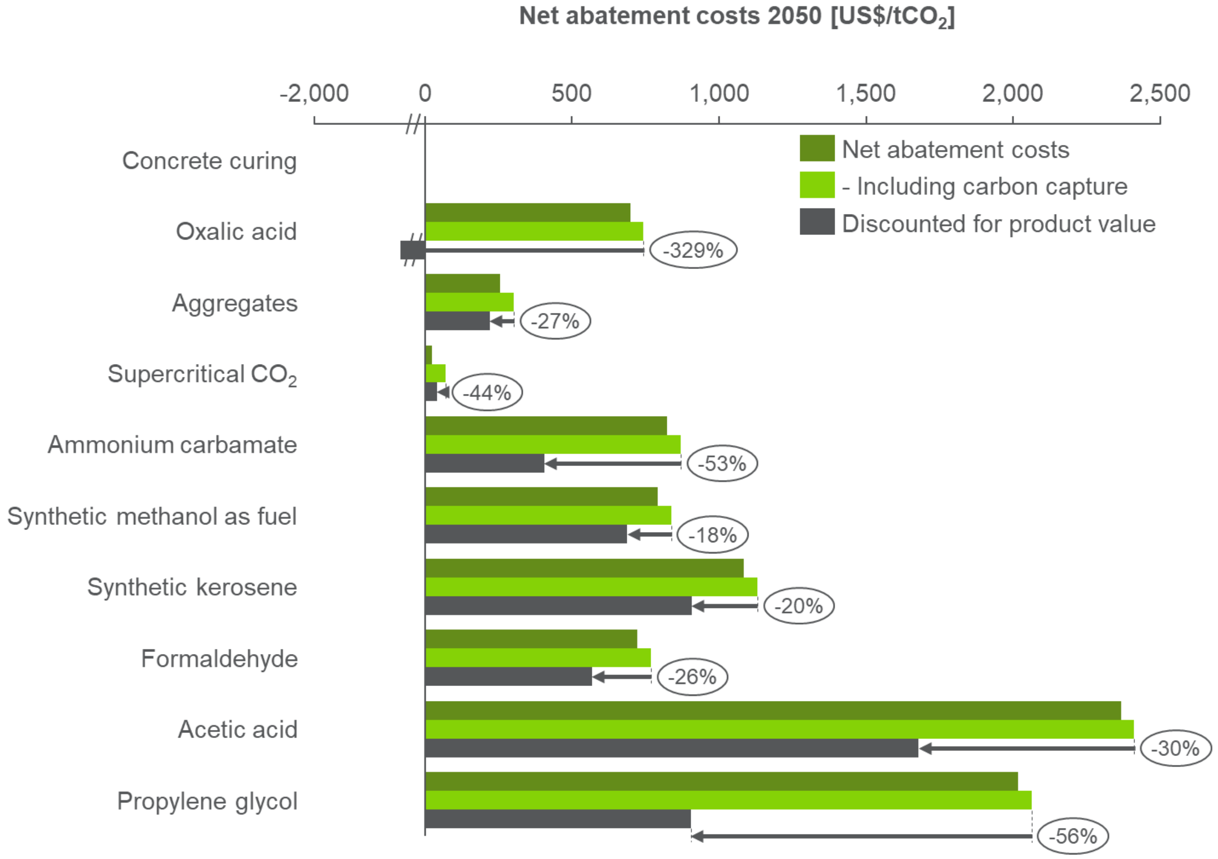


Source: Navigant analysis, zoom in of the first 3.6 million tonnes of CO_2 from Figure 7

---

[355] It should be noted that other commercial aspects can play a role that were not considered here, such as avoiding landfill tax in the case of aggregates.

Figure 28. The effect on net abatement costs in 2050 of including capture costs and selling CCU-derived products under the Reference scenario.

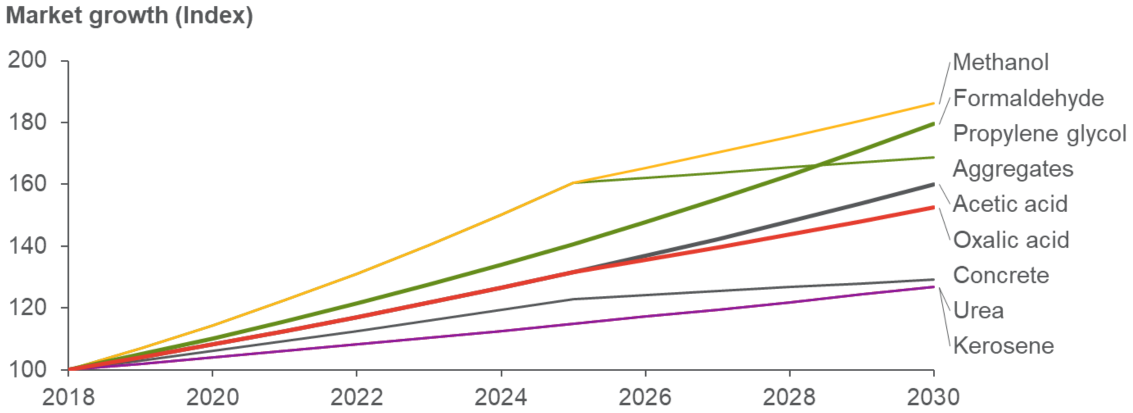


Source: Navigant analysis. The weighted average capture costs of 46 US$/tCO$_2$ are applied. The full range is 14-58 US$/tCO$_2$, see Figure 27. The additional costs for producing concrete with concrete curing are zero, since any costs are offset by savings in the manufacturing process. The revenue from concrete sales cannot also be subtracted in this instance.

4.4.6 Future growth potential of CCU products

The figures displayed in the previous section assume a stable abatement potential per technology, reflecting the single plant approach. Because projected growth paths vary for different technologies and markets, this section provides insight by comparing projected growth rates towards 2030. As can be seen from Figure 29, the market for (synthetic) methanol is expected to grow the fastest. Data underlying this graph can be found in the respective technology deep dives, under the heading “Future growth potential.”

Figure 29. Market growth for products from shortlisted technologies



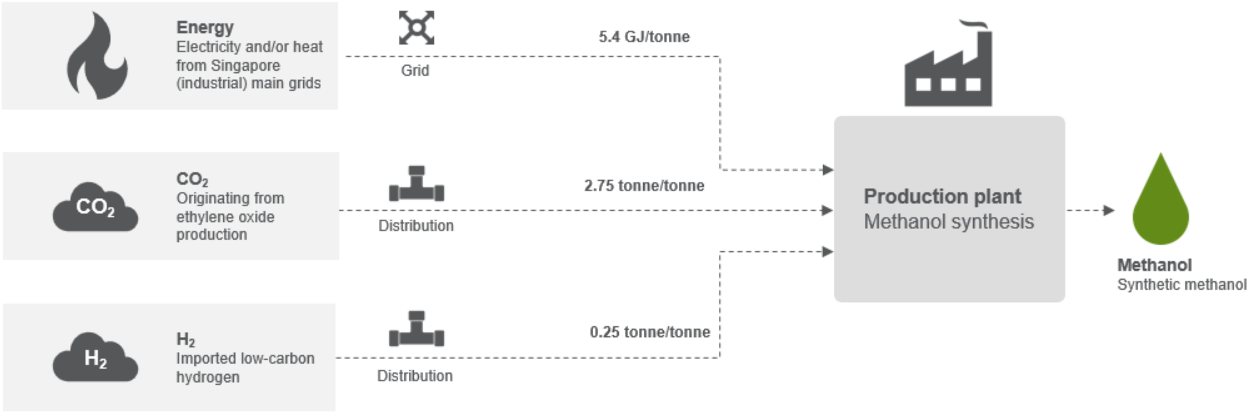
Source: Navigant analysis

4.4.7 Example route: producing synthetic methanol from ethylene oxide production flue gas

Based on the technology heat map in Figure 22, synthetic methanol could be one of the potentially interesting utilisation technologies to explore further. In the synthetic methanol deep dive (Section 4.3.4) we noted that a typical synthetic methanol plant could be expected to produce in the order of 40 kilo tonnes of methanol per year and requires some 110 kilo tonnes of CO_2. With 0.25 tH_2 per tonne of synthetic methanol as renewable hydrogen requirement, such a plant requires an estimated 10 kilo tonnes of hydrogen. In this analysis, this (low carbon) hydrogen is imported.

The deep dive on synthetic methanol explains this process requires relatively high concentration and purity CO_2 to not jeopardise the functionality of catalysts. To ensure this requirement is met relatively quickly and to select the lowest cost CO_2 available in Singapore, we select the CO_2 that results from ethylene oxide production. In Section 2.1.5, we estimate the total emissions of CO_2 from this industrial process be 110 kilo tonnes—just enough to meet our demand. To ensure stability and security of supply, it is advisable to look beyond just this process to source CO_2. This is not explored for this example. Despite its high purity of CO_2, the flue gas from ethylene oxide may contain traces of H_2O, N_2, and CH_4. These are not explicitly flagged as being problematic for the catalysts used in producing synthetic methanol, but this should be explored further.

Figure 30. Simplified scheme to produce synthetic methanol



Source: Navigant analysis

4.4.8 Mapping CO_2 sources to utilisation processes

Throughout the deep dive sections, a note is made on the CO_2 feedstock requirements (concentration/purity) of the utilisation process. In general, we recognise that at this stage of technology development, most technologies require high concentration and high purity CO_2 gas to not upset the synthesis process, such as through catalyst poisoning. As technology advances, this may be subject to change. Two exceptions can be made. In producing aggregates, lower concentrations (down to 70%, see Section 4.3.2) are tolerable and have been used in practice already. In the curing of concrete, it is assumed a greater tolerance towards impurities and lower concentrations exists, but we are unaware of any tests that have been performed to validate this.

In addition, for a view on full system costs, it is helpful to understand the CO_2 processing steps from capture to utilisation and how this can be optimised. Various capture technologies yield different concentrations of CO_2, as seen from Table 28. If membranes are chosen as the preferred capture method, only the CCU technologies that have a low CO_2 concentration requirements can be used, such as CO_2 mineralisation in aggregates. This is unless additional purification is introduced. Most CCU technologies require pure CO_2 or concentrations close to 100%. This means that in most cases, additional purification is needed to meet the required specifications for further reuse. Distilling a gas mixture with a high concentration of CO_2 to a level of 99.9% CO_2 does not require a lot of energy relative to the energy requirement for capturing the CO_2 from the flue gas, around 7 kWh per tonne of CO_2.[356]

---

[356] Xu et al., 2014. *An Improved CO_2 Separation and Purification System Based on Cryogenic Separation and Distillation Theory*. http://www.mdpi.com/1996-1073/7/5/3484/pdf

Table 28 Overview of high-level CO_2 capture methods and associated CO_2 concentrations

Capture method	Concentration CO_2 after capture
Chemical absorption	~98%
Physical absorption	>90%
Adsorption	>95%
Membranes	up to 90%, but more cost-efficient at lower %

Source: See section 3.1.1 and further for a detailed analysis; these figures depend on the process characteristics such as CO_2 concentration before capture and partial pressure

4.4.9 Potential R&D investment areas for CCUS

In this section we aim to identify CCUS technologies and associated research areas where Singapore would either need to invest in or collaborate with others to materialise the envisioned climate and environmental benefits. We start by making an inventory of CCUS research capabilities and focus areas in Singapore. The list of research areas is in no way exhaustive but is meant to provide a rough indication of the research areas where most of the R&D efforts are concentrated. We cover research from A*STAR, NUS and NTU as these institutes are responsible for driving most of the research and development activities in the country. These institutes also collaborate with other research organisations globally to stay abreast of developments in the CCUS domain.[357] Once we have identified focus areas in Singapore, we then try to assess areas where global R&D investments have been made in recent years around CCU. Finally, we summarise the required R&D efforts as listed in the technology deep dives for all the shortlisted CCU technologies, and suggest certain actions based on the combined insights obtained from local and global R&D status. We also provide a high-level overview of the global R&D status of carbon capture technologies. It is crucial to highlight that for any specific investments that concern skill or technology capacity development, more detailed assessment should be performed to inform the decision-making process.

Since the chemical industry is a key driver of the national economy, there is an increasing interest in exploring innovative pathways that can improve process conditions to make valuable products with reduced climate and environmental impacts. Many experts are active in exploring CO_2 to chemicals and fuels conversion pathways and possess capabilities that include catalyst development (homogeneous catalysis, heterogenous catalysis, computational catalysis, electrocatalysis, etc.), reactor design, process modelling and simulation. In the chemicals sector, the pathways that are most widely explored cover CO_2 hydrogenation, reforming, electro-chemical and photocatalytic reduction. Next to chemicals, advanced materials and aggregates production via carbonate mineralisation are major focus areas. Techno-economic assessments, process modelling and design, and advanced material development are key strengths in this field. Some biological conversion pathways are also being studied. On the capture side, there are noteworthy developments on adsorption-based CO_2 separation, membrane as well as chemical looping technologies. It must be noted that it is very likely that there are other relevant CCUS related activities in Singapore that are not documented here but could be worth consideration to make this assessment more concrete.

To help guide future CCU related R&D investment efforts in Singapore we need to have an overview of the scope of global research in CCU domain. The interest in CCU technologies has spiked internationally in recent years. The Innovation for Cool Earth Forum (ICEF) roadmap[358] provides an overview on how the

---

[357] There are noteworthy R&D activities around CCSU in Singapore already. For instance, the C4T initiative setup by Cambridge Centre for Advanced Research and Education in Singapore (CARES) is established to address the complexities around carbon abatement with special focus on CCSU technologies. In this initiative researchers from Singapore collaborate with the University of Cambridge. A new programme called Intra-CREATE has started eCO_2EP project in Singapore that aims to explore CCU pathways that are useful for chemical industry. The project provides platform for Singapore researchers to collaborate with the University of Cambridge and the University of California, Berkeley. https://www.create.edu.sg/about-create/research-centres/cares

[358] ICEF, *Global Roadmap for Implementing CO_2 Utilisation*, 2016.

number of companies that are actively developing a CCU technology changed between 2011 and 2016. It also documents improvements in the technical maturity of their technologies over the same time period. We treat these developments as a proxy to locate areas where most of the R&D related investments have been made in recent years. We summarise these developments in the following paragraphs and distil in Table 29 the key areas of research for various CCU technology categories.

For building materials, there is relatively high density of developers, and many have reached near commercialisation. Several early stage entities disappeared partly because of lack of incentives for concrete manufacturers to reduce carbon emissions but various new developers with focus on aggregates production have entered the market. Factors that contribute to successful commercialisation are low energy requirements for carbonation route and better performance characteristics of CO_2-derived concrete. However, the demonstration of aggregates at large scale and at low costs remains a challenge. Efforts are being put to achieve production at scale and reduce costs for mineral aggregates to make them competitive with traditional construction materials.

In chemicals sector, a small number of developers are near commercialisation with only a few that moved from pilot to near commercialisation stage. A variety of pathways are being researched but most widely developed products are methanol, syngas and formic acid. There has been a dramatic increase in start-ups that tend to focus on catalysis and CO_2 conversions by reduction. So, the development of catalysts with high selectivity for desired products is a key research area in this sector. To achieve full commercialisation and to become competitive with incumbent products it is important that renewable energy is made available at low cost. For syngas production which is an important chemical intermediate, integration of different processes for efficient CO_2 conversion to different chemicals is a challenge. In addition, achieving scaled up production remains a key hurdle.

Table 29. Focus areas of global R&D efforts around CCU

CCU category	Widely researched technologies	Developers near commercialisation	Key research areas
Building materials	Concrete curing Carbonate aggregates	CarbonCure, Solidia Technologies, Carbon8 Aggregates, Orbix, Calix Limited, Calera, New Sky Energy, Carbstone Innovation, Mineral Carbonation International	The demonstration of aggregates at large scale and at low costs remains a challenge. Pay back periods could also be too long for aggregates production.
Chemical intermediates	Methanol Syngas Formic acid	Mitsui Chemicals, Carbon Recycling International, Haldor Topsoe, BioAmber	Appropriate catalyst development and improvement in process economics are some of the key areas that need further research. Especially for syngas synthesis, process integration and scaling up of production are major barriers.

CCU category	Widely researched technologies	Developers near commercialisation	Key research areas
Fuels	Liquid fuels (gasoline, kerosene, diesel as well as fuel additives such as methanol and formic acid) Gaseous fuels (mainly methane)	Liquid fuels: Mitsui Chemicals, Carbon Recycling International, LanzaTech, Sunfire Gaseous fuels: ETOGAS, Audi, Electrochaea	Liquid fuels: The focus of development has been on process integration, efficiency improvement of CO_2 to fuels conversion and availability of low-cost renewable energy. Gaseous fuels: The focus of development has been on process integration, efficiency improvement of CO_2 to fuels conversion and availability of low-cost renewable energy. In addition, current research is underway to develop reactor types that are better suited to operate at small scale and with intermittent operations.
Polymers	Polyols Polycarbonates	Covestro, Asahi Kasei, Novomer, Econic[359]	Catalyst development, improvement in conversion efficiency and availability of low-cost feedstocks are areas of research focus

Source: ICEF[358], Sacha Alberici et al.[222]

Fuels are distinguished into liquid and gaseous fuels. A small number of developers are near commercialization with only a few that moved from pilot to near commercialization stage. For liquid fuels there is a considerable amount of new developers that have entered the market whereas the market for gaseous fuels has not seen any noticeable new entries. The focus of collaborations in fuels category has been on process integration which covers integration of CO_2 capture, renewable energy supply, hydrogen generation and CO_2 conversion to fuels. To render fuels cost-effective the availability of low-cost renewable energy remains a challenge. In addition, catalytic methanation is usually applied at large scale and for plants with continuous operations. However, for production at small scale and with intermittent operations, new reactor designs are needed. This is one of the areas of research that is being studied widely.[360]

In the field of polymers, a lot of activities are underway to make polycarbonates and polyols (which are also used in polyurethane formations). Several developers are near commercialization, and many have moved from lab to commercialization stage. Production at scale is technically possible and has also been demonstrated to be economically viable in some cases.[359,361] However, the lack of new initiatives indicates that follow-up projects from these developers and competing companies are rare most likely due to lack of financial incentives and potential resistance from users in downstream applications.[222] The research is concentrated on finding novel catalysts to improve processes.

Next to the investments and research efforts of developers, there are numerous research and development platforms globally such as CO_2Chem, The Global CO_2 Initiative, CO_2Net+, EnCO_2re and The Global CCS Institute that are investing funds to research and further develop CCU technologies with the aim to activate a market in re-used CO_2. This is achieved by establishing value chains and by involving industrialists as well as policy makers over a wide range of disciplines. These platforms are leading the research in this area to actualize the decarbonisation potential of these technologies and to accelerate the progress towards industrial circular economy. Europe remains on the fore front in introducing mandates that facilitate the

---

[359] Econic Technologies has started UK's first demonstration plant in 2018 for making CO_2 based polyols. The technology can produce polyols at lower temperatures and pressures compared to traditional polyol production, savings energy costs of the process. The company claims that the manufacturers can save up to 30% on raw materials as CO_2 substitutes relatively expensive fossil derived feedstocks. https://www.edie.net/news/8/UK-s-first-carbon-capture-utilisation-demonstration-plant-opens/

[360] Manuel Gotz et al., Renewable Power-to-Gas: A technological and economic review, "Renewable Energy", no. 85 (2016), https://doi.org/10.1016/j.renene.2015.07.066

[361] Covestro, "Fit with CO_2", November 23, 2018, https://press.covestro.com/news.nsf/id/b6sdlx-fit-with-co2

development of certain CCU options and has also commissioned studies on CCU that will inform the allocation of innovation fund which is established to support innovative low carbon technologies.[362, 363, 364]

Given the status of global and Singapore's research focus in CCU domain we attempt to suggest certain actions for Singapore against each of the shortlisted CCU technologies. Table 30 provides a summary of required R&D efforts that are discussed as part of the technology deep dive and gives some recommendations towards further technological development for our technology shortlist.

Table 30. Summary of required RD&D areas and recommended actions against shortlisted CCU technologies

Technology	TRL	RD&D areas	Recommended actions
Concrete curing	9	Performance testing in structural applications	There are several companies that have developed technologies which are at advanced functional stage. It is recommended to seek support from these companies in testing and monitoring the performance of CO_2-cured concrete in large structural applications in Singapore.
Aggregates based on carbonated waste	9	Potential leaching effects of carbonated aggregates containing waste Improvement in process economics	While compliant with EU waste legislation, Carbon8 has highlighted potential leaching effects related to their products. Since Singapore is active in this research area it is advised to explore any collaboration opportunities with the company to understand key considerations in the Singapore environment. Singapore should continue techno-economic evaluations to find opportunities for business case improvement, especially in relation to the Semakau landfill fee, and find suitable waste streams that can be carbonated in Singapore's context.
Ammonium carbamate (green urea)	9	Integration of different technology components that are relatively mature for green urea synthesis	Local urea demand is negligible so installing a synthesis facility might not be attractive. Production of green ammonia is the key component of green urea synthesis. The technology to synthesize urea is available if Singapore ever decides to install such a facility in future. However, interest/willingness to pay for green urea, desirability of ammonia infrastructure in Singapore and green ammonia sourcing are potential areas for further research.
Synthetic methanol	7-9	Improvement in process economics Several pathways are being researched with focus on catalyst development and material testing for electrodes	Explore possibilities to collaborate research efforts with other prominent players in catalyst synthesis and material testing. The final product is very expensive due to high feedstock costs and for production at scale some sort of support mechanism is needed. Process economics would partly improve once renewable energy production costs reduce globally.

---

[362] European Commission, Stakeholder event: Carbon Capture and Utilisation Technologies - Technological status, environmental impacts and policy developments, September 9, 2018. https://ec.europa.eu/clima/events/stakeholder-event-carbon-capture-and-utilisation-technologies-technological-status_en

[363] European Commission, "Novel carbon capture and utilisation technologies: scientific advice based on existing research on the climate mitigation potential of carbon capture and utilisation (CCU) technologies", https://ec.europa.eu/research/sam/index.cfm?pg=ccu

[364] ETIP SNET, New €10 billion EU Innovation Fund for low-carbon technologies, March 06, 2019. https://www.etip-snet.eu/energy-new-e10-billion-eu-innovation-fund-established-period-2021-2030/

Technology	TRL	RD&D areas	Recommended actions
Synthetic kerosene	5-7	Improvement in process economics Better integration of multi-step CO_2 to fuel conversion, efficiency improvement and production at scale	Explore benefits of investing in integration projects. Consider developing partnerships with companies that are active in this area. Process economics would partly improve with reduction in renewable energy production costs globally.
Formaldehyde	1-3	Catalyst development	The technology remains at lab scale. Since Singapore has capabilities in terms of catalyst testing and development, it must be evaluated if dedicated R&D efforts are worth the indicated market and environmental returns.
Acetic acid	2-4	Development of right genetically engineered microorganisms Improvement in fermentation conditions Development of suitable bioreactors	The market for acetic acid is likely to continue to expand in the region. With expertise in biochemical engineering and reactor design, Singapore should explore any collaboration possibilities with leading developers in the field.
Propylene glycol	1-3	Catalyst development	There is no evidence of the technology being tested at lab scale. However, the product is an important industrial chemical feedstock, so it is worth assessing if investing in the technology would give the desired returns. However currently, Singapore does possess the right set of capabilities to make noticeable advancements in technology development.
Oxalic acid	3-4	Recyclability of the anode, reactor design improvements, improving catalyst performance and reducing the precipitation of oxalate on the electrodes	If the recyclability of the anode improves, this technology has the potential to offer an interesting business case. Also, there are synergies between Singapore's R&D capabilities and the research support needed for this technology. Investment in the development of this technology deserves further analysis.
Supercritical CO_2 in chemicals production	9	Heterogenization of homogenous catalysts Continuous operation of the process Cost reduction of compression	Focus of research should be catalysts improvement and on the continuous operation of the reaction process. High energy costs related to the compression of CO_2 are also a significant barrier limiting application in the chemical industry. Singapore has these capabilities. Collaboration with local experts could point out how supercritical CO_2, for example for polymer production, could provide synergies with CCU in the context of Singapore.

Source: Navigant Analysis

For carbon capture technologies, post-combustion systems have received great attention as a possible near-term CO_2 capture technology that can be retrofitted with existing installations.[365] Given Singapore's emission profile, post combustion capture seems an appropriate choice at least in the short term for most of the identified point sources. These capture technologies, however, are energy intensive and result in high costs. Once CCS is installed, the high energy consumption associated with CO_2 separation as well as compression reduces the overall energy efficiency of the process. These inefficiencies lead to more fossil

---

[365] Giorgia De Guido et al., "Mature versus emerging technologies for CO_2 capture in power plants: Key open issues in post-combustion amine scrubbing and in chemical looping combustion", Frontiers of Chemical Science and Engineering 12, no. 2 (2018), https://link.springer.com/article/10.1007/s11705-017-1698-z

fuels being consumed to achieve same output levels.[366] However, there are emerging capture technologies that aim at performance improvement and cost reduction. For post-combustion configuration, a wide range of technologies are being developed in this context including two-phase solvents, adsorption, cryogenic distillation as well as membranes.[50] Pre-combustion options could be more attractive for future green field constructions as the cost of CO_2 separation stage is considerably lower than for post-combustion capture. Technologies that fit pre-combustion configuration offer the prospects of cost reduction not only from CO_2 separation but also from other process units such as shift conversion and CO_2 compression. For oxy-combustion configuration, there are emerging technologies which require new turbine cycles such as Allam cycle and may offer substantial efficiency and cost improvements compared to conventional post combustion carbon capture.[50] In addition, various solid looping and fuel cell technologies are being investigated that could be promising capture options in the future.[367] All these capture technologies are heavily researched areas where significant R&D resources have been invested especially in the developed economies. There is no single technology that can address diverse carbon capture related challenges in the power and industrial sectors. It is still a bit too early to narrow down the research focus to a few technologies recognising the fact that some are more promising than the others in terms of technological maturity and cost reduction. Therefore, Singapore needs to maintain a diverse portfolio for carbon capture related research.

---

[366] Tabbi Wilberforce et al.," Outlook of carbon capture technologies and challenges", Science of the Total Environment 657, no. (2019), https://www.sciencedirect.com/science/article/pii/S004896971834779X

[367] Wood, Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology, Department for Business, Energy and Industrial Strategy, 2018.

5. SCENARIO ANALYSIS OF CCUS

Up until this point of the analysis, Business-as-Usual assumptions were made to estimate future abatement potential and associated marginal costs for utilisation technologies. This chapter explores the impact on CCUS within two other scenarios, an Enhanced Decarbonisation (EDS) scenario and a Long-Term Decarbonisation Scenario (LTDS). These scenarios are designed to demonstrate the impact of achieving higher levels of ambition in developing a regional or global low-carbon hydrogen economy that will improve the economics and abatement effect of CCU technologies.

5.1 Defining and exploring scenarios using signposts

Scenarios are internally consistent narratives describing a future system state. Scenarios are not predictions but descriptions of alternative worlds. We define a LTDS, an EDS, and a reference scenario (equal to the BAU scenario as used in the previous chapter) to analyse shortlisted CCU technologies.

LTDS describes a scenario that where there is widespread global implementation of ambitious long-term mid-century GHG emissions strategies. The reference scenario is an extrapolation of current policy and developments including fulfilling commitments made in Singapore's NDC. EDS is a medium ambition scenario (i.e. a midpoint between the LTDS and reference scenarios).

The quantification underpinning these scenarios are called signposts. Signposts may indicate which scenario out of a set of scenarios is currently unfolding. Our signposts are quantitative metrics that will influence the abatement potential and cost of certain technology pathways and, with that, their likelihood of development.

In creating our scenarios, we defined different levels of ambition and tested the impact of the following three signposts:

1. **Carbon price:** A higher carbon price will result in increased competitive advantage of CCU-derived versus incumbent products and processes.

2. **Electricity price:** A higher local electricity price will increase overall operating costs of CCU processes and thereby hurt competitiveness.

3. **Imported hydrogen price:** With seven out of ten technologies heavily dependent on hydrogen (derived) feedstock, hydrogen costs reduction will boost their competitiveness.

The electricity price is modelled based on assumed levels of solar PV in the future grid mix, thereby influencing the overall GEF. The GEF in turn influences the abatement effect of CCUS technologies that source electricity. This has all been considered to ensure internal consistency.

5.2 Potential and costs of CCUS in the enhanced decarbonisation scenario

In the EDS, increased climate action becomes apparent through an increased share of renewables in the Singapore grid (influencing prices and GEF), a higher carbon tax compared to the reference scenario, and lower hydrogen production costs abroad that can also be imported at lower cost to Singapore[368]. This

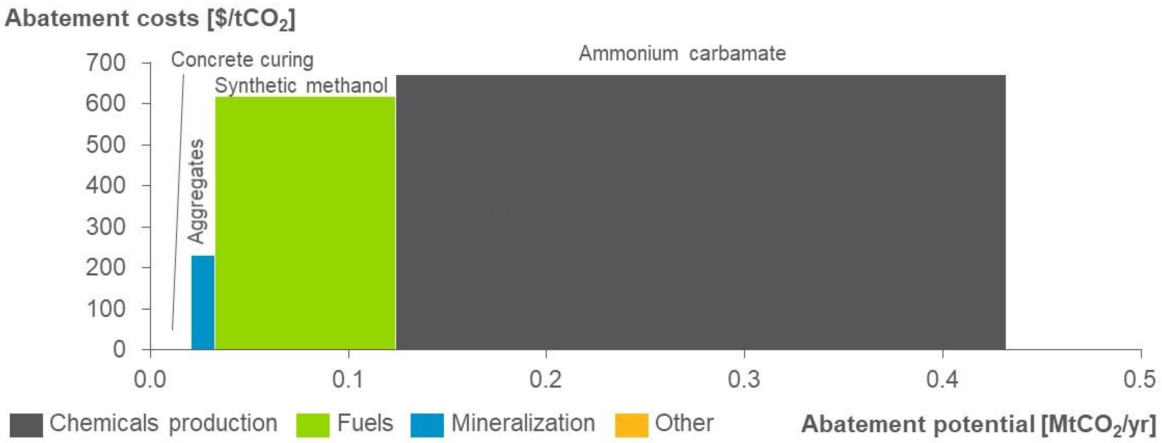
---

[368] In the EDS scenario, compared to the refence scenario, it was assumed that the carbon price will increase by ~60% in 2025, while the price of electricty & hydrogen as well as the GEF will decrease by ~10%, ~50% and ~20% respectively in 2050.

section explores the implications of such a scenario for the target years 2025 and 2050, using Marginal Abatement Cost Curves (MACCs).

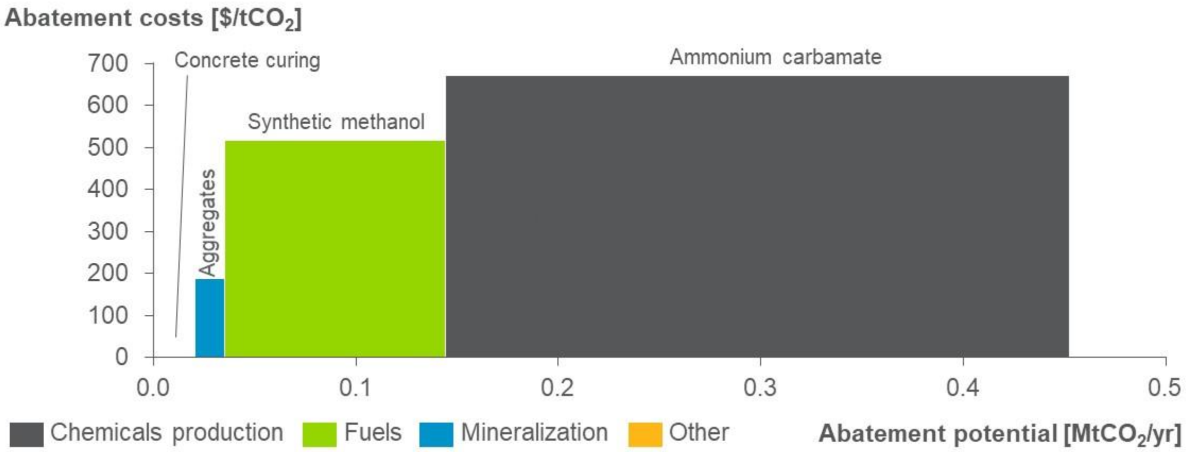
5.2.1 Target year 2025

Figure 31. Net abatement MACC for 2025 in the EDS scenario, assuming one 'typical' plant per technology is developed.



Source: Navigant analysis. Four technologies deployed at the scale of one reference plant per technology.

Figure 32. Direct abatement MACC for 2025 in the EDS scenario, assuming one 'typical' plant per technology is developed.



Source: Navigant analysis. Four technologies deployed at the scale of one reference plant per technology.

The above MACC reflects that by 2025, five out of 10 shortlisted technologies have a reasonable chance of developing to full maturity and, therefore, of being deployed in the form of one single plant in Singapore.[369] Supercritical CO_2 is not shown due to the low abatement potential (around 300 tCO_2 per year). The MACCs show the effect of an overall increase in abatement potential at marginally lower cost if only the direct abatement is considered, and the CO_2 emissions associated with energy inputs are ignored.

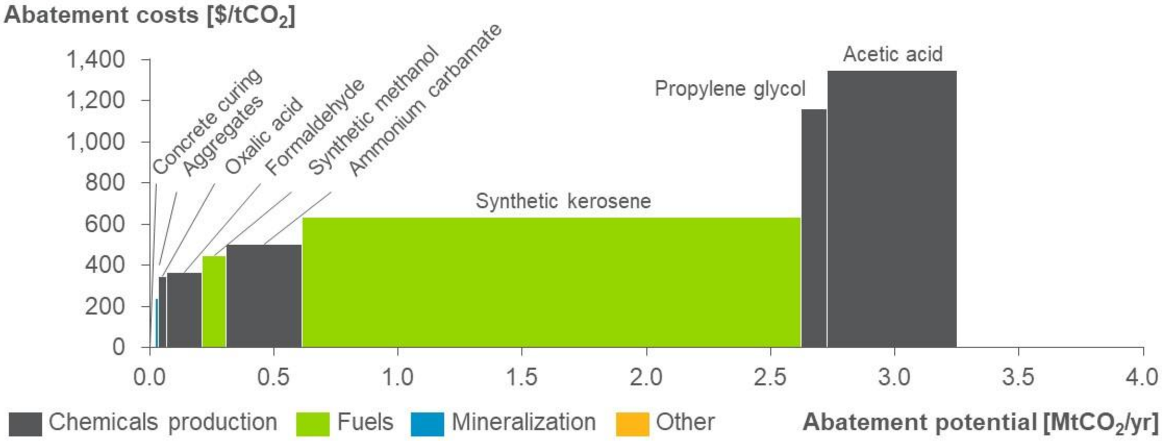
---

[369] This is based on an assumed 2 TRL level increase per decade, reflecting a high-level average technology maturation timeline.

The effect of decreasing costs for hydrogen imports becomes apparent in the marginal net abatement costs for both synthetic methanol and ammonium carbamate. The costs for synthetic methanol are lowered further due to a lower electricity price and a lower GEF, the latter increasing the net abatement effect and therefore reducing net abatement costs. In the reference scenario, the direct abatement cost and net abatement costs were estimated at US\$974/tCO_2 and US\$1,016/tCO_2 by 2025, respectively, where in the EDS they fall to US\$617/tCO_2 and US\$671/CO_2.

5.2.2 Target year 2050

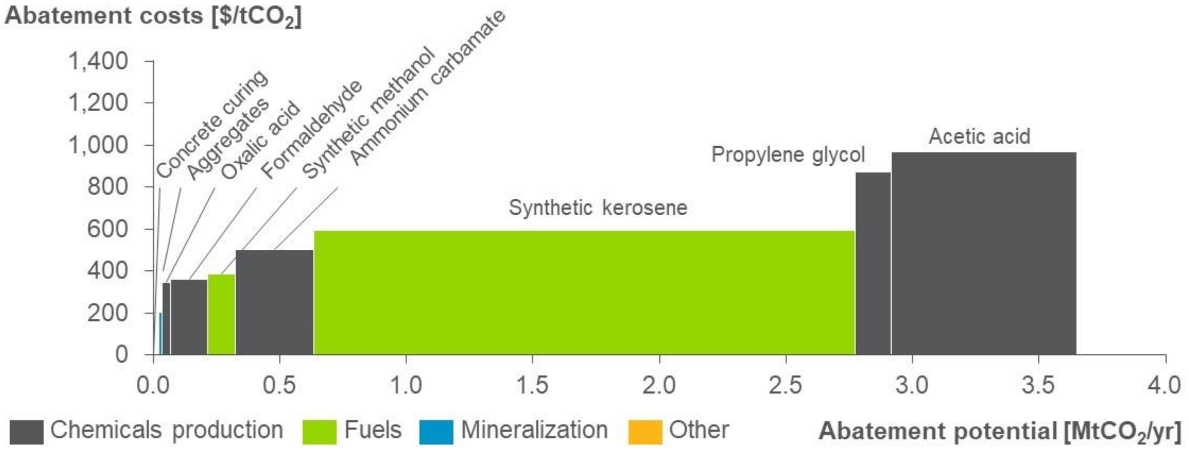
Figure 33. Net abatement MACC for 2050 in the EDS scenario, assuming one 'typical' plant per technology is developed.



Source: Navigant analysis. Nine technologies deployed at the scale of one reference plant per technology

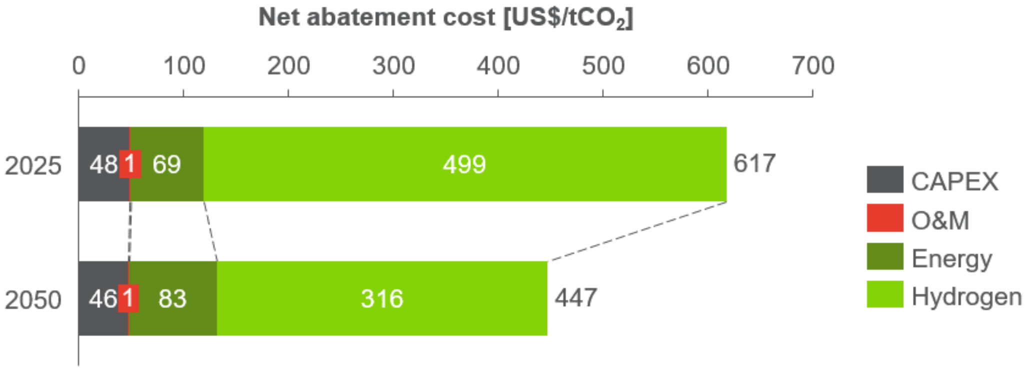
By 2050, all shortlisted technologies have a reasonable chance of being fully mature. Synthetic kerosene stands out in terms of abatement potential. This potential reflects the relatively large reference plant size. Due to lower costs for hydrogen by 2050, the net abatement costs for synthetic methanol and ammonium carbamate came down further from 2025. Methanol drops 28% to US\$447/tCO_2 whereas ammonium carbamate drops 25% to US\$635/t$CO_{2.}$ The breakdown of this cost development is exemplified for synthetic methanol in Figure 35.

Figure 34. Direct abatement MACC for 2050 in the EDS scenario, assuming one 'typical' plant per technology is developed.



Source: Navigant analysis. Nine technologies deployed at the scale of one reference plant per technology

Figure 35. Net abatement cost development for synthetic methanol production in the EDS scenario



Source: Navigant analysis

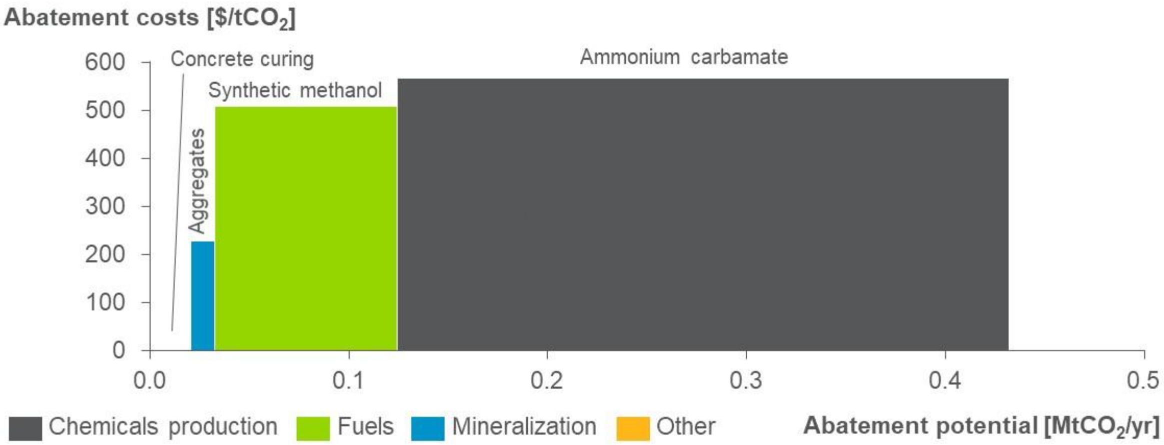
These technologies come closer to being economically viable when purely viewed as abatement measures compared to the reference scenario. However, for most technologies, the remaining economic "gap" is still substantial. Hence, to support these technologies to become viable abatement measures, either costs need to come down or support mechanisms would need to be developed that benefit these technologies. In Section 5.4 we explore how the value of a resulting product may help to further discount abatement costs for CCU technologies.

5.3 Potential and costs of CCUS in the long-term decarbonisation scenario

In the LTDS, we explore the local effect of a world that globally implements ambitious long-term mid-century GHG emissions strategies. In our simplified model, this large increase in climate action becomes apparent through a larger share of renewables in the Singapore grid (affecting prices and GEF), a higher carbon tax compared to the other two scenarios, and lower hydrogen production costs abroad that can also be imported at lower cost to Singapore[370].

5.3.1 Target year 2025

Figure 36. Net abatement MACC for 2025 in the LTDS scenario, assuming one 'typical' plant per technology is developed.

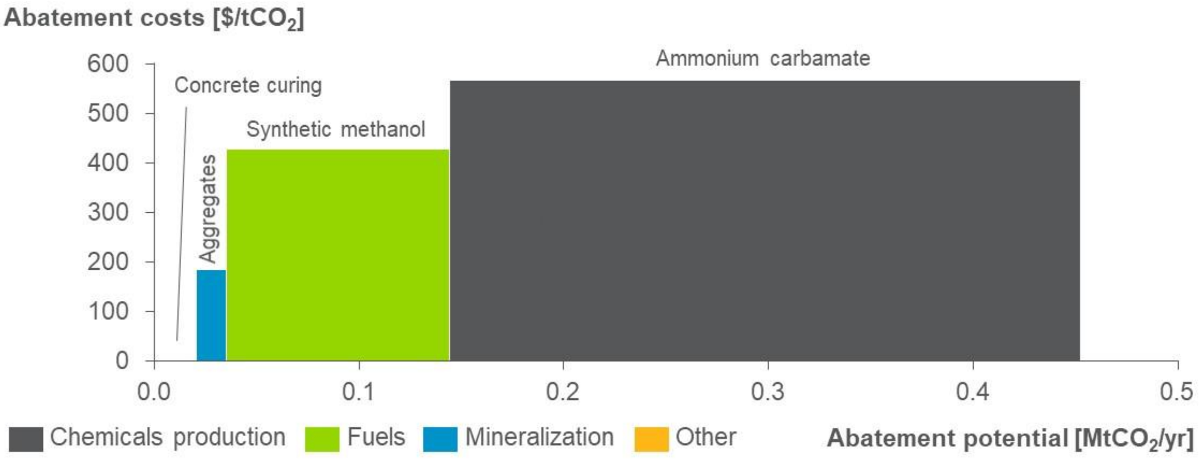


Source: Navigant analysis. Four technologies deployed at the scale of one reference plant per technology.

---

[370] In the LTDS scenario, compared to the refence scenario, it was assumed that the carbon price will increase by ~410% in 2050, while the price of hydrogen as well as the GEF will decrease by ~65% and ~40% respectively in 2050. Due to the larger share of renewables which would increase the cost of deployment, it was assumed that electricity prices will increase by ~5% in 2050 compared to the refence scenario.

Figure 37. Direct abatement MACC for 2025 in the LTDS scenario, assuming one 'typical' plant per technology is developed.



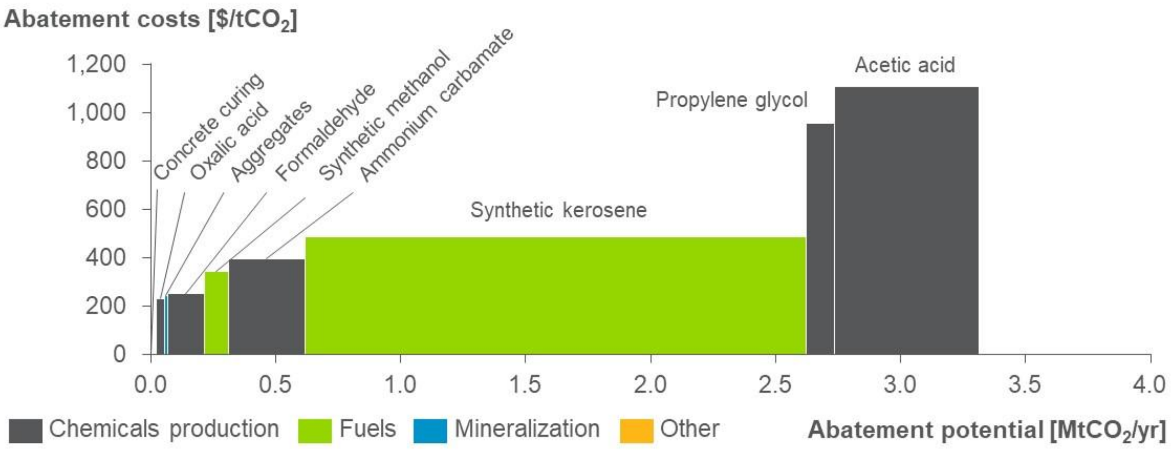
Source: Navigant analysis. Four technologies deployed at the scale of one reference plant per technology.

The above MACC reflects that by 2025, five out of 10 shortlisted technologies have a reasonable chance of developing to full maturity and, therefore, to be deployed in the form of one single plant in Singapore. As in the previous scenario, supercritical CO_2 is not shown due to the low abatement potential (around 300 tCO_2 per year). The MACCs show the effect of an overall increase in abatement potential at marginally lower cost if only the direct abatement is considered, and the CO_2 emissions associated with energy inputs are ignored.

Compared to the EDS, the landed hydrogen costs are on a steeper decline curve. By 2025 in the reference scenario, the direct abatement cost and net abatement costs were estimated at US$974/$tCO_2$ and US$1,016/$tCO_2$, respectively, where in the EDS they fall to US$617/$tCO_2$ and US$671/$CO_2$. In the LTDS, the costs continue to decline to US$509/$CO_2$ and US$567/$CO_2$, respectively.

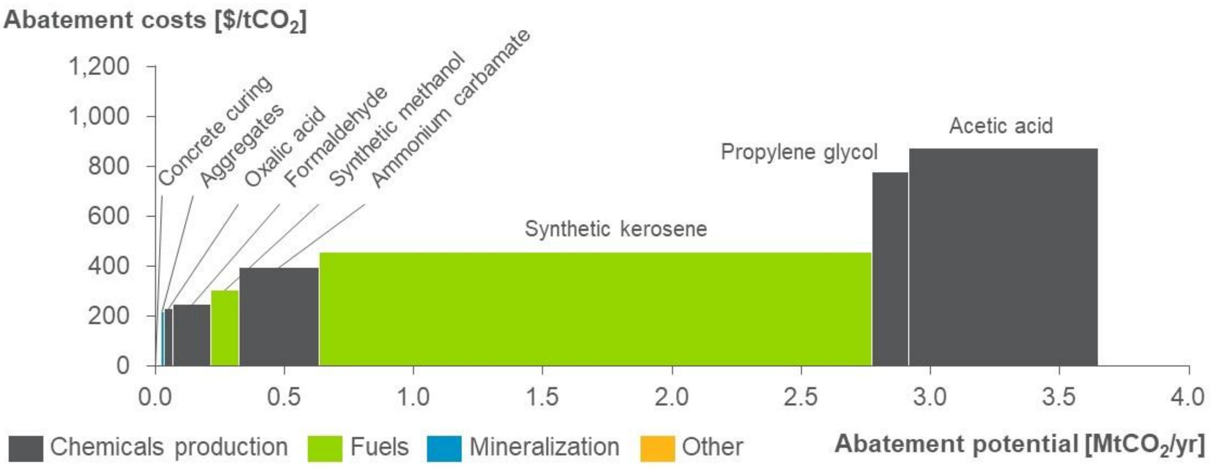
5.3.2 Target year 2050

Figure 38. Net abatement MACC for 2050 in the LTDS scenario, assuming one 'typical' plant per technology is developed.



Source: Navigant analysis. Nine technologies deployed at the scale of one reference plant per technology.

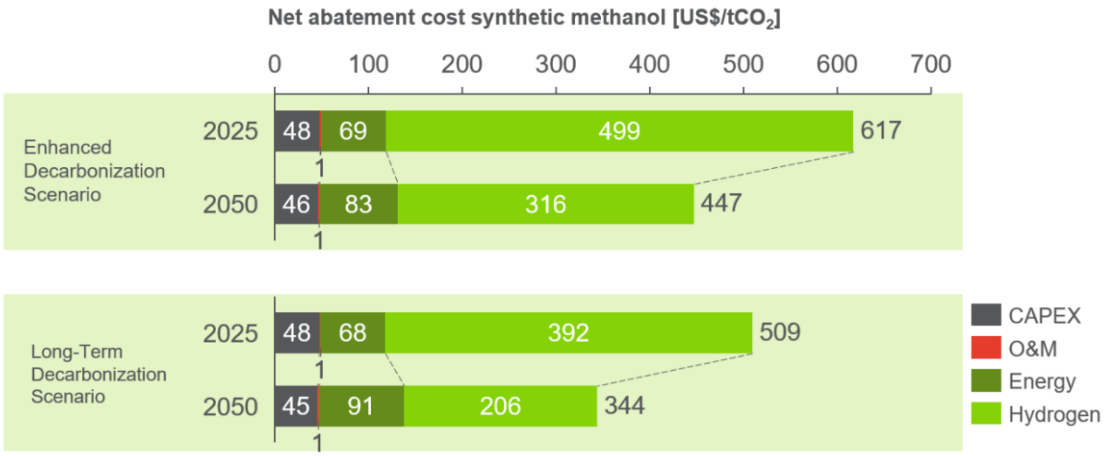
Figure 39. Direct abatement MACC for 2050 in the LTDS scenario, assuming one ‘typical’ plant per technology is developed.



Source: Navigant analysis. Nine technologies deployed at the scale of one reference plant per technology.

By 2050, all shortlisted technologies have a reasonable chance of being fully mature and hence all are depicted in the 2050 MACCs. In terms of abatement potential, synthetic kerosene stands out. This potential reflects the relatively large reference plant size. Compared to 2025, but also compared to the other two scenarios, technologies that source hydrogen or hydrogen-derived feedstock have a lower overall abatement cost due to the aggressive decrease in these feedstock costs. This has a material impact on the hydrogen-dependent technologies. Figure 40 demonstrates this effect for synthetic methanol. This figure also shows the effect of an increasing electricity price on the overall abatement costs. This increase in electricity price arises from the projected increased costs incurred for accommodating a largeshare of intermittent renewables (solar PV).

Figure 40. Net abatement cost development for synthetic methanol production in the EDS and LTDS scenarios



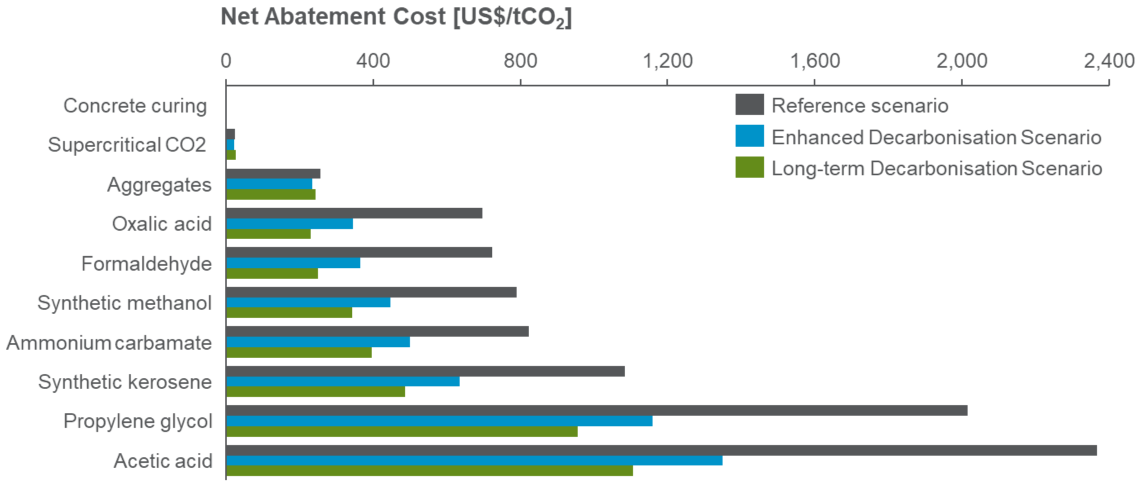
Source: Navigant analysis

Several technologies, when purely viewed as (net) abatement measures, may come closer to being economically viable if a significant carbon tax is applied. These technologies could then function as abatement measure from a purely economic viewpoint, where the costs for carbon capture and concentration and the market value of resulting products are not considered yet. At carbon prices that run in the hundreds of US dollars per tonne CO_2, technologies such as concrete curing, aggregates from carbonated waste, oxalic acid, and formaldehyde would become economically viable. In the next section, we explore how the market value of resulting products may help to increase economic viability further.

5.4 Integrated net abatement cost assessment in LTDS

The net abatement costs for CCU technologies come down at increasingly ambitious scenarios. This effect is depicted for all technologies in Figure 41.

Figure 41. Decreasing net abatement costs by 2050 at increasing climate ambition levels under the scenarios defined in this study

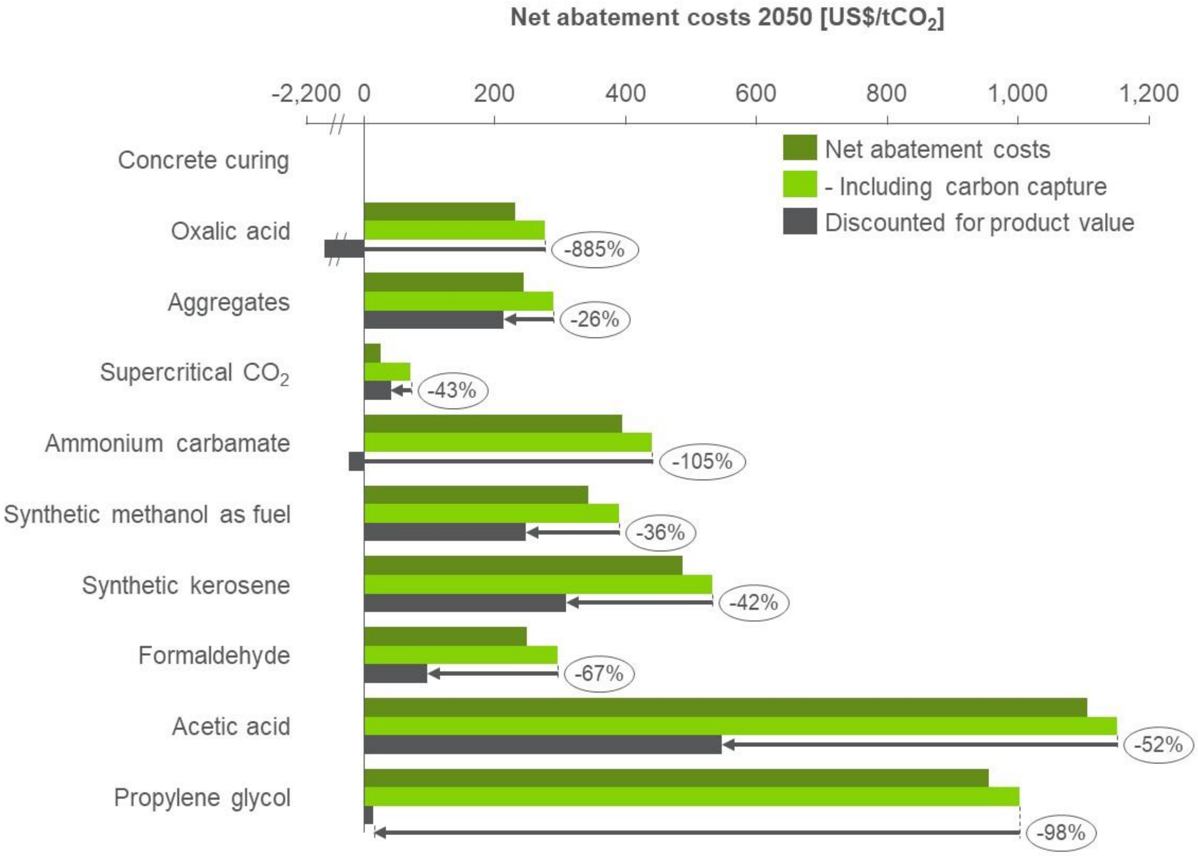


Source: Navigant analysis

In exploring these scenarios in the previous sections, abatement costs and potentials are provided as-is; we do not consider the abatement impact (the potential reduction of GHG emissions in Singapore or elsewhere) of displacing incumbent products, we exclude capture costs and we do not account for value of resulting products that could be sold. In this section, we explore how abatement costs change when we include capture costs and discount for the fact that resulting products have a value. We perform this analysis for the LTDS and in target year 2050. Projecting product value towards 2050 comes with increased additional uncertainty. No further product value developments have been considered and hence the resulting analysis and figure should be taken as highly indicative only. Section 4.4.5 details how weighted average capture costs are derived, and which product values have been used for this assessment.

In Figure 42, the additional costs for producing concrete with concrete curing are zero, since any costs are offset by savings in the manufacturing process. Therefore, the revenues from concrete sales cannot be subtracted in this instance. The figure shows that when the product value is considered, marginal net abatement costs are discounted to much lower levels for most technologies, thus bringing into reach most CCU pathways of the shortlist when a relatively high carbon tax would be applied. It should be noted that other commercial aspects can play a role that were not considered here, such as avoiding landfill tax in the case of aggregates from carbonated waste.

Figure 42. The effect on net abatement costs in 2050 of including capture costs and selling CCU-derived products under the LTDS scenario.



Source: Navigant analysis. Weighted average capture costs of 46 US$/tCO$_2$ are applied. The full range is 14-58 US$/tCO$_2$, see Figure 27. The additional costs for producing concrete with concrete curing are zero, since any costs are offset by savings in the manufacturing process. Therefore, the revenues from concrete sales cannot be subtracted in this instance.

6. KEY FINDINGS

This study looked at three main points: the CO_2 emissions profile of the energy and chemicals sectors, the carbon abatement potential and cost of implementing CCUS technologies, and the technical and commercial barriers to near (by 2025-2030) and long-term (2050) implementation of such technologies. We also identified enablers required to facilitate successful implementation. This chapter highlights key findings.

- The emissions profile of the energy and chemicals sector shows that an estimated **38.8 million tonnes CO_2 is emitted annually**, of which the lion's share (96%) is from low CO_2 concentration flue gas (3–8%). Considering this emissions profile, the **weighted average cost for carbon capture and concentration is US$85/t$CO_2$,** though options for low-cost capture exist (full range of US$14–100).

- Specifically, for Singapore, **no subsurface CO_2 sequestration (CCS) options** are identified. **In the wider region, around 85 giga tonnes of CO_2 storage potential is identified**. Using this potential would require long-distance transport of CO_2. The potential for enhanced oil recovery in the region should be explored further.

- By 2050, all ten shortlisted CCU technologies may reach maturity. Their **net abatement potentials range between 0.3 – 2,000 kilo tonnes of CO_2,** based on one reference plant per technology**.** All technologies with **substantial abatement potential require significant amounts of hydrogen or ammonia.**
    - For CCU technologies to be effective climate mitigation measures, this feedstock needs to be low-carbon. It is important to **explore the future availability and costs of these low-carbon commodities**.

- To increase the probability of realising most of these CCU technologies at industrial scale in Singapore, **economics needs to improve** through cost reductions, technology development and other supporting mechanisms.
    - The high abatement costs through CCU show that reaching commercial maturity is a **key barrier** for most CCU technologies.
    - For higher TRL technologies, either **further cost reductions** related to hydrogen feedstock or a **level playing field is required** to compete with incumbent production methods and overcome commercial barriers.
        - The development of low-carbon hydrogen and renewable energy production pilots require support to reduce production costs.
        - Especially for globally traded commodities, international certification needs to be adopted and harmonised to accept CCU-derived products.
    - On the basis of cost, abatement potential, scalability of the technology and co-benefits, for the higher-TRL technologies, the following technologies would be promising to pursue in the context of Singapore: **concrete curing, aggregates based on carbonated waste and synthetic methanol.**
    - For the lower TRL technologies, **technological breakthroughs are required** to scale and improve efficiency. Targeted R&D support may help to achieve this.

- Based on abatement potential, scalability of the technology and co-benefits, for the lower-TRL technologies the following technologies would be promising to pursue in the context of Singapore: **synthetic kerosene, oxalic acid and acetic acid.**
- Other supporting mechanisms can aid CCU further:
    - In incumbent markets, enhanced uptake of low-carbon alternatives such as CCU can increase abatement potential. Examples are prescribing a fuel blend for sustainable fuels or recognising CCU-based materials in existing green building schemes.
    - Carbon pricing policies, as modelled in the Enhanced Decarbonisation Scenario and the Long-Term Decarbonisation Scenario would also incentivize the development of a CO_2 market.

APPENDIX A. CCU TECHNOLOGIES

A.1 CCU assessment methodology, parameters, and assumptions

A.1.1 Longlist assessment parameters

In evaluating longlist of CCU technologies, several parameters describing emissions intensity and energy requirements were used. These describe or approximate the present-day industrial reality in Singapore. The table below indicates EFs associated with energy and feedstock inputs.

Energy and emission factors	Value	Unit
Singapore grid emission factor	0.42	$kgCO_2/kWh$
Standard emission factor industrial heat	0.19	$kgCO_2/kWh$
Hydrogen emission factor	8.10	$tCO_2/tonne$
Ethylene emission factor	1.84	$tCO_2/tonne$
Ethylene Oxide emission factor	0.66	$tCO_2/tonne$
Methanol emission factor	0.52	$tCO_2/tonne$
Propylene emission factor	1.84	$tCO_2/tonne$
Propylene oxide emission factor	0.66	$tCO_2/tonne$

Source: EMA, DEFRA, Rostrup-Nielsen, IEA, NEA, DECHEMA

For several technologies, no direct energy requirements were available from literature. In these instances, a theoretical approach was taken by first establishing the Gibbs free energy of the reaction. Afterwards, an approximation was made from Gibbs free energy (expressed in GJ per tonne of product) to actual process energy needs where we distinguish exergonic and endergonic processes. This methodology was chosen to arrive at a more realistic estimation of process cost; the actual process costs entail energy penalties such as for purification, reactant recycling and compression. The table below listing the delta (Δ) describing an average difference between current (2006-2008 depending on technology) large-scale commercial chemical production process energy demand and the theoretical minimum, all excluding feedstock. In this table, exothermic and endothermic processes are provided separately. Data retrieved from Saygin.[371]

Product	Current best practice technology	Thermodynamic minimum	Resulting Δ for endothermic reactions	Resulting Δ for exothermic reactions
		Specific energy consumption (GJ/tonne product)		
Ethylene	20.6	6.7	13.90	
Methanol	8.8			
Basic aromatics	2.2	0		
PE	1.4	-3.8		5.20
PP	1	-2.5		3.50
PET	4.8	0.2	4.60	
Ethylene glycol	4.9	-2.7		7.60
Polystyrene	0.9	-0.7		1.60
Terephtalic acid	2.9	-7.6		10.50

---

[371] Saygin, Assessing industrial energy use and CO_2 emissions, PhD thesis, 2012

Product	Current best practice technology	Thermodynamic minimum	Resulting Δ for endothermic reactions	Resulting Δ for exothermic reactions
Styrene	7.7	1.1	6.60	
Cyclohexane	-1.9	-2.4		0.50
Nitric acid	-9.4	-25.4		16.00
Ammonia	10.9	0		
Average			**8.4**	**6.4**

Source: Saygin

A.1.2 Technology Readiness Level (TRL)

For the assessment of longlist, we also considered TRL as one of the parameters to evaluate the attractiveness of CCU technologies for Singapore. We used globally accepted numeric scale to mark the maturity of these technologies that ranges from 1 to 9. The table below provides descriptions of TRLs which are grouped into three stages: (i) research lab, (ii) simulated world, and (iii) real world.

Stage	TRL	Description
Real world	9	Actual technology proven through successful use in an operational environment
	8	Actual technology completed and qualified through tests and demonstrations
	7	System prototype demonstration in an operation environment
Simulated world	6	System/subsystem model or prototype demonstrated in a simulated environment
	5	Component validation in a simulated environment
	4	Component validation in a laboratory environment
Research lab	3	Analytical and experimental critical function and/or proof-of-concept
	2	Technology concept and/or application formulated
	1	Basic principles observed and reported

Source: NASA

A.1.3 Longlist results

CCU technology	TRL	Land footprint	Net abatement with CO_2 demand		Net abatement effect	CO_2 emitted	Global CO_2 demand
	1 to 9	High/Med/Low	m^2/t product	($MtCO_2$)	(%)	tCO_2/t product	$MtCO_2$
Ammonium carbamate	9	Med	N/A	100	69%	0.17	144
Formaldehyde	2	Med	N/A	22.70	61%	0.57	37
Propylene glycol	5	Med	N/A	1.20	31%	1.01	4
Acetic acid	3	Med	N/A	0.25	1%	1.45	20
Oxalic acid	4	Med	N/A	0.12	63%	0.18	0.18
Butyric acid	2	Med	N/A	0.01	6%	1.88	0.12
Dimethyl carbonate	5	Med	N/A	0.00	-439%	2.64	NA
Ethylene carbonate	9	Med	N/A	0.00	-188%	1.44	NA
Methyl carbamate	9	Med	N/A	0.00	-221%	1.89	NA
Salicylic acid	9	Med	N/A	-0.07	-227%	1.05	0.03

CCU technology	TRL	Land footprint	Net abatement with CO_2 demand		Net abatement effect	CO_2 emitted	Global CO_2 demand
	1 to 9	High/Med/Low	m^2/t product	($MtCO_2$)	(%)	tCO_2/t product	$MtCO_2$
Benzoic acid	9	Med	N/A	-0.14	-80%	0.58	0.17
Acrylic acid	3	Med	N/A	-0.66	-17%	0.72	4
Formic acid	6	Med	N/A	-0.75	-110%	2.02	0.70
Polypropylene carbonate	7	Med	N/A	-1.70	-194%	1.47	1
Ethane diol dicarbamate	2	Med	N/A	-3.54	-197%	0.89	2
Polyethylene carbonate	7	Med	N/A	-3.54	-235%	1.44	2
Sodium bicarbonate	7	Med	N/A	-6.85	-231%	1.72	3
DME	9	Med	0.80	-16.38	-132%	4.43	12
Polyurethane	7	Med	N/A	-17.70	-446%	1.17	4
Ethylene glycol	5	Med	N/A	-26.68	-99%	1.99	27
Ethylene oxide	3	Med	N/A	-41.04	-150%	2.50	27
CO_2 to Methanol to BTX	7	Med	2.17	-94.65	-22%	4.10	423
CO_2 to MTO	9	Med	2.17	-714.71	-91%	6.00	785
Urea yield boosting	9	Low	0.00	10.62	77%	0.17	14
Methanol yield boosting	9	Low	N/A	8.73	80%	0.28	11
Supercritical CO_2 power cycles	6	Low	N/A	0.00	100%	0.00	NA
EOR	9	Low	N/A	0.00	N/A	0.00	300
Enhanced CBM recovery	7	Low	N/A	0.00	N/A	0.00	30
Food freezing, chilling and packaging	9	Low	0.00	8.50	100%	0.00	9
Beverage carbonation	9	Low	0.00	8.00	100%	0.00	8
Horticulture (glasshouses)	9	Low	0.00	1.00	100%	0.00	1
Synthetic kerosene	6	Med	1.29	66.69	9%	2.85	784
Synthetic methanol as fuel	8	Med	N/A	3.05	10%	2.48	31
Synthetic diesel	8	Med	1.29	-647.47	-16%	3.65	4,009
Synthetic methane as fuel	7	Med	9.80	-2,251.12	-70%	4.67	3,226
Formic acid as a fuel	6	Low	N/A	-3,106.99	-110%	2.01	2,835
Hydrocarbon excreting microorganisms (Helioculture)	5	High	512.59	-8,452.67	-1749%	6.65	483
Algae cultivation	6	High	768.88	-15,949.26	-1761%	6.70	906

CCU technology	TRL	Land footprint	Net abatement with CO_2 demand		Net abatement effect	CO_2 emitted	Global CO_2 demand
	1 to 9	High/Med/Low	m^2/t product	($MtCO_2$)	(%)	tCO_2/t product	$MtCO_2$
Carbonate mineralisation - industrial waste streams	9	Low	0.02	1000	100%	0.00	1,000
Concrete curing	8	Low	N/A	140	94%	0.03	150
Carbonate mineralisation - natural minerals	9	High	N/A	0.00	85%	0.06	NA
Water treatment and pH control	9	Low	0.00	5	100%	0.00	5
Electronics	9	Low	0.00	1	100%	0.00	1
Metal working	9	Low	0.00	1	100%	0.00	1
Refrigerant gas	9	Low	0.00	1	100%	0.00	1
Supercritical CO_2	9	Low	0.00	1	100%	0.00	1

Source: Navigant analysis

A.1.4 Calculating abatement potential and utilisation cost

High level approach

Abatement potentials are defined in two ways, the abatement potential associated with:

i. Direct abatement impact, using only the amount of CO_2 utilised in producing the product.

ii. Net abatement impact, using direct impacts as well as the CO_2 emitted in the process for energy needs or to produce energy-related feedstock such as hydrogen or methanol.

Utilisation costs are quantified using OPEX and CAPEX. These are sourced from literature where available. Costs associated with Carbon Capture and Concentration (CCC) are excluded from the MACCs. The value of CCU product has not been discounted for in calculating marginal abatement costs and hence are not reflected in MACCs.

The 2025 MACC's only cover technologies that by that time may have matured to TRL 9, assuming technologies can mature by 2 TRL stages per decade.

Detailed approach

Constructing a MACC requires data and projections on abatement effects and costs. For some of the shortlisted technologies at hand, these data are not readily available from literature. Hence, an approach on estimating these data is required. The table below details the data required to be able to estimate abatement potential and cost, and the way these data are derived.

Data requirements	Approach to estimate
Net abatement† ($MtCO_2$/year)	
+ CO_2 utilised	Available from longlist evaluation.
+ CO_2 emitted, needs:	

Data requirements	Approach to estimate
- CCU energy demand	Energy demand available from longlist evaluation. No changes in energy demand over time assumed.
- Energy emission factors	Projections to 2025 and 2050 for electricity and heat. Feedstock (hydrogen and ammonia) is assumed to be zero emissions.
+ CO_2 demand	CO_2 demand resulting from the product is defined as the CO_2 demand resulting from one typical plant for the CCU technology. Typical plant sizes are based on literature. If multiple different typical plant sizes are derived from literature, the average is taken from these values.
Cost (US$/t$CO_2$)	
+ CCU costs	Cost data from literature used where available. Where no cost data are available, the following approach is taken.
- OPEX	
- Feedstock	Only energy-related feedstock is accounted for, energy costs will require industrial energy costs for today as well as an agreed cost projection for 2025 and 2030.
- Energy	Electricity costs are based on projections of electricity costs towards 2025 and 2030, diversified for different scenario's based on the projected penetration of renewable electricity production. For the cost of industrial heat, the natural gas price in Singapore is used as proxy.
- Personnel & maintenance	A standard 3% surcharge on CAPEX is assumed.[372]
- CAPEX	
- Investment	Investments are based on literature (demo) plant CAPEX if available. When no investment data are available, a CAPEX/OPEX ratio of 60/40 is assumed.
- Capital recovery factor	Interest rate 10%, 20 years levelisation period.[372]

The costs incurred per tonne of product are the same in both direct and net abatement. However, the cost per tonne of CO_2 changes because the net abatement potential is lower than the direct abatement potential; therefore, the relative cost goes up for net abatement.

‡ These parameters are in line with the net abatement effect definition used in the longlist. In wider literature, the term abatement typically includes end-of-life (combustion) EFs and potential (fossil) displacement effects. These effects are not accounted for in this assessment.

Source: references indicated, Navigant analysis

The mathematical formulae to estimate abatement potential and associated marginal cost per technology are as follows:

$$\begin{aligned}\boldsymbol{Net\ Abatement}\ [\boldsymbol{tCO_2/year}] \\ &= \left(\boldsymbol{CO_{2,utilised}}[\boldsymbol{tCO_2/tProd}] - \boldsymbol{E_{energy}}[\boldsymbol{kWh/tProd}] \times \boldsymbol{EF}[\boldsymbol{tCO_2/kWh}] \right. \\ &\left. - \boldsymbol{Feedstock}[\boldsymbol{tonne/tProd}] \times \boldsymbol{EF}[\boldsymbol{tCO_2/tonne}]\right) \times \boldsymbol{Demand}\ [\boldsymbol{tProd/year}]\end{aligned}$$

---

[372] GCCSI, Knowledge sharing report. CO2 liquid logistics shipping concept (LLSC): overall supply chain optimization, 2011; 10.1, https://hub.globalccsinstitute.com/publications/co2-liquid-logistics-shipping-concept-llsc-overall-supply-chain-optimization/101-cost

$$\begin{aligned} \boldsymbol{Cost}\,[\$/\boldsymbol{tCO_2}] = {} & \left(\sum\nolimits_i^n \boldsymbol{Cost_{feedstock,i}}[\$/\boldsymbol{tProd}] + \boldsymbol{Cost_{energy}}[\$\,/\boldsymbol{tProd}] + \boldsymbol{Cost_{P\&M}}[\$/\boldsymbol{tProd}]\right) \\ & \times \boldsymbol{Abatement}^*[\boldsymbol{tCO_2}/\boldsymbol{tProd}] \\ & + \boldsymbol{Investment}[\$] \times \boldsymbol{CRF}\ /\ \boldsymbol{Demand}\ [\boldsymbol{tProd}/\boldsymbol{year}]\ /\ \boldsymbol{Abatement}^*[\boldsymbol{tCO_2}/\boldsymbol{tProd}] \end{aligned}$$

where demand for energy and feedstock and associated emission factors may be differentiated by process and source to calculate abatement potential. $\boldsymbol{Abatement}^*$ differs from the first formula as it is expressed in abatement potential *per tonne of product* as opposed to the abatement potential in tonnes of CO_2 per year for a typical CCU plant. It is equal to the first term (in parentheses) of the total product in the first equation.

Capital Recovery Factor (CRF) is defined as follows:

$$\boldsymbol{CRF} = \frac{\boldsymbol{i(1+i)^n}}{\boldsymbol{(1+i)^n - 1}}$$

Where *i* is the assumed interest rate and *n* the number of years in the levelisation period. When employing cost ranges from literature, assumed CRF's are identified and where possible costs are re-calculated to be in line with the CRF as used for this study. This is done to ensure consistency between cost estimates.

Where necessary, investment costs are estimated from a reference/demo plant using a scaling factor of 0.67 for scaling up the investment costs from a smaller demo plant capacity:[373]

$$\boldsymbol{Investment}[\$] = \boldsymbol{CAPEX_{demo}} \times \left(\frac{\boldsymbol{Capacity}}{\boldsymbol{Capacity_{demo}}}\right)^{0.67}$$

or, when no demo plant costs data are available, investment costs are estimated from an assumed 60/40 CAPEX to OPEX ratio.**Error! Bookmark not defined.**

All costs are expressed in 2019 US$ and are nominal values; besides CRF (annuity) to annuitise investment, future costs are not discounted.

A.1.5 Shortlist scenarios and MACC assessment parameters

Reference plant sizes deployed for all scenarios

CCU technology	Plant size	Unit	Reference
Concrete curing	33,600,000	Tonne/yr	Based on total annual production in Singapore, because it is an add-on technology that all concrete plants could implement in principal.
Mineralisation of CO_2 in aggregates	110,000	Tonne/yr	Based on Carbon8's demonstration plants in the UK
Ammonium carbamate (urea)	550,000	Tonne/yr	EFMA, Production of urea and urea ammonium nitrate, 2000
Synthetic methanol	39,698	Tonne/yr	Iceland plant serves as pilot for a plant about ten times this size, see DECHEMA, Technology study Low carbon energy and feedstock for the European chemical industry, p64.
Synthetic kerosene	688,356	Tonne/yr	Scaled to Malaysia's Bintulu GTL plant.

---

[373] The 2/3-exponent of Remer and Chai can be used to scale CAPEX to capacity. D.S. Remer and L.H. Chai, "Estimate costs of scaled-up process plants," Chemical Engineering, pp. 138-175, April 1990.

CCU technology	Plant size	Unit	Reference
Formaldehyde	100,000	Tonne/yr	Scaled to a recent Dynea plant at the Ibn Sina site in Saudi Arabia.
Acetic acid	500,000	Tonne/yr	Scaled to the Celanese Integrated Acetyls Complex, Jurong Island
Propylene glycol	80,000	Tonne/yr	Scaled to a Shell plant in Bukom Island in Singapore
Oxalic acid	70,000	Tonne/yr	Production capability of the largest oxalic acid manufacturer in China
Supercritical CO_2	325	Tonne/yr	Based on an application in a US fluoropolymer plant using supercritical CO_2

Source: references indicated in section 4, Navigant analysis

A.2 List of technology providers for CCU technologies

This annex provides a list of technology providers mentioned throughout the report by technology. The definition of technology provider is broadly applied, since also companies that implement the technology are mentioned. For propylene glycol and oxalic acid, no providers were found, whereas for supercritical CO_2 too many providers exist due to the high maturity of the technology and are not list in the table.

Technology	Name of company	Country
Concrete curing	CarbonCure	Canada
	Solidia	US
Mineralisation of CO_2 in aggregates	Carbon8 Aggregates	UK
	Blue Planet	US
	CarbiCrete	Canada
Ammonium carbamate (green urea)	Siemens (green ammonia)	Germany
Synthetic methanol	Mitsui Chemicals	Japan
	Carbon Recycling International	Iceland
Synthetic kerosene	LanzaTech	New Zealand
	Sunfire	Germany
	SkyNRG	The Netherlands
Formaldehyde	Dynea	Finland
Acetic acid	LanzaTech	New Zealand
	Petronas	Malaysia
Propylene glycol	-	-
Oxalic acid	-	-
Supercritical CO_2	-	-

Source: Navigant