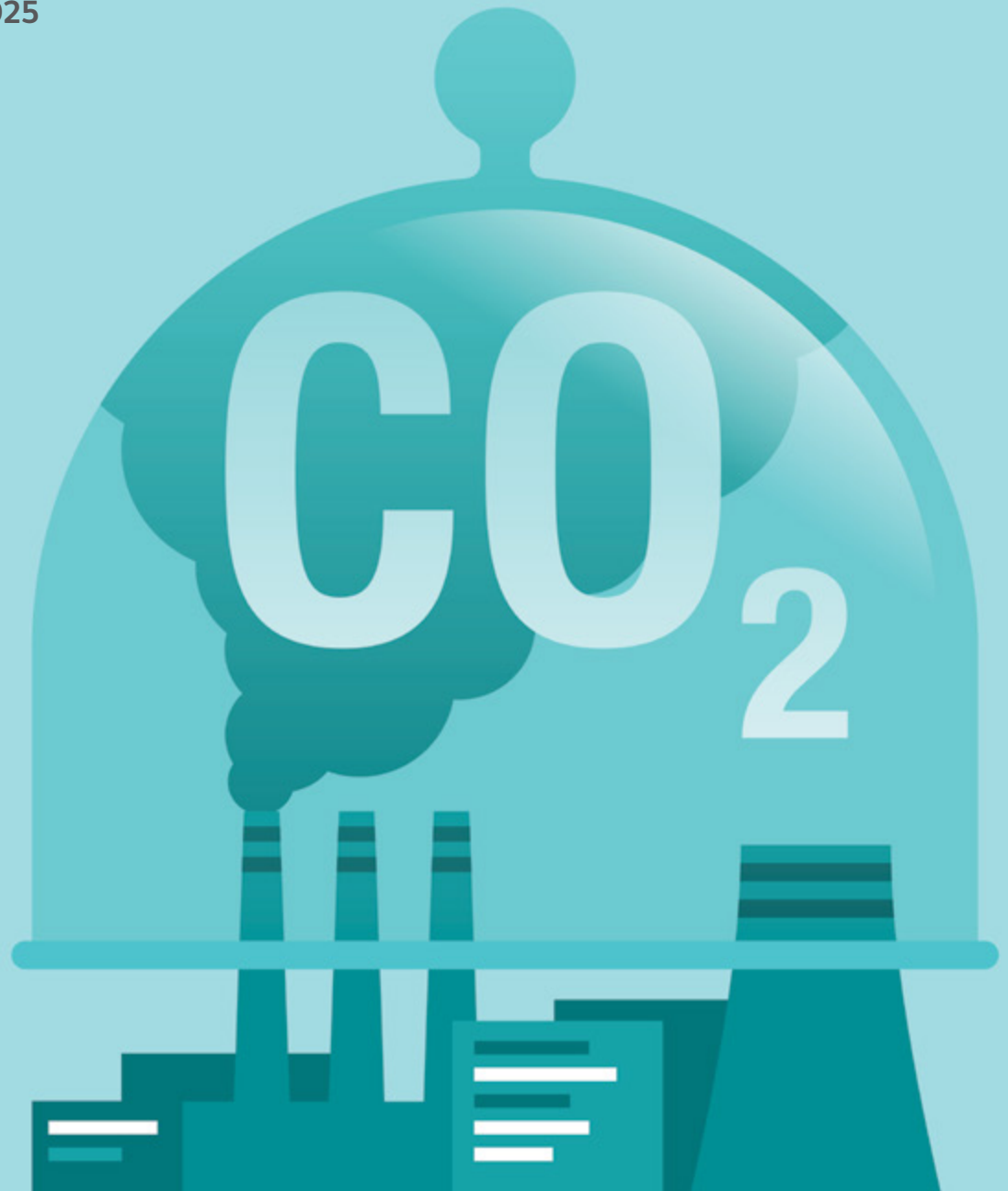


# How can CCUS Decarbonise India's Industrial Sector?

Exploring the Feasibility of Deploying Carbon Transformation Technologies in Hard-to-Abate Industries

Pratheek Sripathy, Kartheek Nitturu, and Deepak Yadav

Report | May 2025





Suggested citation:

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Sripathy, Pratheek, Kartheek Nitturu, and Deepak Yadav. 2025. *How can CCUS Decarbonise India's Industrial Sector? Exploring the Feasibility of Deploying Carbon Transformation Technologies in Hard-to-Abate Industries*. New Delhi: Council on Energy, Environment and Water.

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Cover image:

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Peer reviewers:

Dr Mukesh Kumar, Senior Advisor, Jindal Steel and Power Ltd; Neeraj Goswami, Senior General Manager, Avaada Group; Santanu Sarkar, Principal Scientist, Tata Steel; and Rishabh Jain, Senior Programme Lead, CEEW.

Publication team:

Alina Sen (CEEW), The Clean Copy, Litmus Ink, and FRIENDS Digital Color Solutions.

Acknowledgement:

The authors would like to acknowledge Rishabh Patidar, Research Analyst, CEEW and Hemant Prakash Singh, Research Analyst, CEEW for their help in editing the paper.

Organisations:

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Carbon capture utilisation and storage is imperative for achieving net-zero emissions in the steel and cement sectors.



## Executive summary

India needs to decarbonise its hard-to-abate industrial sector to meet its Nationally Determined Contributions (NDC) targets for 2030 (UNFCCC, 2022) and *Panchamrit* goals till 2070 (PIB 2022a). The steel and cement sectors are together responsible for 19 per cent of India's total emissions (GHG Platform n.d.) and 53 per cent of its industrial emissions (World Bank 2018). While decarbonisation levers such as energy efficiency (EE), renewable energy (RE), alternative fuels (AFs), and material efficiency are necessary to mitigate emissions from the steel and cement industry, these levers alone cannot help achieve net-zero emissions in the sectors. Previous studies by the Council on Energy, Environment and Water (CEEW) show that about 56 per cent of the total emissions from the steel (Elango et al. 2023) and cement (Nitturu et al. 2023) sectors can only be mitigated using the carbon capture, utilisation, and sequestration (CCUS) pathway. Therefore, CCUS will play an instrumental role in achieving net zero emissions in the steel and cement sectors.

CCUS involves capturing CO<sub>2</sub>, which can either be sequestered in geological formations (CCS) or utilised in the manufacturing of various products (CCU). The carbon capture and utilisation (CCU) pathway provides the industry with an opportunity to monetise CO<sub>2</sub> by utilising it in the manufacturing of value-added fuels

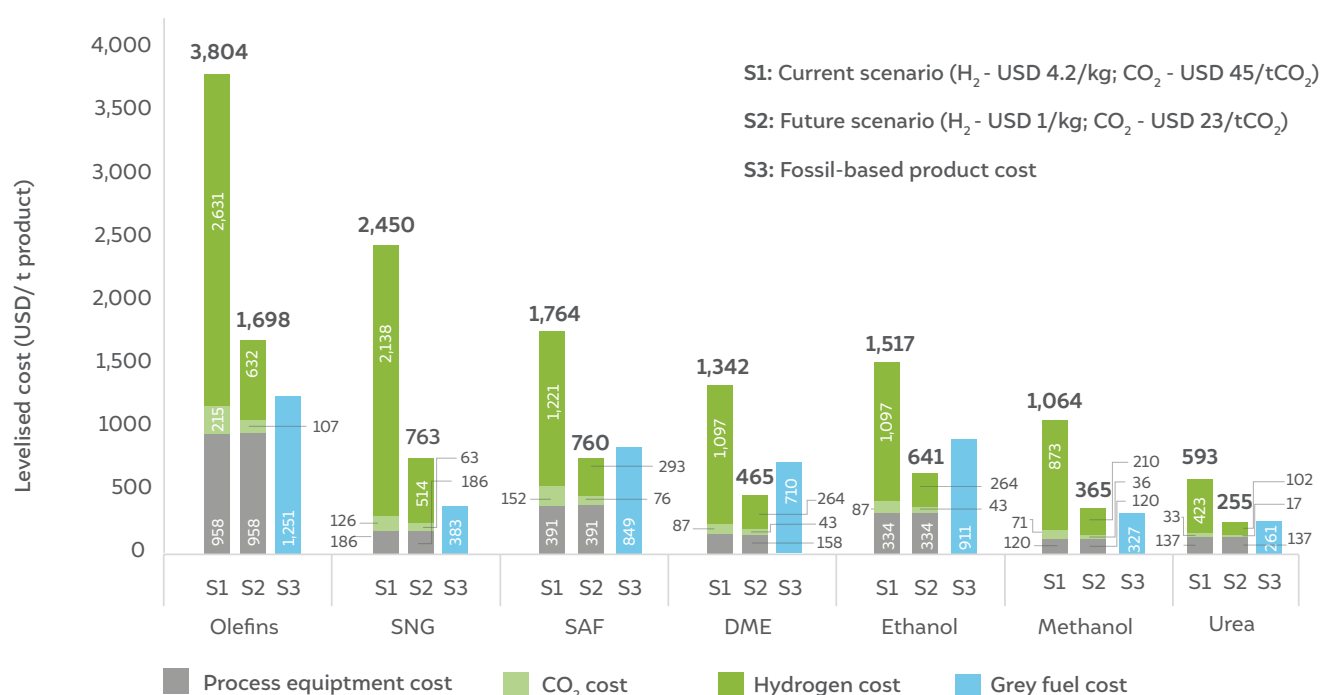
and chemicals. Furthermore, CCU also provides India with an opportunity to reduce its imports of various chemicals like methanol and fuels like natural gas by producing more sustainable alternatives within the country. Producing these chemicals and fuels needs green hydrogen. Therefore, our analysis deliberates on techno-economic and policy aspects related to green hydrogen-based CCU applications for producing value-added fuels and chemicals, particularly in the context of decarbonising the steel and cement industries in India. The study considers green hydrogen-based CCU products such as olefins, synthetic natural gas (SNG), sustainable aviation fuel (SAF), dimethyl ether (DME), ethanol, methanol, and urea.

## A. Key insights

### CCU products are likely to achieve cost-competitiveness in the future

The predominant factor determining the cost of a CCU product is the cost of green hydrogen. Green hydrogen is not cost-competitive today, but it is likely to achieve parity in the future due to government initiatives like the *National Green Hydrogen Mission* (NGHM), bringing down the cost of most CCU products. Figure ES1 compares the levelised cost of products manufactured using CCU across current (S1) and future (S2) scenarios with those of products manufactured using traditional fossil-

**Figure ES1** All CCU products are significantly more expensive than fossil-based products, at H<sub>2</sub> costing USD 4.2/kg, and CO<sub>2</sub> at USD 45/tCO<sub>2</sub>



Source: Authors' analysis

based processes (in blue). The results show that, in the current scenario (S1), none of the CCU applications is commercially viable. This can be attributed primarily to the high hydrogen consumption in these processes and its costs. In the future scenario (S2), a few applications such as SAF, DME, ethanol, and urea production will become commercially viable as the cost of green hydrogen and carbon capture reduces. However, applications such as olefin and SNG production are not expected to become cost-competitive even in the future.

#### Forty-six per cent to seventy-seven per cent of the total investment for CCU projects is dedicated to setting up green hydrogen units

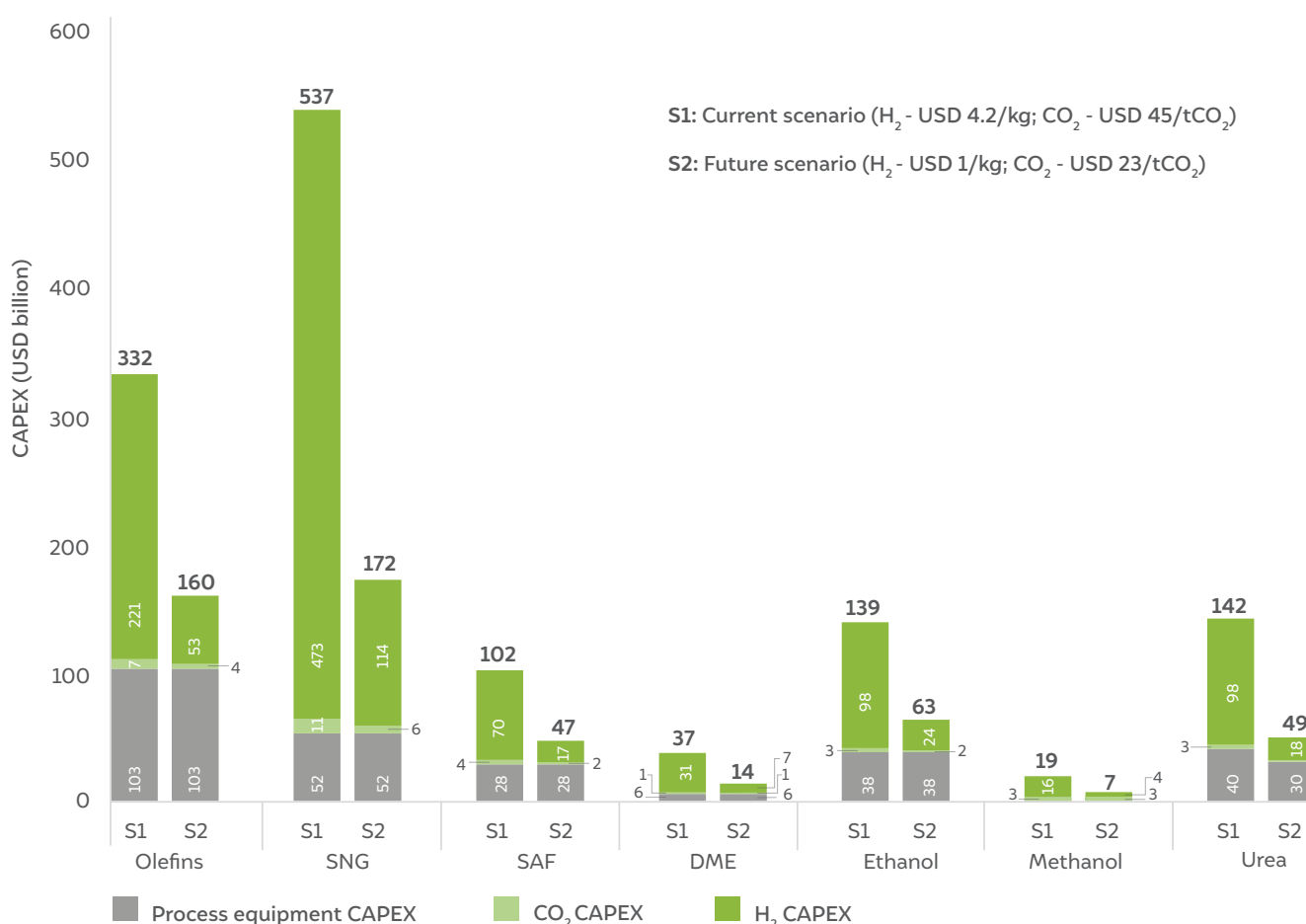
Figure ES2 shows the capital expenditure (CAPEX) requirements across all CCU opportunities discussed in the study for current and future scenarios. The CAPEX requirement was calculated based on India's total consumption of various fuels and chemicals. For ethanol and DME, we estimated the CAPEX for a 20 per cent and

5 per cent blend with gasoline and diesel, respectively. In the current scenario (S1), we estimate a total investment requirement of USD 1,307 billion (INR 98 lakh crore) across all CCU applications considered in the study. This CAPEX requirement will reduce to USD 511 billion (INR 38 lakh crore) in the future scenario (S2) due to a decline in the cost of green hydrogen and carbon capture. It assumes the utilisation of 229 million tonnes per annum (MTPA) of CO<sub>2</sub> and the production of 34 MTPA of green hydrogen.

#### CCUS has a significant impact on the cost of producing steel and cement

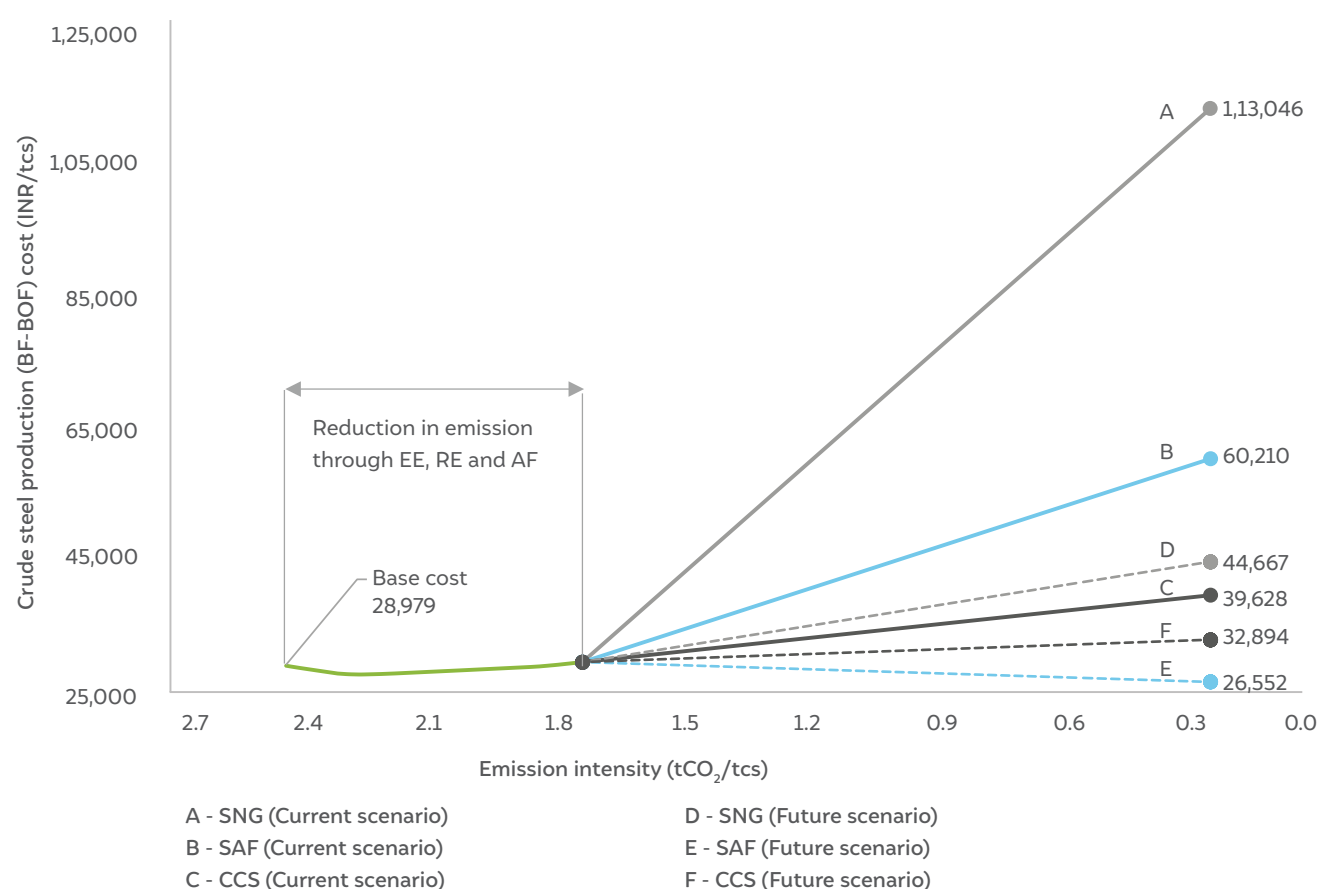
All green hydrogen-based CCU applications incur a significant premium, with a CO<sub>2</sub> abatement cost of 273–744 USD/t-CO<sub>2</sub> in the current scenario, depending on the pathway. The CCUS required to abate 56 per cent of the total emissions from steel and cement manufacturing also entail significant costs. As shown in Figure ES3, our research indicates that in the current scenario,

**Figure ES2** India needs an investment of USD 1,307 billion in the current scenario (S1) and USD 511 billion in the future scenario (S2) to unlock all CCU opportunities



Source: Authors' analysis



**Figure ES3** CCUS has a significant cost impact on hard-to-abate industrial sectors

Source: Authors' analysis

Note: BF-BOF, blast furnace–basic oxygen furnace; tcs, tonne of crude steel

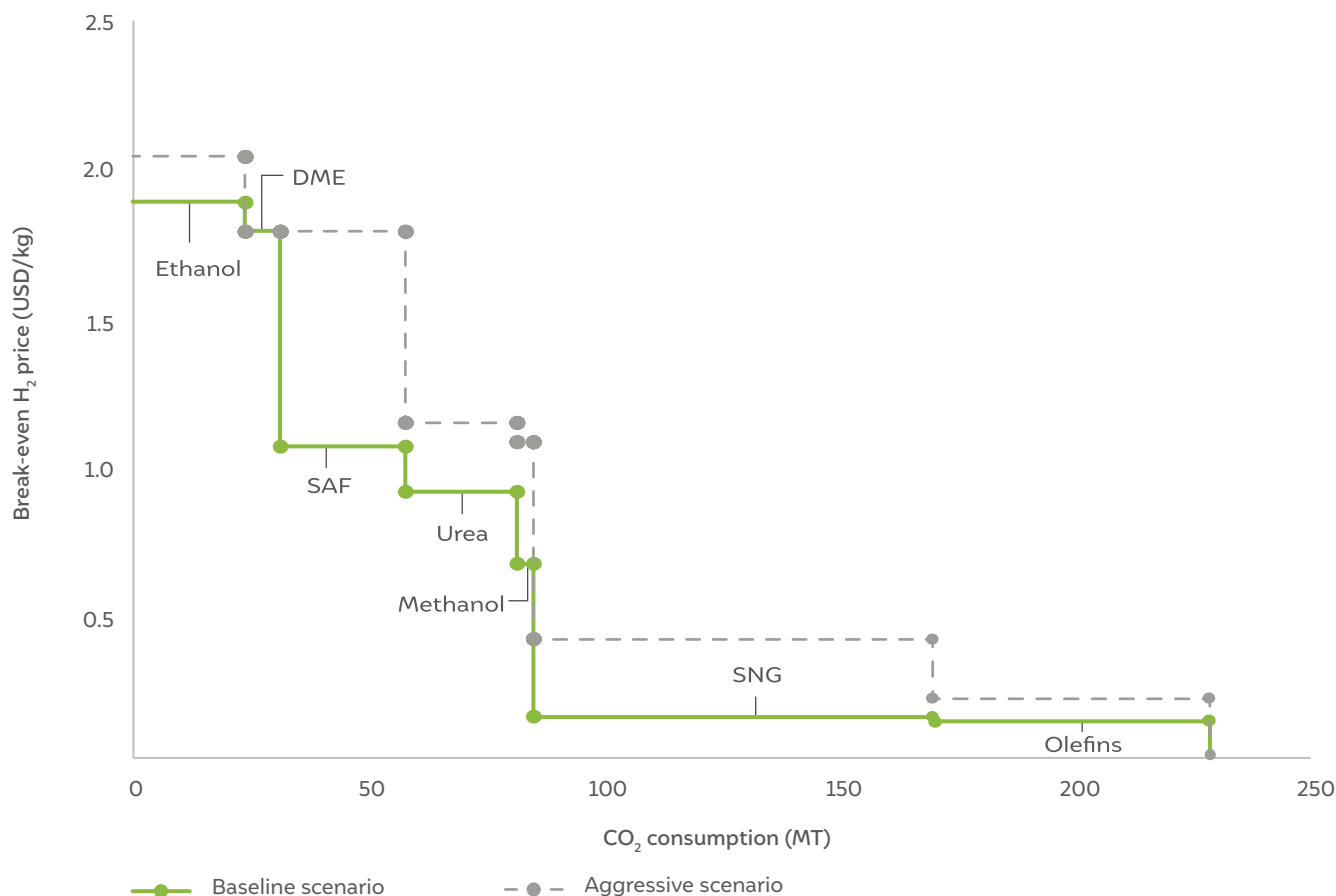
near-zero steel is 37–290 per cent more expensive than conventionally produced steel. However, in the future scenario, since the cost of abatement with CCU pathway reduces to (–)27–135 USD/t-CO<sub>2</sub>, the product cost will reduce by (–)8–54 per cent (negative sign implies a reduction in cost). We evaluate a 34–283 per cent increase in the current scenario and a (–)11–51 per cent change in production costs in future scenarios for the cement sector. Furthermore, although CCU is more expensive than carbon capture and sequestration (CCS) in the current scenario, it is expected to become cheaper in the future for most applications.

**India could utilise ~ 60 MT of CO<sub>2</sub> and consume ~6 MT of green hydrogen if the green hydrogen cost falls below USD 1 per kg**

Our research indicates that CCU products can become commercially viable only if the cost of green hydrogen

reduces significantly. Figure ES4 presents the break-even prices of hydrogen that need to be achieved for CCU applications to become commercially viable as well as the corresponding amount of CO<sub>2</sub> utilised. The base scenario considers the five-year average price of incumbent fuels and chemicals, whereas the aggressive scenario utilises the highest price achieved in this time frame. The analysis shows that India can utilise ~60 MT of CO<sub>2</sub> up to a green hydrogen price of USD 1 per kg in new applications such as DME, ethanol, and SAF production, for which the green hydrogen consumption would be ~6 MT. Further mitigation of 141 MT of CO<sub>2</sub> with the production of SNG and olefins can be achieved only if the green hydrogen price goes below USD 0.13 per kg.

**Unlike CCU products, which are expected to achieve cost parity in the future, the use of CCS will always increase the cost of steel and cement.**

**Figure ES4** The break-even price of H<sub>2</sub> is the highest for ethanol, at USD 1.88 per kg

Source: Authors' analysis

### India can reduce its import bill by USD 46 billion per year

Our research shows that by utilising CO<sub>2</sub> to produce synthetic variants of jet fuel, urea, methanol, olefins, and natural gas, India can reduce its import bills by USD 46 billion per year – the import bill was USD 209 billion in 2022 (Department of Commerce 2023).

## B. Key recommendations

- **Develop favourable policies to build a CCU ecosystem in the country:** It is evident from previous research that most CCU applications require green hydrogen. Therefore, the next phase of the *National Green Hydrogen Mission* (NGHM) should focus on creating an environment that enables the development of the CCU ecosystem in India.
- **Develop a CCS ecosystem in the country:** While there is significant potential for abating emissions through CCU pathways, CCS is inevitable for a carbon-

neutral steel and cement industry. Therefore, India should also prioritise developing a CCS policy and ecosystem.

- **Develop and update existing standards and regulations to incorporate CCUS:** A thorough assessment is required to identify and develop the necessary safety standards and regulations for the entire CCUS value chain.
- **Indigenous technology development and piloting:** In the short term, the research, development and demonstration (RD&D) fund under the NGHM should include the development of indigenous technologies and pilots for all CCU applications as a priority research area.
- **Build a collaborative research network:** The Department of Science and Technology (DST) should build a domestic research network that facilitates collaboration between academia, government institutes, policy think tanks, and industry.

# 1. Introduction

India has set an ambitious goal of achieving net-zero emissions by 2070. To realise this goal, the Indian economy has to be decarbonised in a phased manner. In 2018, industrial processes and product use emissions accounted for 7 per cent (GHG Platform n.d.) of India's total greenhouse gas (GHG) emissions (GHG Platform n.d.). The steel and cement sectors are amongst the largest emitters of GHGs in India. Our estimates show that the cumulative CO<sub>2</sub> emissions from the manufacture of 337 million tonnes of cement in 2018–19 was 218 million tonnes of CO<sub>2</sub> (MtCO<sub>2</sub>) (Nitturu et al. 2023). The Indian steel industry emitted 297 MtCO<sub>2</sub> in 2021–22 to produce 120.3 million tonnes of crude steel (Elango et al. 2023). The steel and cement sectors together are responsible for 19 per cent of national emissions (GHG Platform 2023; World Bank 2018) and 53 per cent of industrial emissions in India (GHG Platform 2023).

Deploying carbon capture, utilisation, and sequestration (CCUS) is inevitable if the steel industry in India is to be carbon-neutral, given that there exist a significant number of blast furnaces (BFs) – with plans to increase their number – which are not amenable to decarbonisation through the use of alternative fuels (AFs) such as green hydrogen. Similarly, in cement

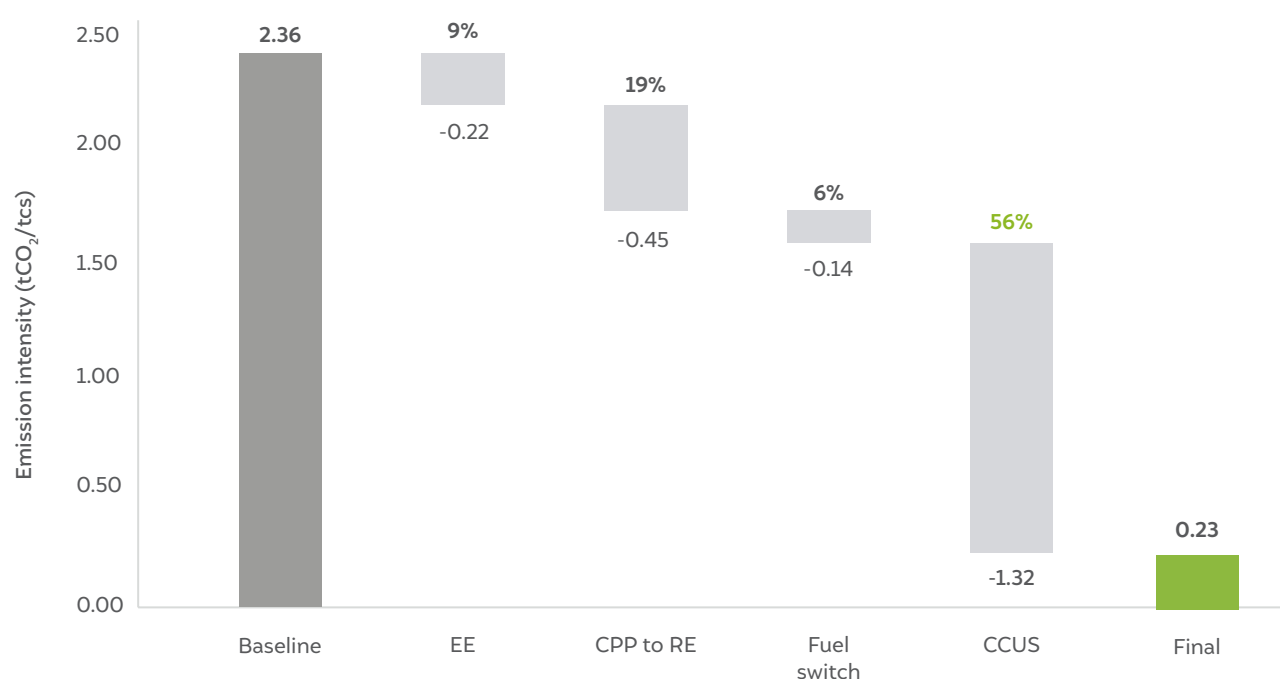
manufacturing, due to the indispensable nature of the materials used for cement production, process emissions, which constitute 56 per cent of the total emissions, cannot be abated. While energy efficiency (EE), renewable energy (RE), and AFs do abate a significant share of emissions, for deep decarbonisation, carbon management techniques such as CCUS are essential.

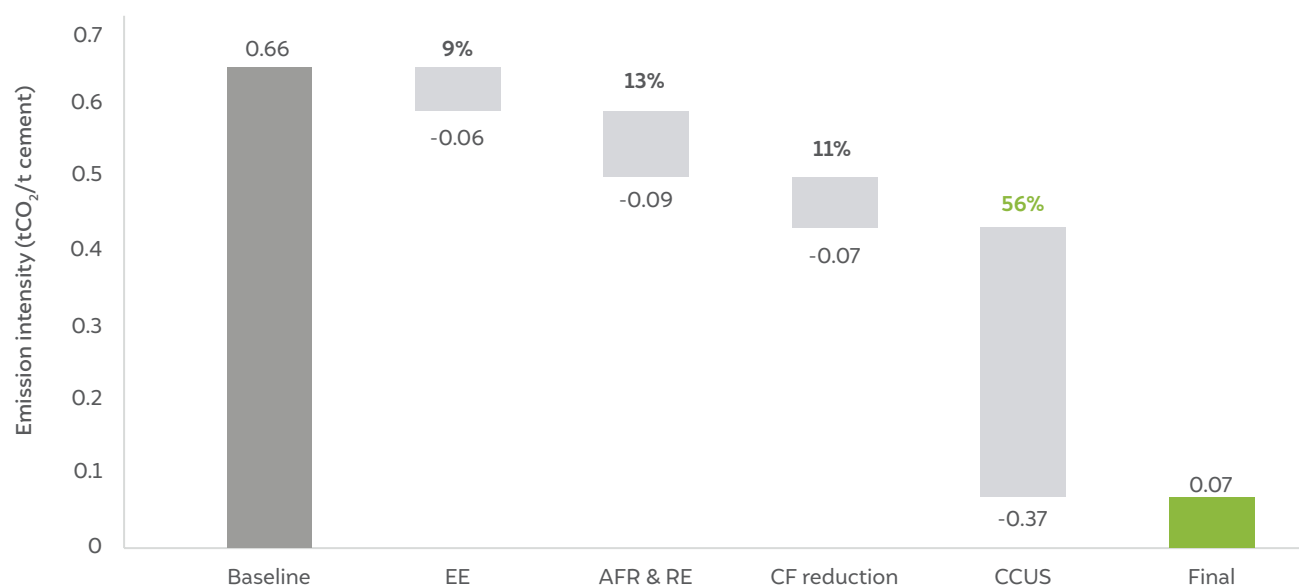
Figure 1(a) shows the emission-intensity reduction trajectory for the steel industry (Elango et al. 2023). Deploying EE measures in steel-making will only lead to a 9 per cent reduction in emissions, and switching from fossil-based captive power plants (CPP)/grid power to RE will only result in a 19 per cent reduction. However, 56 per cent of sectoral emissions could be abated through CCUS. It should be noted that the baseline emissions of 2.36 tCO<sub>2</sub> per tonne of crude steel (tcs) is the weighted average emissions from all steel production pathways.

Similarly, for the cement industry, as depicted in Figure 1(b), with base case emissions at 0.66 tCO<sub>2</sub> (Nitturu et al. 2023) per tonne of cement, EE can abate around 9 per cent, while the use of AFs, sustainable raw materials, and RE can abate around 14 per cent of emissions. A reduction in the clinker factor has the potential to abate an additional 11 per cent. However, the bulk of emissions – 56 per cent – needs to be abated through CCUS.

**Figure 1** CCUS is essential to abate emissions from the steel and cement industries

## (a) Emission-intensity reduction in the steel industry



**(b) Emission-intensity reduction in the cement industry**

Source: Elango, Sabarish, Kartheek Nitturu, Deepak Yadav, Pratheek Sripathy, Rishabh Patidar, and Hemant Mallya. 2023. *Evaluating Net-Zero for the Indian Steel Industry: Marginal Abatement Cost Curves of Carbon Mitigation Technologies*. New Delhi: Council on Energy, Environment and Water. <https://www.ceew.in/sites/default/files/How-Can-India-Decarbonise-For-Net-Zero-Sustainable-Steel-Production-Industry.pdf>.

Nitturu, Kartheek, Pratheek Sripathy, Deepak Yadav, Rishabh Patidar, and Hemant Mallya. 2023. *Evaluating Net-Zero for the Indian Cement Industry: Marginal Abatement Cost Curves of Carbon Mitigation Technologies*. New Delhi: Council on Energy, Environment and Water. <https://www.ceew.in/sites/default/files/How-Can-India-Decarbonise-For-Net-Zero-Sustainable-Cement-Production-Industry.pdf>.

The primary objective of this study is to assess the role of carbon capture and utilisation (CCU) in decarbonising the Indian steel and cement industries. CCU involves capturing CO<sub>2</sub> to produce value-added fuels and chemicals while carbon capture and storage (CCS) involves permanently storing CO<sub>2</sub> in underground reserves. Currently, there is a dearth of knowledge about carbon abatement through CCU in the Indian context. This study focuses on estimating the amount of CO<sub>2</sub> that can be utilised across various end-use applications. The amount of green hydrogen needed, the techno-economics of CCU applications and the implications of CCU on the final cost of the products like steel and cement are also estimated.

## 2. Pathways for CCU in India

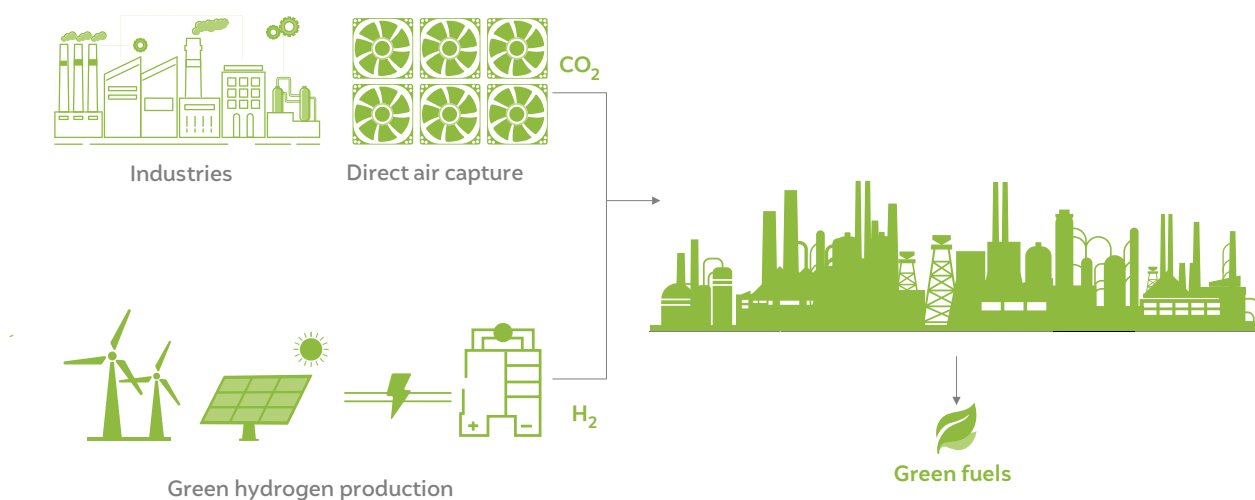
CCUS is the process of capturing CO<sub>2</sub>, which can then be sequestered in geological formations or utilised to produce value-added products that would have been otherwise synthesised using fossil fuels.

CO<sub>2</sub> capture is generally divided into four categories (Srinivasan et al. 2021):

- **Point-source capture:** CO<sub>2</sub> is captured from flue gases produced through industrial processes and energy generation using fossil fuels.
- **Direct air capture:** CO<sub>2</sub> is captured from ambient air.
- **Biological uptake:** CO<sub>2</sub> is naturally taken up by biological organisms, such as plants and algae, which then convert it to biomass.
- **Passive capture:** CO<sub>2</sub> is absorbed passively by non-organic materials, such as through mineral carbonation and other aggregates.

Figure 2 shows the schematic of a typical CCU process used to produce green fuels and chemicals. The process involves capturing CO<sub>2</sub> either from point sources or through direct air capture and reacting it with green hydrogen to produce value-added chemicals, fuels, and commodities in a process plant. Green hydrogen can be obtained from electrolyzers that are powered by solar and



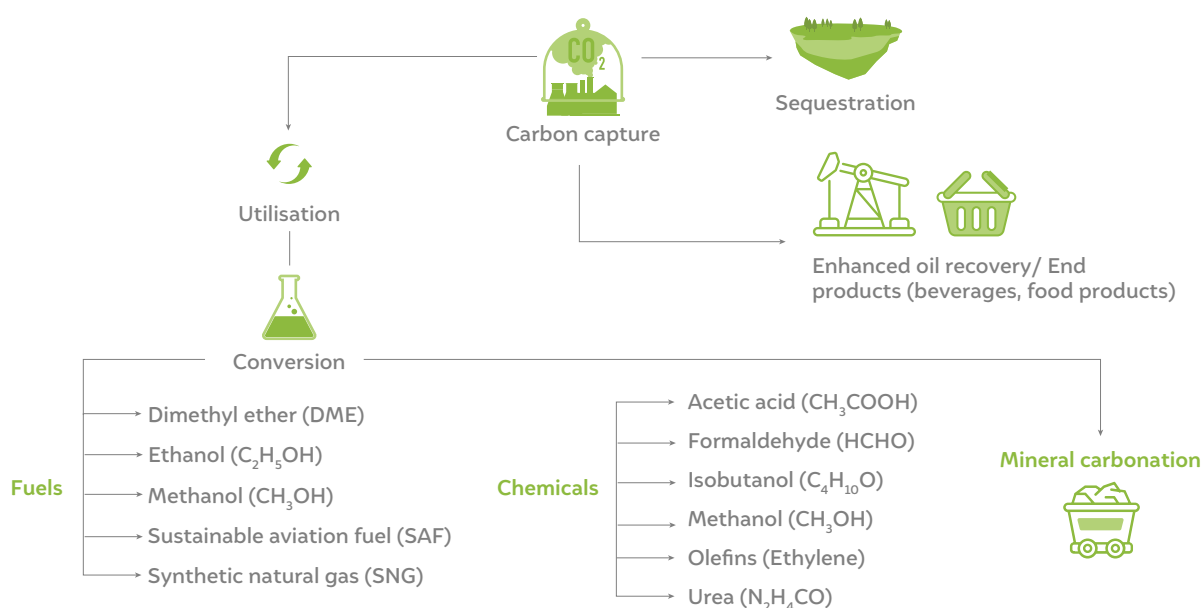
**Figure 2** CO<sub>2</sub> and green hydrogen can be used to produce fuels and chemicals

Source: Authors' analysis

wind energy. The chemical plant design for the process will depend on the desired output. It must be noted that this study exclusively analyses CO<sub>2</sub> utilisation pathways that require green hydrogen for producing value-added fuels and chemicals.

Typically, there are three pathways for CO<sub>2</sub> utilisation. Captured CO<sub>2</sub> can either be directly used in sectors such as refineries and food and beverage industries or as a feedstock in the production of synthetic alternatives to chemicals and fuels that are currently produced using

fossil fuels. Additionally, CO<sub>2</sub> can also be passively stored through mineral carbonation. Mineral carbonation is the fixation of CO<sub>2</sub> using alkaline and alkaline-earth oxides, which occur naturally in the form of silicate rocks such as serpentine and olivine. This analysis covers only green hydrogen-based CCU applications that involve CCU for producing value-added fuels and chemicals and does not include CO<sub>2</sub> utilisation through mineral carbonation despite its relevance. Figure 3 depicts the pathways for CO<sub>2</sub> utilisation and the potential synthesis of chemicals and fuels.

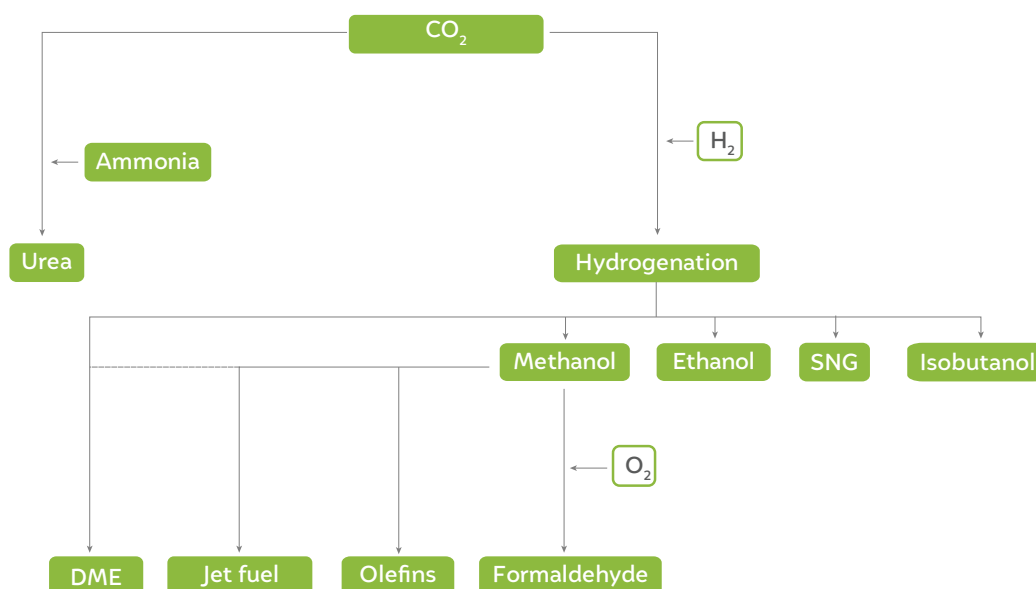
**Figure 3** CO<sub>2</sub> can be utilised to produce a variety of fuels and chemicals

Source: Authors' analysis

Figure 4 shows the pathways for producing various chemicals and fuels. CO<sub>2</sub> is already utilised in the fertiliser industry for producing urea from ammonia (Bhaskar and Das 2007). Similarly, when CO<sub>2</sub> undergoes hydrogenation with specific amounts of hydrogen, typically in the presence of a catalyst, products like

methanol, ethanol, synthetic natural gas (SNG), and isobutanol can be synthesised (Encyclopaedia Britannica n.d.). Alcohol-based chemicals such as methanol and ethanol can be further upgraded to produce chemicals and fuels such as sustainable aviation fuel (SAF) (jet fuel), olefins, formaldehyde, and dimethyl ether (DME).

**Figure 4** Pathways for producing various chemicals and fuels; methanol is an intermediary product that has many applications



Source: Authors' analysis

#### Box 1

#### Basic chemistry of Carbon Capture and Utilisation processes to obtain hydrocarbons

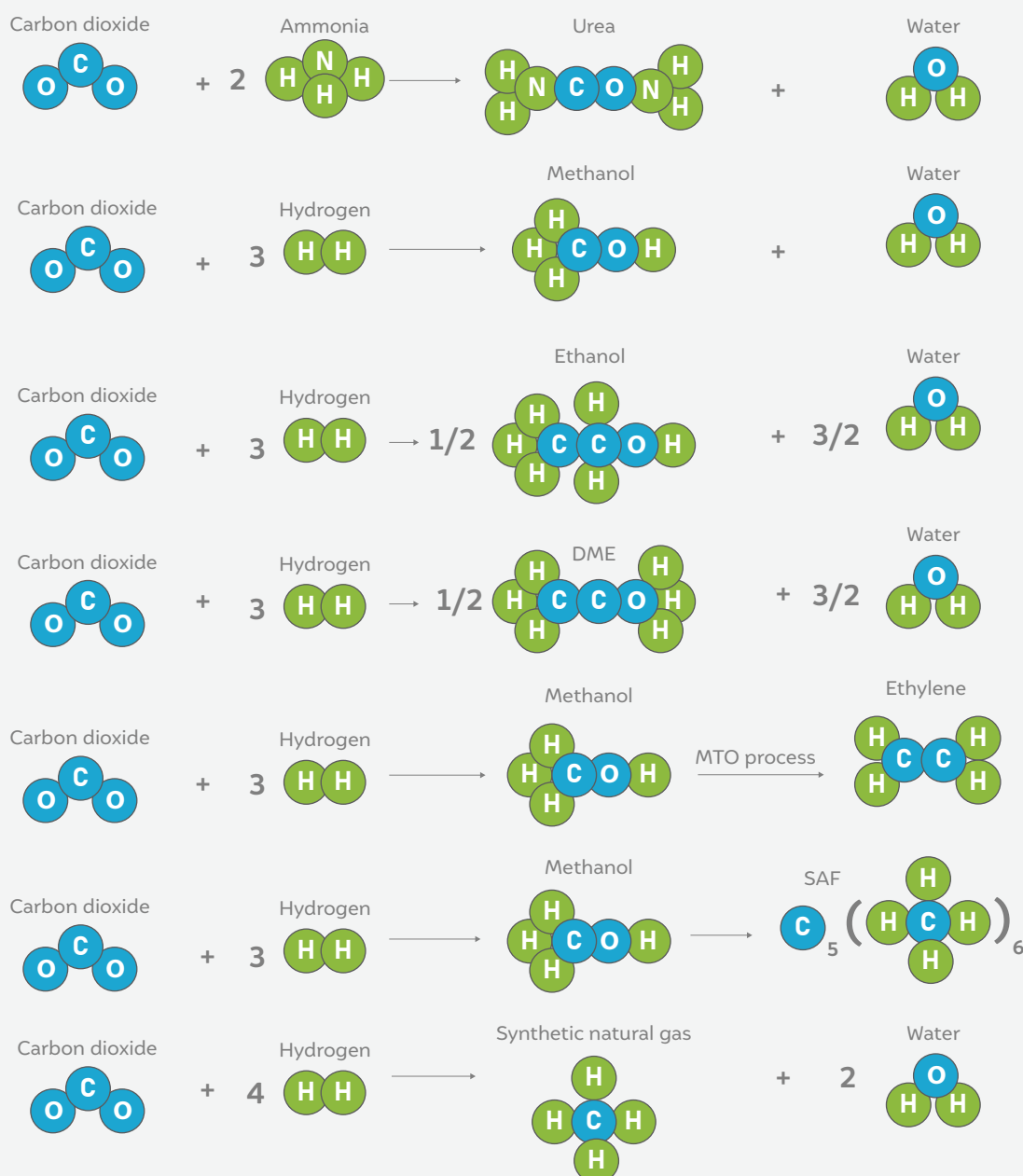
CCU involves breaking the bond between carbon and oxygen atoms in CO<sub>2</sub> and using hydrogen to form hydrocarbon products that can be used as chemicals and fuels. Figure 5 shows the basic chemistry involved in select CCU applications such as urea and olefin manufacturing (commodity) and the production of methanol, ethanol (chemicals and fuels), synthetic natural gas (SNG), and sustainable aviation fuel (SAF) (jet fuel).

In the urea manufacturing process, the steam methane reforming process generates the hydrogen required for ammonia production, while the nitrogen is sourced through the air separation process. The ammonia produced through the Haber–Bosch process is then combined with CO<sub>2</sub> in stoichiometric quantities to produce urea as the end product (Haugen et al. 2017). While a significant share of the CO<sub>2</sub> consumed in the process is sourced from the flue gas produced from the steam methane reforming process, CO<sub>2</sub> can also be sourced from outside the confines of the urea production plant. Furthermore, as the industry moves to using green ammonia, CO<sub>2</sub> from other point sources such as steel and cement plants can be used for producing urea.

The methanol synthesis reaction through direct hydrogenation of CO<sub>2</sub> is shown in Figure 5. In this process, CO<sub>2</sub> and hydrogen are mixed in a 1:3 ratio and fed to a reactor for methanol synthesis in the presence of catalysts such as copper (Cu) or zinc oxide (ZnO<sub>2</sub>) doped with zirconium dioxide (ZrO<sub>2</sub>). Although only 21 per cent of CO<sub>2</sub> is converted in this process (Anicic, Trop, and Goricanec 2014), the conversion rate is expected to increase with the use of newer catalyst combinations. Figure 5 also shows the reaction for ethanol production from captured CO<sub>2</sub>. This is a two-step process in reality. First, CO is produced through the reverse water gas shift reaction, which is then followed by the hydrogenation of CO to form ethanol (Atsonios, Panopoulos, and Kakaras 2016). Finally, SNG is produced by the hydrogenation of CO<sub>2</sub> when it is mixed with H<sub>2</sub> in the ratio of 1:4. The methanation process is an exothermic reaction; however, low temperatures promote methanation. Therefore, the reaction occurs in a series of reactors with cooling in between (Srinivasan et al. 2021).

The literature shows that DME can be produced by using methanol as an intermediate product (Brunetti et al. 2020). This is a single-step process, and methanol synthesis through hydrogenation and dehydration of methanol happens in situ in the same reactor under reaction conditions that are largely similar to those of methanol synthesis in the presence of a bifunctional catalyst. The figure also shows the net reaction for the synthesis of SAF. Kerosene, a colloquial term used for jet fuel, typically consists of hydrocarbons with 6 to 16 carbon atoms per molecule. The reaction shown in the figure is for a typical grade of jet fuel consisting of 11 carbon atoms, where SAF is produced through the methanol-to-olefins (MTO) and olefins-to-gasoline (OTG) distillation process (Srinivasan et al. 2021; Schmidt and Weindorf 2016). The figure also shows the olefins (ethylene) production route through the methanol-to-olefins process, where methanol is converted to olefins at a reaction temperature of 40°C and pressure of 1.2 bar (Srinivasan et al. 2021).

**Figure 5** CO<sub>2</sub> can be utilised to produce a variety of chemicals and fuels



Source: Authors' analysis

### 3. How much CO<sub>2</sub> can be utilised through CCU and what would be the hydrogen requirement?

Table 1 presents the market prices of various fossil-based chemicals and fuels and their current consumption in India, which we use to estimate the potential market for CCU products. The prices are indicated for the base scenario and an aggressive scenario. It is worth noting that the consumption of chemicals such as isobutanol, acetic acid, and formaldehyde is very minimal. Hence, while these have been used to evaluate the market size of CCU products in India, they have not been considered for a techno-economic evaluation. Furthermore, while

DME and ethanol are gaining attention in India, their consumption as chemicals in the pure form is not significant. However, ethanol can be blended in petrol up to 20 per cent (Sarwal et al. 2021), and DME can be blended in diesel up to 5 per cent (PIB 2023). While the blend percentages of these fuels especially ethanol can be even higher with the use of flex fuel vehicles (FFV), we consider these are ceiling limits due to the policy target set by the government. Therefore, the corresponding consumption values are considered in the study and

**Table 1** Olefins have one of the highest market prices amongst fossil-based products

Component	Market price of fossil-based products (USD/tonne)		Consumption in India (MT)	Source
	Base scenario	Aggressive scenario		
Olefins	1251	1299	11.80	(Department of Commerce 2023), (Department of Chemicals & Petrochemicals 2021)
SAF	849	1886	8.00	(Ministry of Petroleum and Natural Gas 2023), (Ministry of Petroleum and Natural Gas 2022)
Ethanol	911	951	12.51 <sup>+</sup>	(PIB 2022b), (Sarwal et al. 2021)
DME	710	870	3.93 <sup>++</sup>	(Mike, 2024)
Methanol	327	413	2.60	(Department of Commerce 2023), (Department of Chemicals & Petrochemicals 2022)
Urea	261	642	32.53	(Department of Commerce 2023), (Ministry of Chemicals and Fertilizers 2022)
SNG	8.08 <sup>*</sup>	10.9	31.00 <sup>**</sup> (41 BCM)	(Department of Commerce 2023), (Petroleum Planning & Analysis Cell. n.d.)
Isobutanol	-	-	0.07	(ChemAnalyst 2023a), (ChemAnalyst 2023b)
Acetic acid	-	-	1.08	(Department of Chemicals & Petrochemicals 2021)
Formaldehyde	-	-	0.25	(Department of Chemicals & Petrochemicals 2021)

<sup>+</sup> Volume corresponding to a 20 per cent blend in gasoline and existing industrial consumption

<sup>++</sup> Volume corresponding to a 5 per cent blend in diesel

<sup>\*</sup> price in USD/MMBtu

<sup>\*\*</sup> After removing consumption in the refinery and fertiliser industry

Source: Authors' compilation



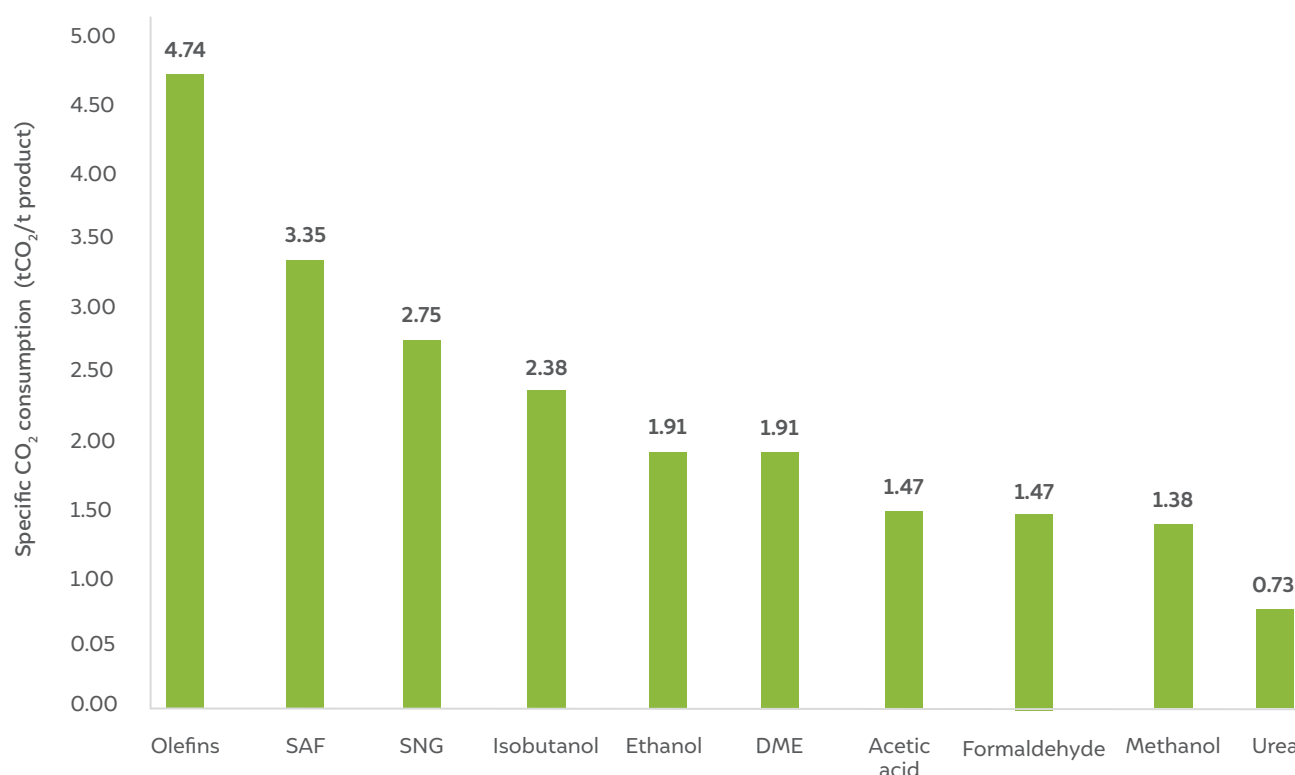
benchmarked against the respective incumbent fuels. Synthetic natural gas (SNG) consumption, in billion cubic metres, in the table reflects the net consumption after subtracting volumes consumed in refineries and fertiliser plants, as green hydrogen can be directly used in these sectors without converting them into SNG.

The graph in Figure 6a compares the specific CO<sub>2</sub> consumption for the production of the fuels and

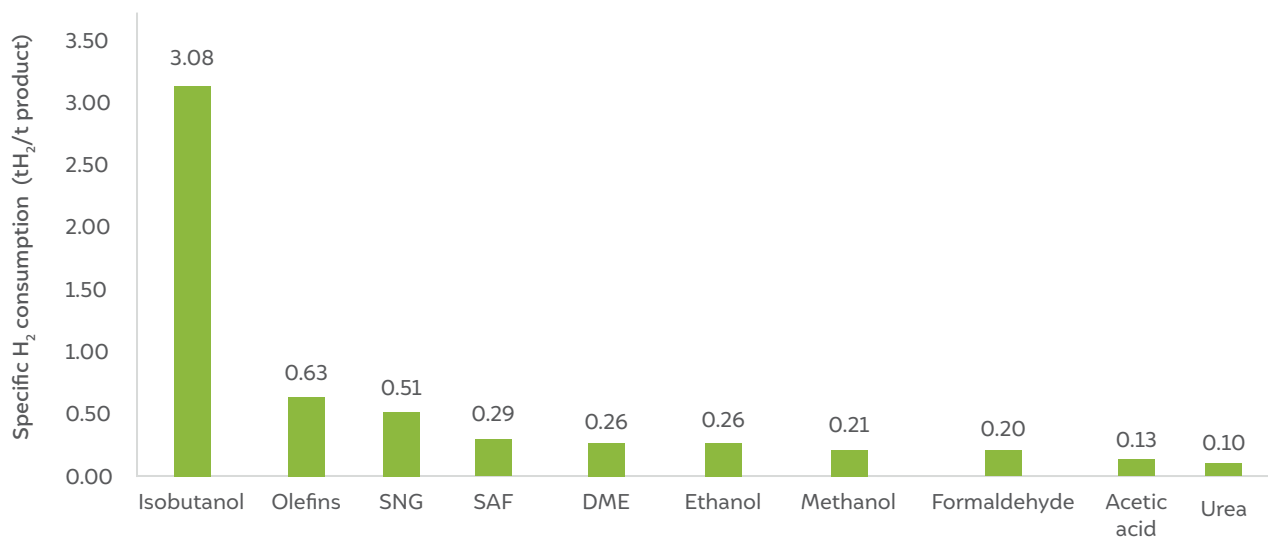
chemicals considered in the study. It is highest for the production of olefins like ethylene, followed by SAF. The graph in Figure 6b shows the specific H<sub>2</sub> consumption for producing various fuels and chemicals. While isobutanol production has the highest specific consumption of hydrogen, olefins, SNG, and SAF production require the highest volumes of hydrogen amongst bulk consumers. It must be noted that these values represent the stoichiometric demand for CO<sub>2</sub> and H<sub>2</sub>.

**Figure 6** Specific CO<sub>2</sub> consumption is the highest for olefin production

**(a) Specific CO<sub>2</sub> consumption**



**(b) Specific H<sub>2</sub> consumption**



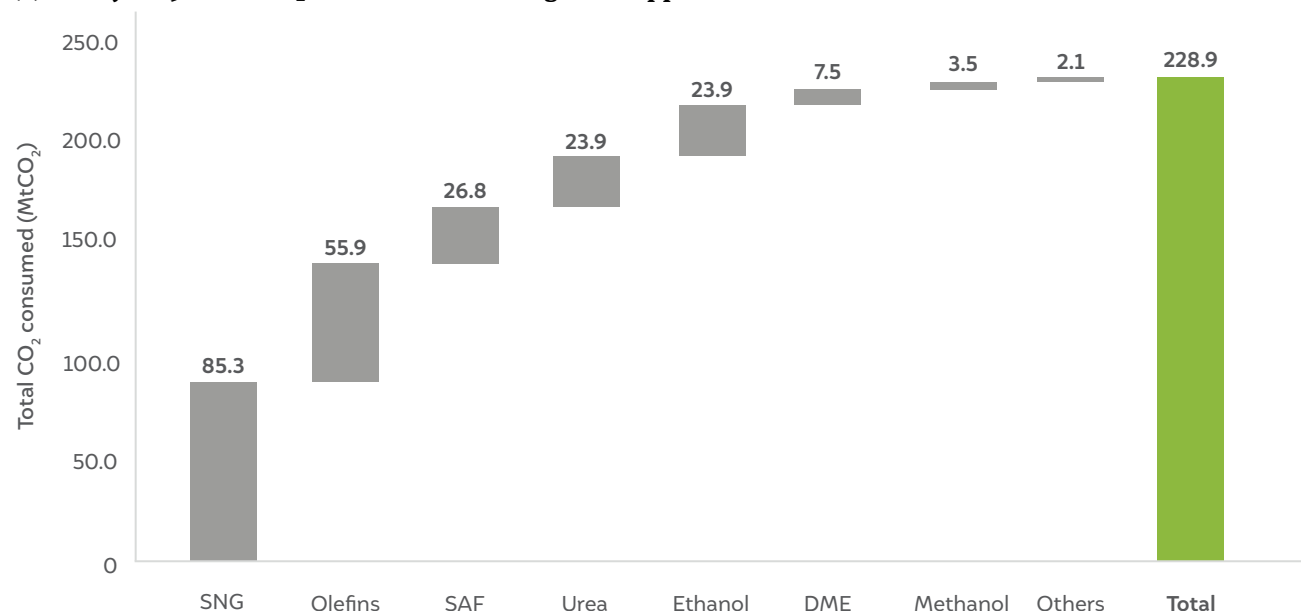
Source: Authors' analysis

Based on the data presented in Table 1 and the specific CO<sub>2</sub> consumption for each of the chemicals and fuels, the CO<sub>2</sub> consumed to replace each of the fossil-based products with synthetic alternatives is shown in Figure 7a. Given that the specific CO<sub>2</sub> consumption for SNG production is one of the highest, at 2.78 t-CO<sub>2</sub>/t-SNG, and the fact that among the fuels analysed, natural gas has one of the highest consumption volume in the country, the cumulative CO<sub>2</sub> utilised or abated by producing the synthetic alternative to natural gas is ~85 MtCO<sub>2</sub>. SNG is followed by olefins, SAF, urea, and ethanol, in descending order of consumption rates.

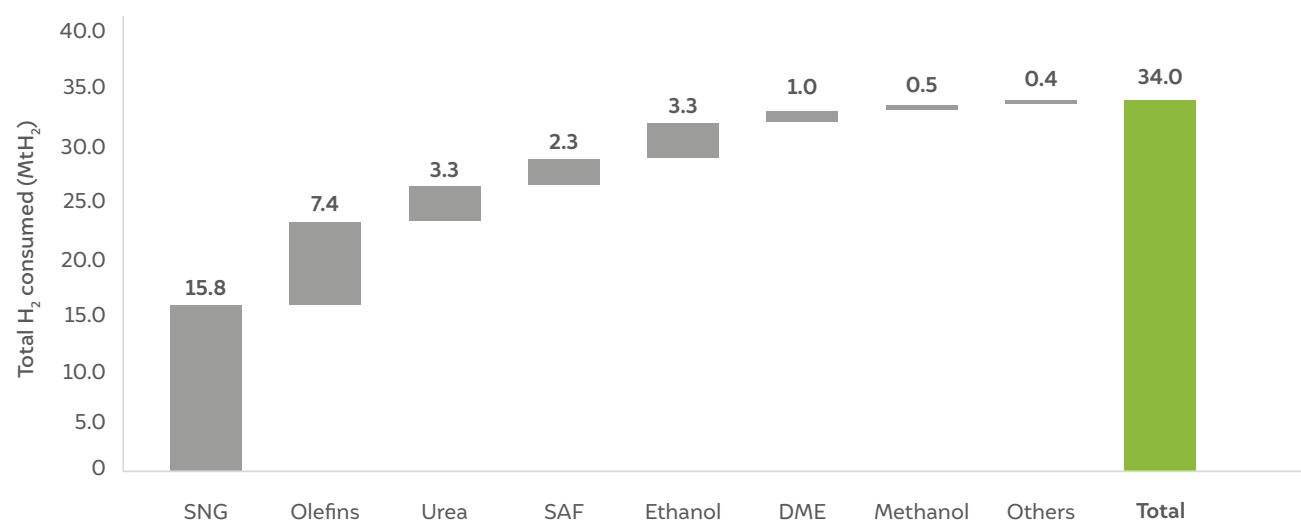
The CO<sub>2</sub> consumed for ethanol and DME production corresponds to the amount consumed when 20 per cent of ethanol is blended in petrol, along with existing industrial consumption, and 5 per cent of DME is blended in diesel. The CO<sub>2</sub> consumption in the 'others' category, which includes isobutanol, acetic acid, and so on, is only 2.1 MT, which is a very small amount compared to the consumption in other fuels and chemicals. The study estimates that across all the fuels and chemicals considered, the cumulative CO<sub>2</sub> utilised by producing synthetic alternatives is nearly ~229 MtCO<sub>2</sub> per annum.

**Figure 7** Utilising 229 MT of CO<sub>2</sub> across all CCU applications will need 34 MT of green hydrogen

**(a) Nearly ~229 MT of CO<sub>2</sub> can be abated through CCU applications**



**(b) India needs 34 MT of green hydrogen to offset fossil-based fuels and chemicals**



Source: Authors' analysis

Similarly, Figure 7b shows the product-wise hydrogen consumption pattern. As per the stoichiometric reaction shown in Figure 6, synthesising one tonne of SNG requires half a tonne of hydrogen. Amongst the fuels considered here, SNG production is associated with the highest hydrogen consumption. Consequently, the demand for hydrogen to produce SNG is the highest. A significant amount of hydrogen is also required in the production of other chemicals such as olefins (ethylene), urea, and SAF. In total, the production of these chemicals and fuels requires nearly 34 MT of hydrogen annually.

## 4. Implications of CCU on the cost of the final product

This section of the report deliberates on the techno-economic aspects of CCU pathways. The techno-economic assessment are based on the models available in the public domain. For example, we rely on models developed in the literature (Srinivasan et al. 2021) for the

cost of methanol, olefins, SAF, and SNG. The cost of urea synthesis with green ammonia is based on our studies for the fertiliser sector (Patidar et al. 2024; Kothadiya et al. 2024), and we rely on results from the literature (Clausen et al. 2011) for the cost of DME. We only take into account ethanol produced through the gas fermentation pathway because we have access to reliable data for this process alone. The capital and operating costs for the gas fermentation technology are obtained from literature sources (IOCL 2006). Table 2 compiles the plant sizes considered for the cost evaluation, which is based on fuel output to cater to existing consumption in the country. Detailed discussions on each model can be found in the respective publications and are not included here for brevity.

**The cost of a CCU product depends significantly on the cost of green hydrogen.**

**Table 2** CCU plant capacities considered for assessment

Fuel/Chemical	CO <sub>2</sub> consumption (TPD)	H <sub>2</sub> consumption (TPD)	Fuel output (TPD)	Source
Methanol	1000	132	636	(Srinivasan et al. 2021)
SAF	1000	132	263	(Srinivasan et al. 2021)
Olefins	1000	132	211	(Srinivasan et al. 2021)
SNG	1000	183	360	(Srinivasan et al. 2021)
Urea	2810	385	3850	(Patidar et al. 2024; Kothadiya et al. 2024)
Ethanol	193	26	101	(IOCL 2006)
DME	6387	869	3344	(Clausen, Elmegaard, and Houbak 2010)

Source: Authors' compilation

We assess two cases – the current (2023) and the future. In the current case, we consider a green hydrogen cost of USD 4.2 per kg and a carbon capture cost of USD 45 per tonne of CO<sub>2</sub>. The future scenario considers the best possible case for CCU applications, where the cost of green hydrogen reduces to USD 1 per kg and the cost of CO<sub>2</sub> capture drops to USD 23 per tonne of CO<sub>2</sub>. The future scenario essentially indicates the lowest possible cost of a CCU product. While the cost of process chemical plants can also potentially be reduced in the future, the study does not consider this in the future scenario due to its low impact on the overall production cost and the relative maturity of the process equipment used in chemical plants, leaving very little room for improvements that could significantly reduce costs.

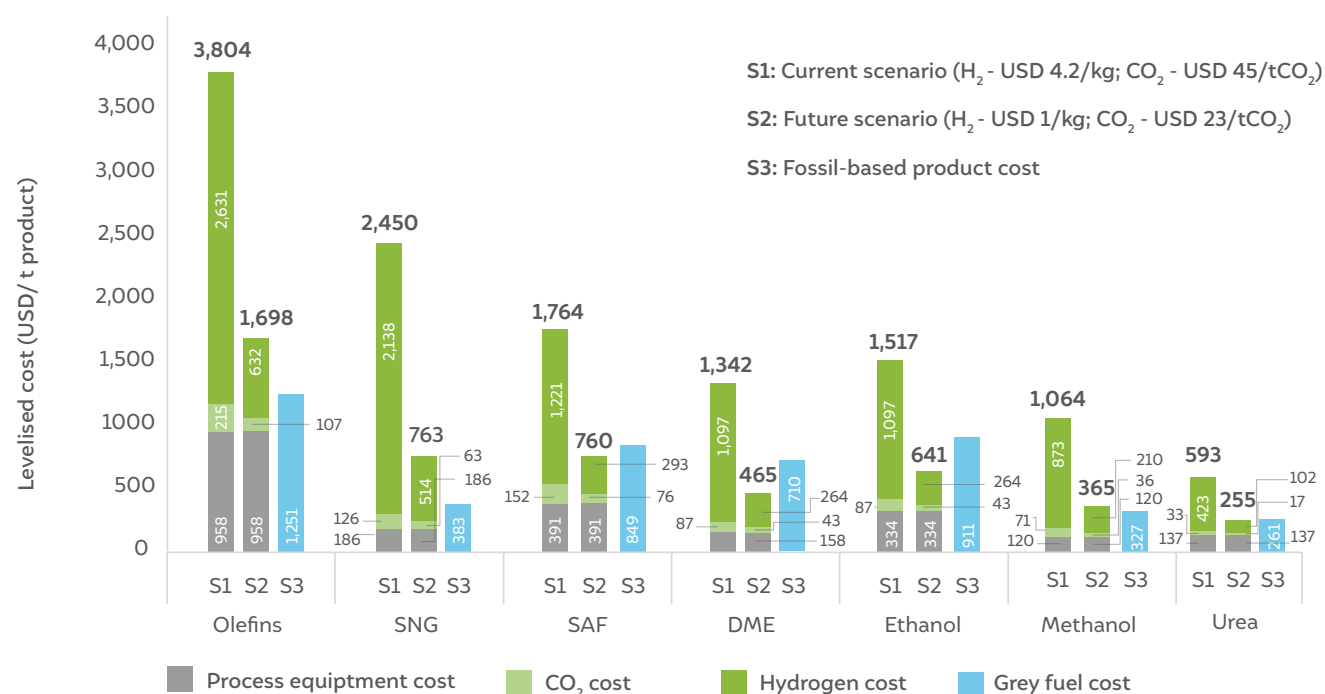
## 4.1 Techno-economics of CCU applications

Figure 8 compares the levelised cost of the CCU products analysed in the study across current (S1) and future (S2) scenarios with their counterparts produced using fossil-based processes (in blue). Chemicals like isobutanol,

formaldehyde, acetic acid, and so on are not included in the current assessment because, as shown in Table 1, their total CO<sub>2</sub> mitigation potential is significantly lower than that of other fuels and chemicals. The results show that, in the current scenario (S1), none of the CCU applications is commercially viable. This can be attributed to high specific hydrogen consumption, as depicted in Figure 6b. For example, for SNG and SAF, green hydrogen constitutes 87 per cent and 69 per cent of the cost, respectively. Essentially, the bulk of the cost of these products can be attributed to the cost of green hydrogen, whereas CO<sub>2</sub> capture costs do not have a significant impact on the cost of CCU products.

In the future scenario (S2), a few applications such as SAF, DME, ethanol, and urea production will become commercially viable. However, applications such as olefin and SNG production do not become commercially viable even in the future scenario. For olefin production, the costs of the process plant and the carbon capture unit itself are as high as the cost of fossil-based olefin, leaving very little to invest in green hydrogen. A similar trend can be observed for SNG production.

**Figure 8** Most CCU products are expected to become commercially viable in the future scenario



Source: Authors' analysis



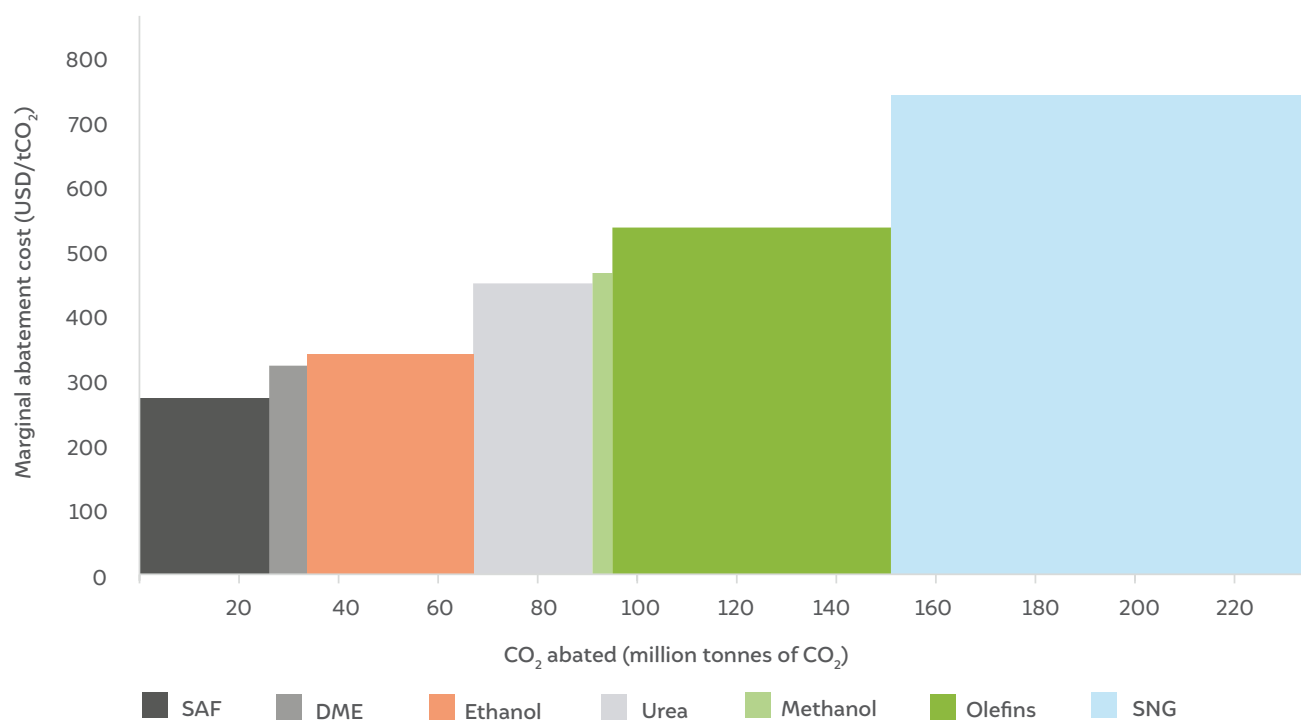
## 4.2 Prioritising CCU applications

Figure 9 shows that, in the current scenario, all CCU products are significantly more expensive than their fossil-based counterparts. Even in the future scenario, when CCU applications become cost-competitive, there is a need to prioritise them based on the associated cost of mitigation. Furthermore, there is also a need to quantify the cost of CO<sub>2</sub> mitigation for all CCU applications. Marginal abatement cost (MAC) curves estimate the incremental costs incurred for producing a chemical compound using the CCU pathway in comparison to its incumbent fossil-based process. The mitigation costs range from negative to positive – a negative cost indicates a net economic gain from using the CCU pathway, whereas a positive cost indicates that the producer will incur additional expenses to produce a particular chemical or fuel. The MAC curves also indicate the order of prioritising CCU products, with the applications being arranged in ascending order of cost of mitigation. Consequently, applications to the left are to be prioritised first, followed by applications to the right in the sequence.

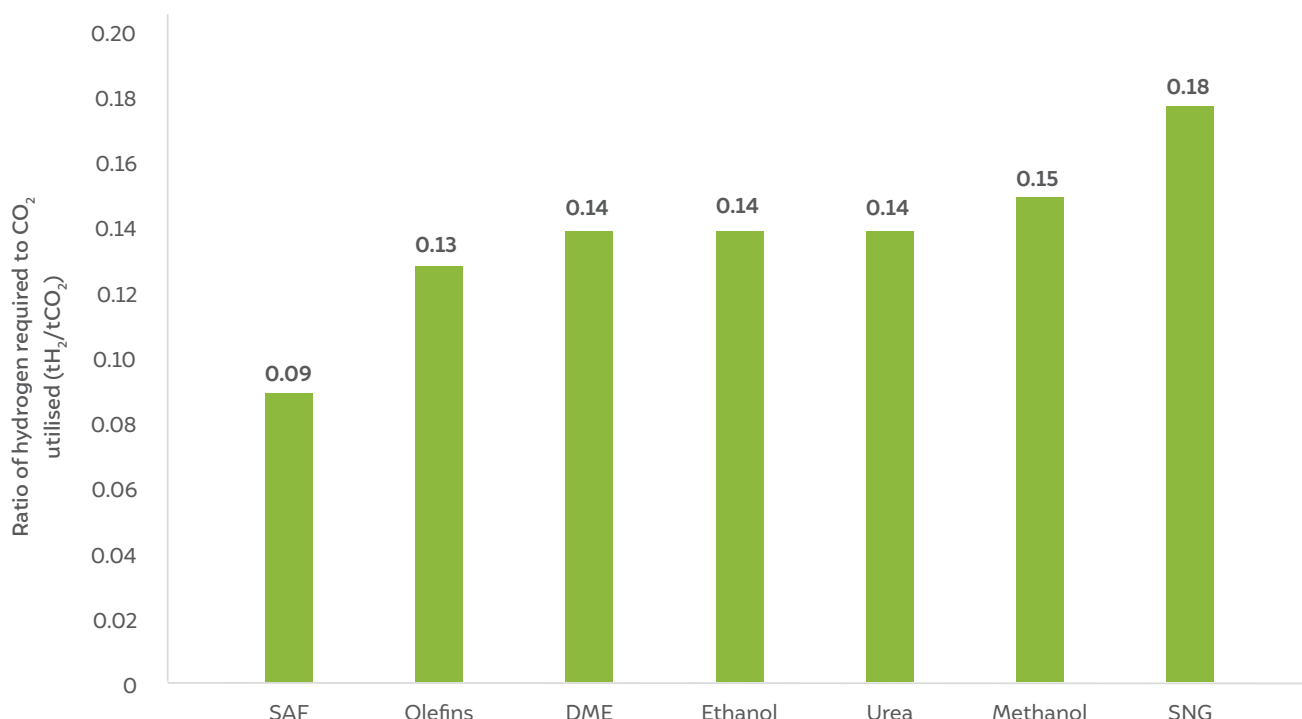
The MAC curve shown in Figure 9a compares the cost of abatement for all the chemicals and fuels analysed in the current scenario. It can be seen that the abatement cost for SNG is the highest, whereas it is the lowest for SAF. Figure 9b shows the rate of hydrogen consumption with respect to the CO<sub>2</sub> utilised. Since this ratio is the highest for SNG, implying hydrogen consumption is the highest for every tonne of CO<sub>2</sub> consumed in this process, the cost of abatement is also the highest. The cost of abatement for DME, urea, methanol, olefins, and SAF is in the range of USD 273–539 per tonne of CO<sub>2</sub>; it is the least for SAF at USD 273 per tonne of CO<sub>2</sub>. Essentially, the high cost of abatement is primarily due to the cost of green hydrogen, which is taken to be USD 4.2 per kg. The other factor determining the cost of abatement is the cost of the incumbent fossil fuel. Natural gas, which is directly obtained in its natural form, has a lower energy price compared to aviation fuel, which is obtained from processing crude oil.

**Figure 9** Cost of abatement for SNG is the highest amongst the chemicals and fuels analysed

**(a) MAC curve for Carbon Capture and Utilisation products**



Source: Authors' compilation

**(b) Cost of abatement is the highest for SNG due to higher rates of hydrogen consumption**

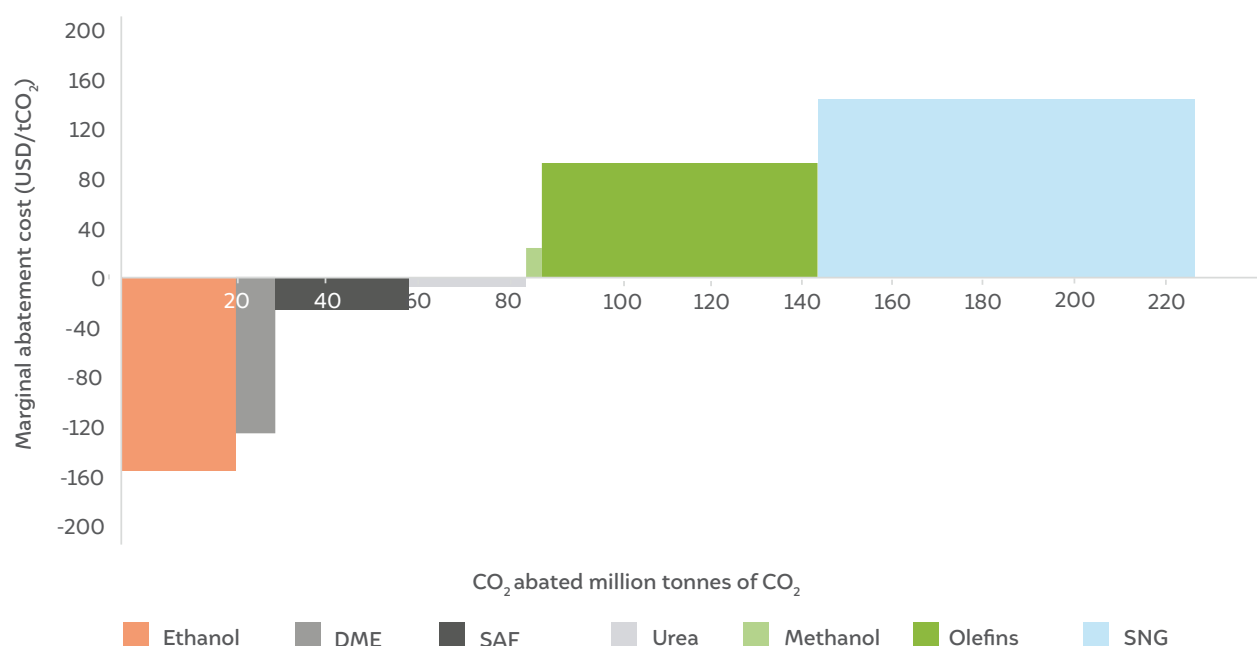
Source: Authors' analysis

As shown in Figure 8, most CCU applications will become commercially viable in the future. Therefore, it is expected that the MAC for these applications will also be reduced in the future. Figure 10 shows the MAC curve for the CCU applications considered in the study for the future scenario. It is seen that ethanol, DME, and urea will have a negative MAC, implying that there is a net financial gain in deploying these technologies for carbon mitigation. While the abatement costs for the other fuels and chemicals, such as methanol, olefins, and SNG, still remain positive, there is a significant decrease compared to the scenario where the cost of green hydrogen was USD 4.2 per kg. This further validates our earlier argument that the viability of CCU pathways is highly dependent on the cost of green hydrogen.

It is seen that the sequence of MAC across various

products changes in Figure 10 compared to Figure 9(a). While SAF has the lowest abatement cost in Figure 9(a), ethanol and DME have lower MAC in Figure 10. This can be attributed to varying hydrogen consumption per unit of CO<sub>2</sub> used across various products indicated in Figure 9(b). SAF consumes only 0.09 tH<sub>2</sub>/tCO<sub>2</sub> compared to 0.14 tH<sub>2</sub>/tCO<sub>2</sub> for DME and ethanol. Therefore, a decrease in green hydrogen cost from USD 4.2/kg to USD 1/kg significantly improves the competitiveness of ethanol and DME compared to SAF. Consequently, the mitigation cost of ethanol and DME are lower than SAF.

**All CCU applications have prohibitively high costs today and will become commercially viable only if the cost of green hydrogen decreases significantly.**

**Figure 10** Most CCU applications have a negative MAC if the cost of hydrogen is reduced to USD 1 per kg

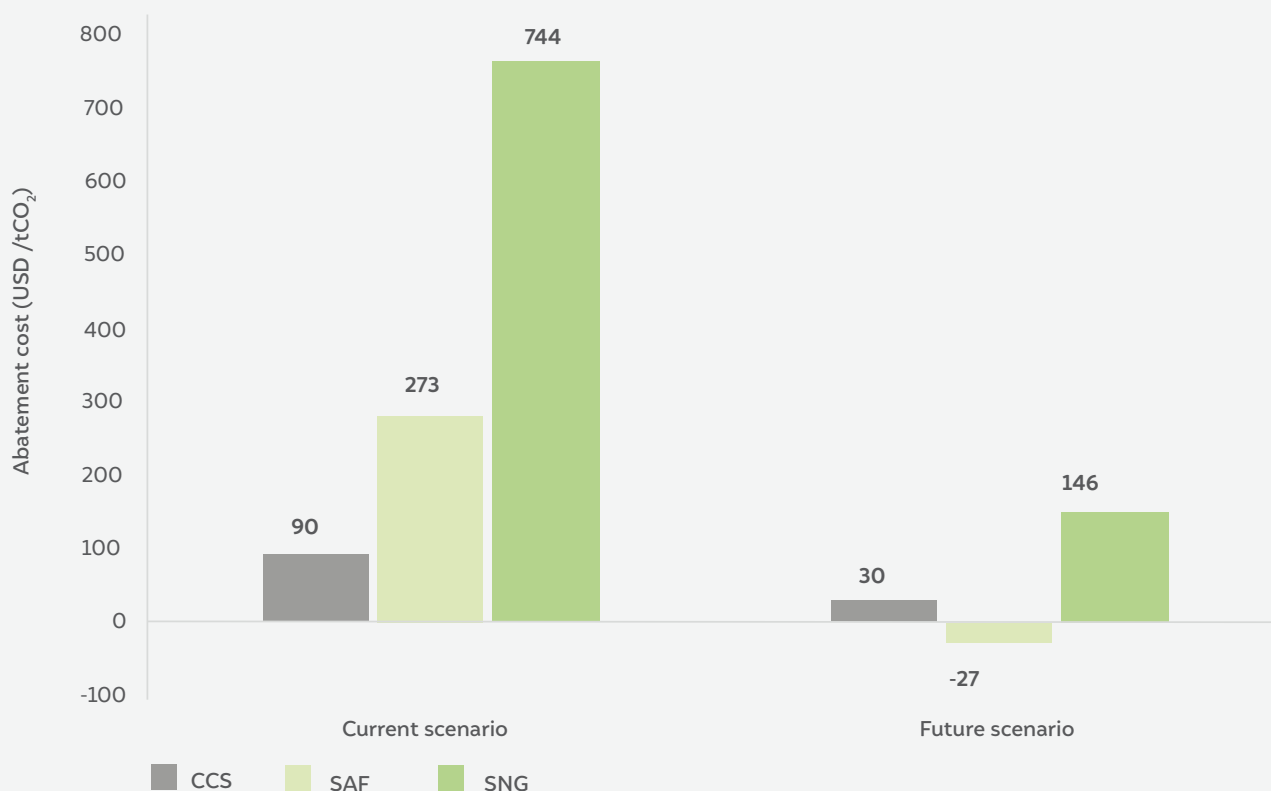
Source: Authors' analysis

## Box 2

### Which is a better decarbonisation option: Carbon Capture and Sequestration (CCS) or Carbon Capture and Utilisation (CCU)?

CCU and CCS are avenues for deep decarbonisation of the industrial sector. CCS involves the permanent storage of CO<sub>2</sub> in deep underground reservoirs (Bakshi, Mallya, and Yadav 2023), whereas CCU involves utilising CO<sub>2</sub> to produce value-added chemicals, fuels, and industrial commodities. In addition to the above, there are two important differences between CCU and CCS. The first difference relates to the amount of CO<sub>2</sub> mitigated with these two pathways. Although, in theory, India has a CO<sub>2</sub> storage capacity of 649 GT, the actual capacity after taking into consideration the above-ground challenges is 101–358 GT. In contrast, as indicated in Figure 6(a), CCU can mitigate only 213 MT of CO<sub>2</sub> per annum, considering the current and targeted production capacities of value-added fuels and chemicals, which is only a fraction of the total CO<sub>2</sub> that can be abated by CCS.

The second difference relates to the cost of CO<sub>2</sub> mitigation. Figure 11 compares the cost of abatement for one of the most (SNG) and the least (SAF) expensive CCU products with the cost of CO<sub>2</sub> capture and storage. Today, the cost of CCS is difficult to estimate due to the uncertainties in the CCS value chain. Therefore, in Figure 11, we present a range of CCS costs for current and future scenarios. Similarly, for CCU, we show the range of costs for the current and future scenarios. In the current case, the abatement cost for the two CCU pathways – that is, for SAF and SNG – is USD 273 and USD 744 per tonne of CO<sub>2</sub>, respectively, which is significantly higher than that for CCS, which is USD 90 per tonne of CO<sub>2</sub>. However, for the future scenario, the abatement cost of CCU applications will be significantly reduced to USD ~27 and USD 146 per tonne of CO<sub>2</sub>, respectively. The cost of abatement for other fuels and chemicals is between these two extremes. The cost of CCS, however, will always be positive, except for enhanced oil recovery (EOR). For these reasons, in the future, it is expected that CCU will take precedence over CCS, although CCS will be necessary for achieving net-zero emissions in the industrial sector.

**Figure 11** CCS is cheaper than CCU today and will play a key role in decarbonisation even in the future

Source: Authors' analysis

## 5. Investment sizing India's CCU market

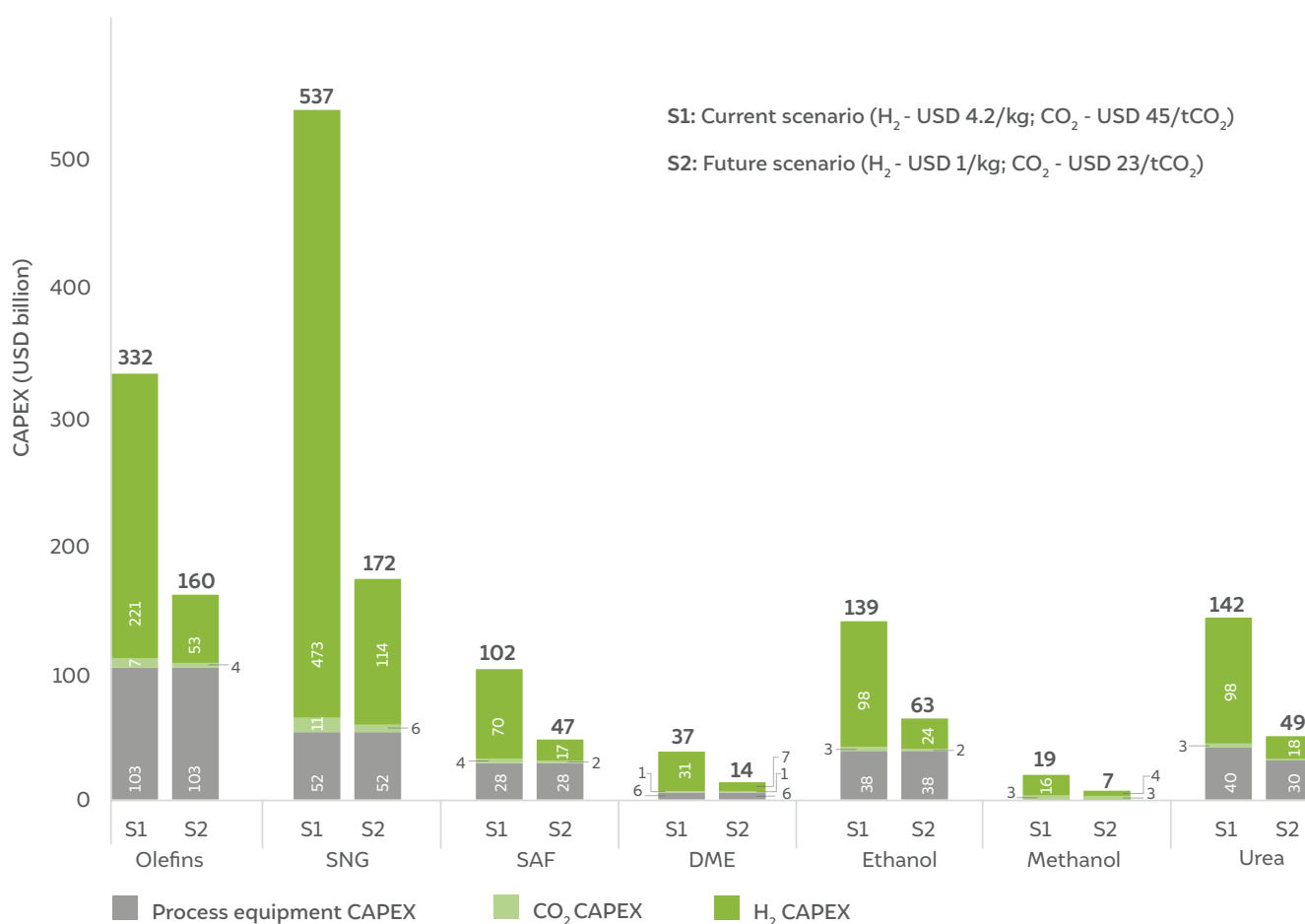
This section highlights the investments required to transition from fossil-based productions of fuels and chemicals to synthetic alternatives. Figure 12 shows the capital expenditure (CAPEX) requirement across all CCU opportunities discussed in the paper for current and future scenarios. Assuming a green hydrogen CAPEX of USD 30 billion per million tonnes per annum (MTPA) (Biswas, Yadav, and Baskar 2020) and CO<sub>2</sub> capture CAPEX of USD 133 million per MTPA (NITI 2022), we estimate that the CAPEX requirement for hydrogen production alone constitutes 77 per cent of the total USD 1307 billion in the current scenario. The CAPEX requirement is the

highest for SNG, while it is the least for DME. Therefore, the CAPEX required for hydrogen production must be reduced drastically to utilise CO<sub>2</sub> to effectively produce chemicals and fuels. For the future scenario, we expect an investment of USD 511 billion (INR 38 lakh crore) to produce 34 MTPA of green hydrogen and utilise 229 MTPA of CO<sub>2</sub>.

**Utilising 227 MT of CO<sub>2</sub> requires an investment of USD 1.3 trillion in the current scenario and USD 0.5 trillion in the future scenario.**



**Figure 12** India needs an investment of USD 1.3 trillion (INR 98 lakh crore) in the current scenario and USD 0.511 trillion (INR 38 lakh crore) in the future scenario to unlock all CCU opportunities



Source: Authors' analysis

## 6. What will it take for CCU to become commercially viable?

As seen from the discussions in Section 4, all green hydrogen-based CCU applications come at a significant premium, with a  $CO_2$  abatement cost range of 273–744 USD/t- $CO_2$ . As evident from Figure 8, green hydrogen accounts for 69–87 per cent of the cost of any CCU product. Therefore, all CCU products can become commercially viable only if the cost of green hydrogen is reduced significantly. This section of the report identifies the desired cost of green hydrogen needed for CCU applications to become commercially viable by developing a cost curve for green hydrogen.

Figure 13 presents the break-even price of hydrogen that is needed to be achieved for CCU applications to become commercially viable as a function of the corresponding amount of  $H_2$  consumed and  $CO_2$  mitigated. Figure 13a shows that the break-even cost of hydrogen is the highest for ethanol. If the cost of DME needs to achieve parity with its fossil-based counterparts, then the cost of hydrogen needs to reduce to USD 1.88 per kg from the current price of USD 4.2 per kg. However, if the price of ethanol increases to a peak of INR 56.4 per litre, then the break-even

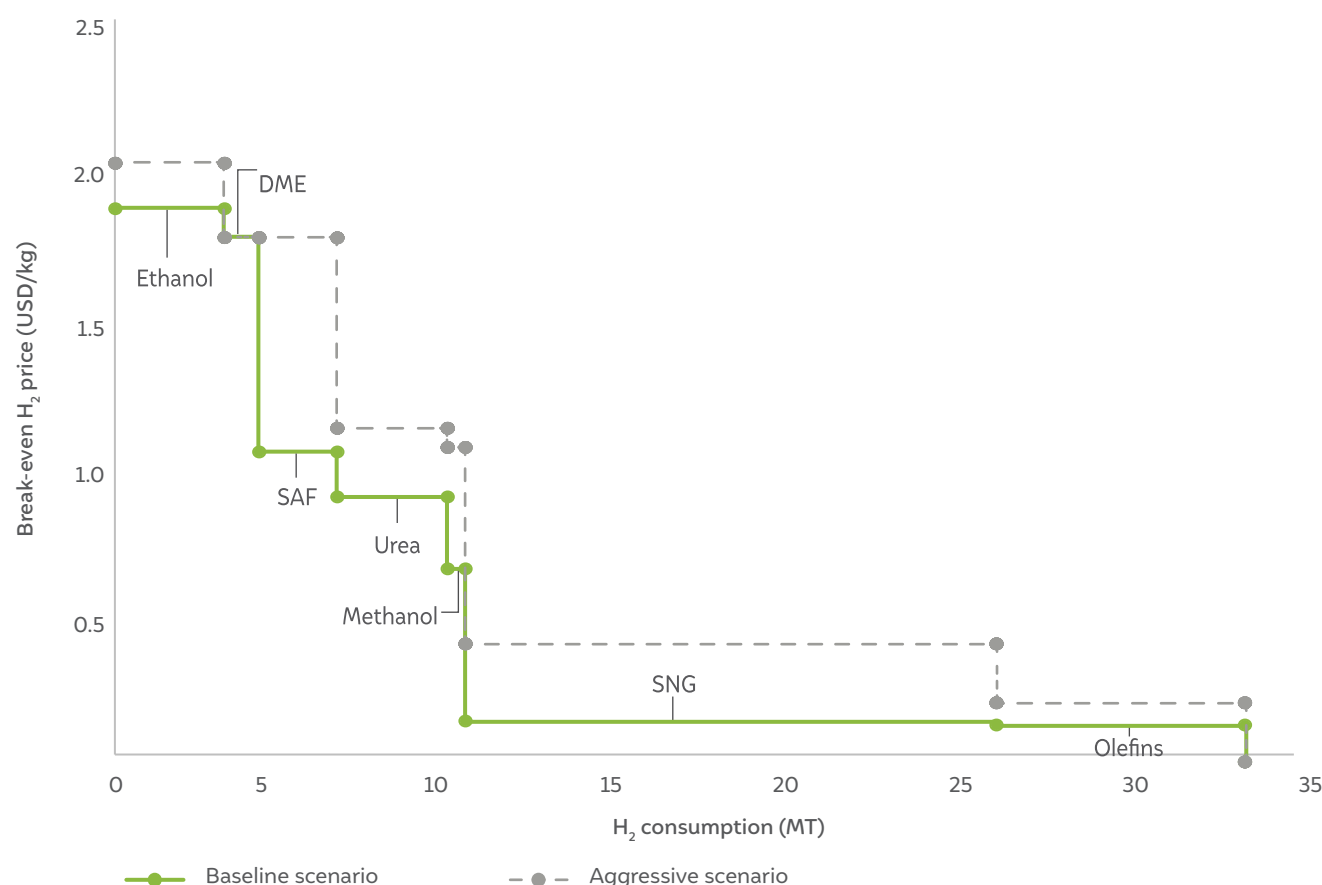
price of hydrogen used for the production of synthetic ethanol is even higher, at USD 2.04 per kg. The figure similarly presents the cost of hydrogen that needs to be achieved for the other CO<sub>2</sub> utilisation pathways to become commercially viable. The analysis shows that India can potentially consume 6.6 MT of green hydrogen in new applications such as DME, ethanol, and SAF production at a green hydrogen cost of USD 1 per kg. However, for unlocking applications beyond this value, the cost of green hydrogen has to be reduced significantly. Our assessment indicates that India can potentially uptake 16 MT of green hydrogen to produce SNG. However, this becomes commercially viable only if the cost of green hydrogen is reduced to USD 0.14 per kg. There are also other factors to consider with regard to increasing the production of SNG, given that there are diverse decarbonisation levers across various sectors of the economy. For example, using battery electric vehicles (BEVs) might be a better alternative than using SNG in automobiles. Similarly, the use of green hydrogen for producing ethanol might not materialise due to the increase in the use of crop-based ethanol, which has seen significant investments in recent years.

In the aggressive scenario (denoted by dotted lines in the figure), where the prices of the fossil-based counterparts are taken to be equal to their highest value in the past five years and indicated in Table 1, the break-even price is the highest for ethanol at USD 2.04 per kg. Other applications such as SAF, DME, and urea also break even at a green hydrogen price exceeding USD 1 per kg. In both scenarios, the lowest break-even price needs to be achieved for olefins (ethylene). However, unlike in other applications where CO<sub>2</sub> will be emitted back to the atmosphere during combustion (SNG, ethanol, etc.) or use (urea), the CO<sub>2</sub> in olefins will be used for producing petrochemical commodities, enabling its long-term utilisation through recycling.

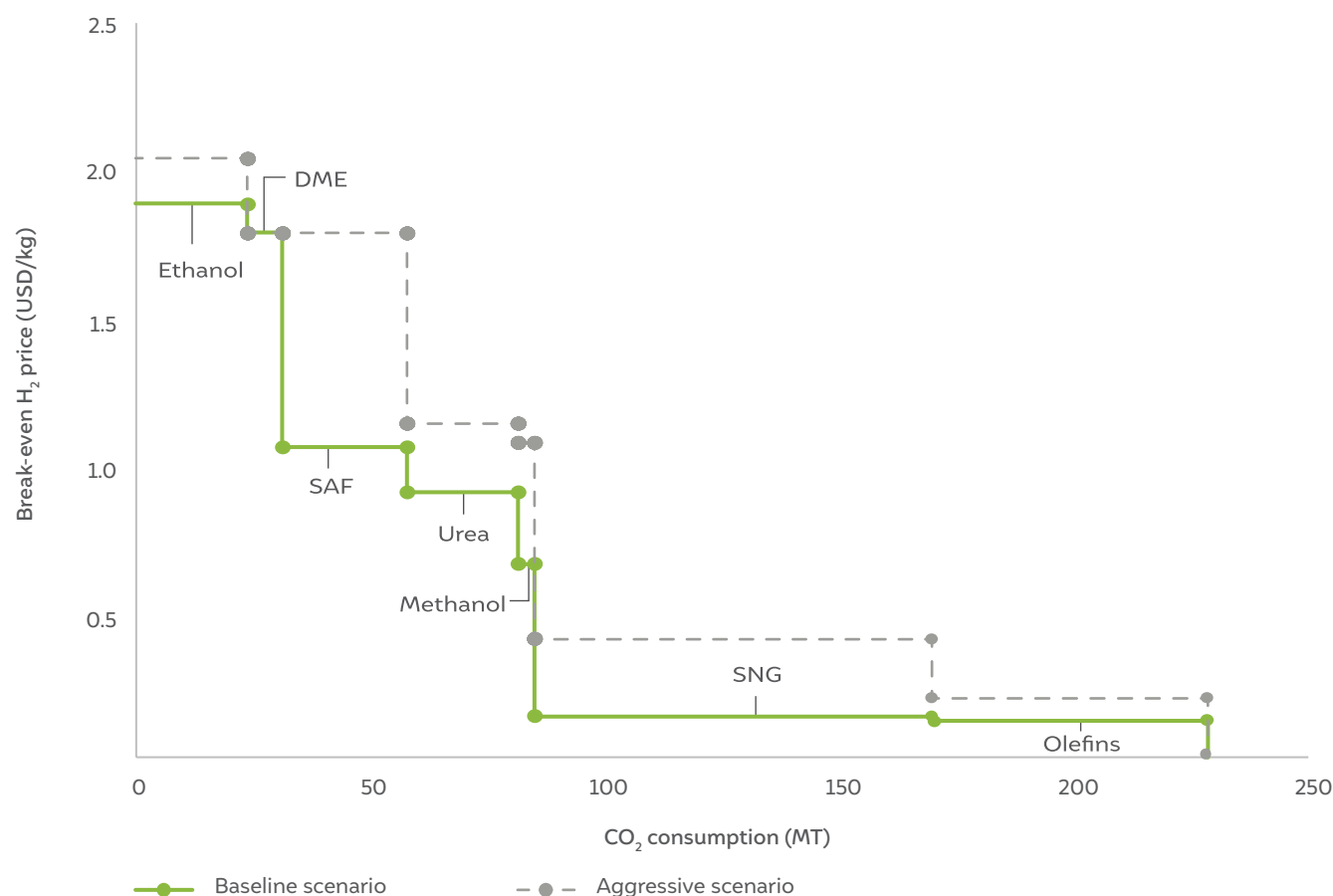
Figure 13b shows the trend of the break-even cost of green hydrogen as a function of CO<sub>2</sub> consumed across various CCU applications. Our analysis shows that India can mitigate only ~60 MT of CO<sub>2</sub> emissions up to a green hydrogen price of USD 1 per kg. Furthermore, to mitigate an additional 141 MT of CO<sub>2</sub> in the production of SNG and olefins, the green hydrogen price should go below USD 0.13 per kg.

**Figure 13** The break-even price of H<sub>2</sub> is the highest for ethanol, at USD 1.88 per kg

**(a) Ethanol has the highest break-even price for H<sub>2</sub> – USD 1.88 per kg in the baseline scenario**



Source: Authors' analysis

**(b) Olefins have one of the highest CO<sub>2</sub> consumption potential with the lowest H<sub>2</sub> break-even price**

Source: Authors' analysis

## 7. How much fossil fuel imports can CCU offset?

India currently imports a significant share of the fossil fuels it consumes. In 2022, India imported fossil fuels worth USD 209 billion (MoC 2023) to cater to increasing demand. Table 3 lists the consumption of various fossil fuels and the corresponding import bill. Our research shows that by utilising CO<sub>2</sub> to produce synthetic variants of jet fuel, urea, methanol, olefins, and natural gas, India can reduce its import bills by nearly USD 46 billion per year. This will need an investment of USD 1307 billion in the current scenario and USD 511 billion in the future scenario.

For a few CCU products such as SAF, ethanol, and DME, we have normalised the savings in crude oil imports based on equivalent energy. An overall energy balance evaluation of India's refinery sector indicates that for every 100 units of energy output from refinery products, 97 units of energy are obtained from crude oil, whereas 10

units are consumed by the refinery for various processes. The savings in energy imports from CCU applications are then quantified based on the energy content after applying the correction factor (1.03 (100/97)) for crude oil). In the case of ethanol and DME, the Government of India has set a target of achieving 20 per cent blending with petrol (PIB 2023a), in addition to the existing ethanol demand of 5 MTPA, and 5 per cent blending with diesel (PIB 2023b), respectively. This translates to a reduction in crude oil imports, from which petrol and diesel are produced after refining, to the tune of 7.7 MTPA and 2.6 MTPA, respectively. Consequently, this reduces imports by USD 4.27 billion with ethanol blending and USD 1.4 billion with DME blending. For urea, the import reduction is normalised to liquefied natural gas prices based on the amount of gas consumed for producing hydrogen/ammonia. In the case of olefins, domestic production is primarily through feedstocks such as naphtha and other

**Table 3** USD 46 billion worth of imports can be reduced by deploying Carbon Capture and Utilisation

Product	Consumption (MTPA)	Reduction in imports (billion USD)	CO <sub>2</sub> mitigated (MT)	Total H <sub>2</sub> required (MT)
SAF	8.00	4.48	26.8	2.31
Urea	32.53	3.54	23.9	3.27
Methanol	2.58	0.86	3.5	0.47
Olefins	11.80	20.83	55.9	7.38
SNG	31.00	10.49	85.3	15.77
DME	3.93	1.40	7.50	1.03
Ethanol	12.51	4.27	23.9	3.30
Total	-	45.87	226.8	33.53

Source: Authors' analysis

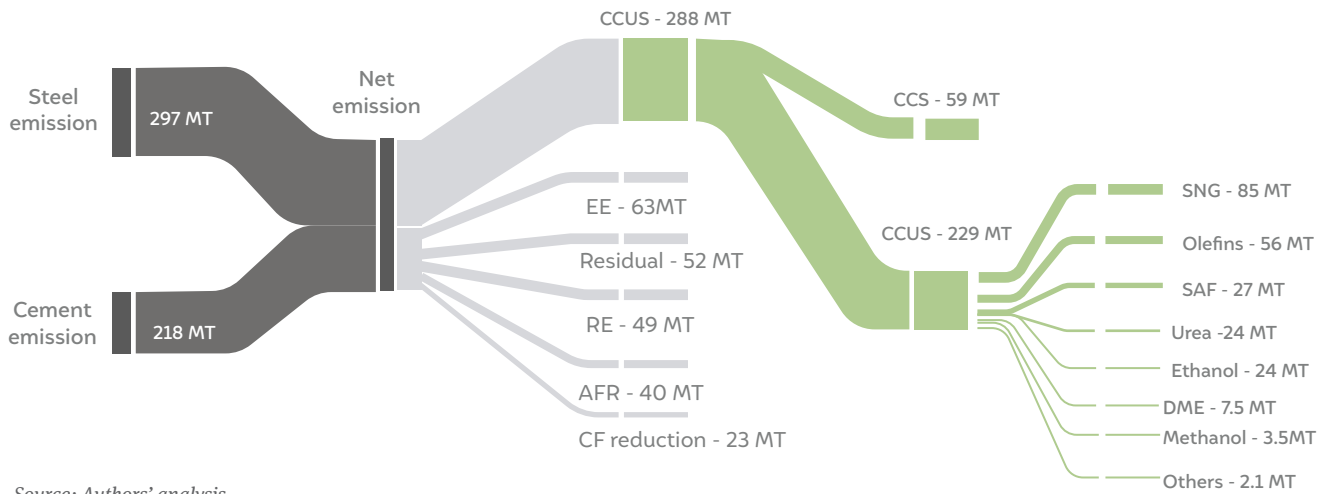
gaseous fuels. Production through this route includes additional capital and operational expenses, which have not been taken into account in our analysis due to a lack of reliable data. Consequently, only the final cost of olefins obtained from the literature (Department of Commerce 2023) for olefin imports is taken into consideration for estimating the reduction in import bills.

## 8. Impact of CCU on the prices of industrial products

Figure 14 presents the emissions from the steel and cement industries and the reduction in emissions that can be achieved through various decarbonisation measures as a Sankey diagram. It is seen that EE, RE, and AFs have a limited role to play in decarbonising these industrial sectors. Our analysis shows that of the 515 MtCO<sub>2</sub> emitted from the cement and steel industries, a major share of 56 per cent of emissions will have to be abated through the CCUS route. Of this, 229 MtCO<sub>2</sub> can

be abated through the CCU route, while the remaining has to be sequestered. Given that among the chemicals and fuels analysed natural gas consumption is the highest, the SNG route consumes the bulk of the CO<sub>2</sub> amounting to 86 MtCO<sub>2</sub>, and olefins consume 56 MtCO<sub>2</sub>. It should be noted that the uptake of CO<sub>2</sub> in SNG and olefin production depends on the cost of green hydrogen, the break-even cost for which is significantly lower than the target considered in the future scenario. Also, as discussed in Section 7, the uptake of CO<sub>2</sub> for producing SNG depends significantly on other decarbonisation alternatives. Therefore, CCS is a must, even if it is for mitigating emissions from the steel and cement industry alone, as CCU options will most likely fall short of the total abatement required in the sector.

As discussed in Section 4, CCU products have a significant premium over the incumbent fossil-based fuels and chemicals. This is expected to impact the cost of producing steel and cement. The following sections assess the impact of CCU products on the steel and cement industries.

**Figure 14** Of the total 288 MTCO<sub>2</sub>, 59 MT would still need to be sequestered

Source: Authors' analysis

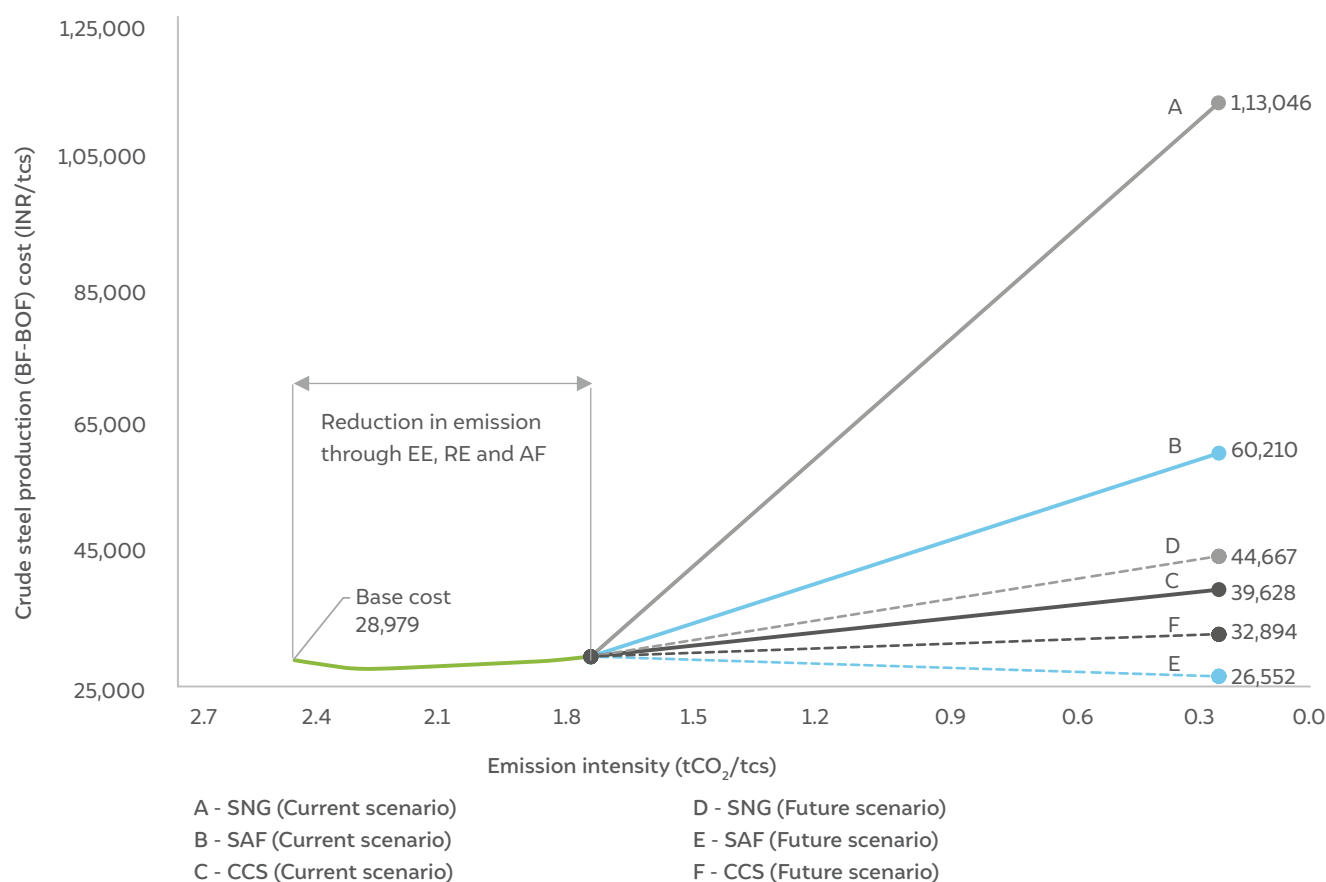
## 8.1 Impact of CCU on steel cost

Figure 15 compares the price increase of steel produced through the blast furnace-basic oxygen furnace (BF-BOF) route for different CO<sub>2</sub> utilisation pathways. The price increase was estimated considering a base price of steel of INR 28,979 per tcs (USD 386 per tcs). The estimation considers the scenario in which all other decarbonisation measures such as EE, RE, AFs, and CCS have been exhausted (Elango et al. 2023). With these measures in place, the steel industry can reach an emissions intensity of only 1.55 tonnes of CO<sub>2</sub>/tcs. Beyond this, further reduction in emissions intensity can be achieved only through the CCUS pathways. The figure also shows the increase in steel cost across current and future scenarios for the extremes that have the highest and the lowest cost of CO<sub>2</sub> mitigation. We compare the change in steel cost with a scenario where emissions reduction is achieved through CCS. It is seen that the increase in the cost of steel is the highest for the SNG pathway, at INR 1,13,046 per tcs (USD 1507 per tcs), which is nearly a 300 per cent increase over the base price. In contrast, the price increase for the SAF pathway is the least, at 107 per cent. The price increase curves for other CCU applications are between these two extremities.

The graph also shows that mitigating residual CO<sub>2</sub> through CCS will come at a 37 per cent premium and is cheaper than any other CCU-based decarbonisation measure in the current scenario.

For the future scenario, it is seen that the steel cost changes by (–)8 and 54 per cent with SAF and SNG adoption, respectively. As indicated in Figure 10, SAF production has a negative cost of abatement. Consequently, the steel production cost is actually reduced with the adoption of SAF as a mitigation measure. In contrast, there is an increase in the cost of steel with SNG as a decarbonisation option primarily because of the positive mitigation cost. With CCS at 30 USD/tonne, the cost of steel increases by only 14 per cent, which is intermediate between the costs for SAF and SNG pathways.

**In the current scenario, CCU increases the cost of steel by 100-300% and should only be considered for adoption in the future, when the cost of green hydrogen decreases substantially.**

**Figure 15** The cost increase for steel is the highest in the SNG pathway

Source: Authors' analysis

Note: BF-BOF, blast furnace–basic oxygen furnace; tcs, tonne of crude steel

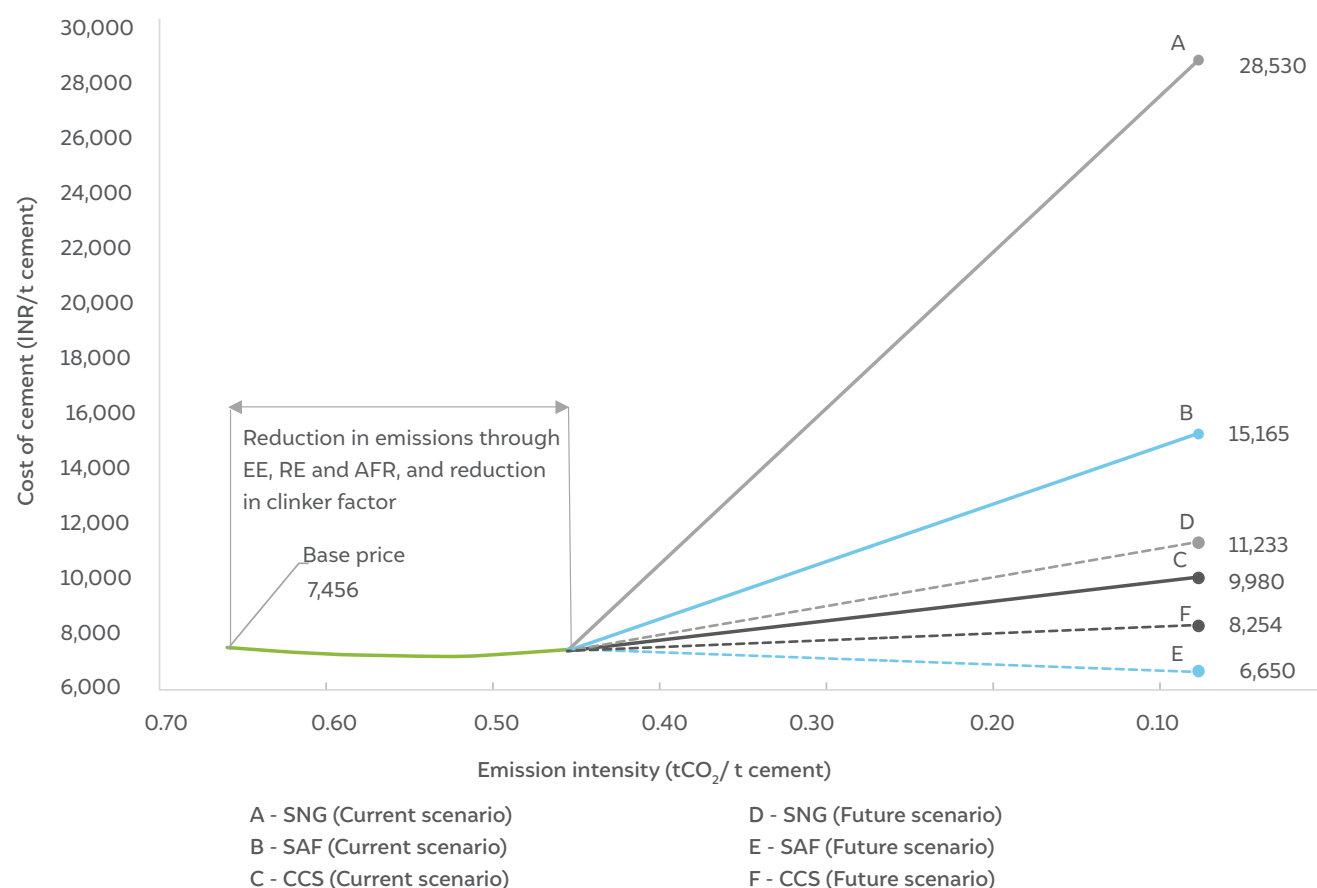
## 8.2 Impact of CCU on cement cost

Figure 16 compares the cost of decarbonising cement for various CO<sub>2</sub> utilisation pathways after exhausting mitigation options such as EE, RE, AFRs and raw materials (AFRs), and CCS (Nitturu et al. 2023). If the base price of cement is considered to be INR 7456 per tonne (USD 99 per tonne) and if the residual emissions after exhausting EE, RE, and AFR are mitigated through the CCUS pathway (beyond an emissions intensity of 0.45 tCO<sub>2</sub> per tonne), then the price of near-zero cement increases by 103–283 per cent depending on the CCU measure (SAF or SNG) adopted. With a CCS cost of 90

USD per tonne, the price increases by 34 per cent. However, as seen in the cost curve of steel, the cost of near-zero cement changes by (–)11 to 51 per cent in a future scenario. With CCS, there will always be an increase in production costs due to a positive abatement cost.

**CCUS can abate approximately 56% of the total emissions from the sector. Therefore, without a significant decrease in the cost of green hydrogen, the cost of cement is expected to rise in the future.**



**Figure 16** Near-zero cement costs the least when the SAF pathway is used

Source: Authors' analysis

## 9. Challenges

Developing and scaling up CCU ecosystem in India faces many challenges. A few challenges are listed below:

- Evolving a green hydrogen ecosystem in India:** The *National Green Hydrogen Mission* (NGHM) was launched in 2023 to establish a green hydrogen ecosystem in the country and has set a target for producing 5 MTPA of green hydrogen by 2030. However, the ecosystem for green hydrogen is still evolving, and production is not done at scale. It will need to be further streamlined to cater to newer use cases such as CCU.
- Renewable energy capacity:** Green hydrogen is one of the key input in achieving carbon abatement through CCU. Our study shows that utilising CO<sub>2</sub> to produce synthetic chemicals and fuels would require the production of 34 MT of green hydrogen, which alone would require 680 GW of RE capacity. This is significantly more than the existing RE capacity of 145 GW (Ministry of New and Renewable Energy 2024), and increasing RE capacity by such a huge amount could be a major challenge.
- Significant land resource consumption:** Past experiences in deploying large-scale renewable power projects show that vast tracts of land will have to be used over extended periods of time. Our estimates show that installing 680 GW of RE capacity would require nearly 2.4–3.4 million acres of land. In a country like India, where there are competing uses for land, this poses a significant challenge.
- Lack of domestic original equipment manufacturers (OEMs):** Currently, very few domestic OEMs have developed CO<sub>2</sub> conversion-related technologies. The market for CO<sub>2</sub> conversion technologies is not competitive enough to bring down

costs, despite the fact that OEMs exist for a variety of CCU applications worldwide. Therefore, domestic CCU project developers will have to bear considerable technical and proprietary costs, which might prove to be a barrier to developing a CCU ecosystem in India.

- **Low demand for carbon-neutral products:** In India, there are currently no procurement mandates to buy or use carbon-based products. Producers of carbon-neutral products are reluctant to deploy substantial capacities in the absence of a mandate guaranteeing a fixed offtake, which impedes the cost reductions that may be realised through economies of scale. In such a scenario, India's CCU projects will stay in the pilot stage till the price of green hydrogen drops.

## 10. Conclusion and recommendations

CCUS will play a pivotal role in achieving net-zero emissions, especially in hard-to-abate industrial sectors such as steel and cement. The study estimates that India can utilise 229 MTPA of CO<sub>2</sub> for producing value-added fuels and chemicals. However, this will also need 34 MTPA of green hydrogen, which is significantly higher than the 5 MTPA target set under the NGHM. Furthermore, unlocking all CCU opportunities will require an investment of USD 1.3 trillion today, which will reduce to USD 511 billion if the cost of green hydrogen is reduced to USD 1 per kg (from USD 4.2 per kg considered for 2024).

The challenges related to the cost of CCU products still persist. Our assessment indicates that CCU products have a MAC of USD 273–744 per tonne of CO<sub>2</sub> today. Consequently, CCU products are 89–540 per cent more expensive than their fossil-based counterparts. However, with a future reduction in the cost of green hydrogen and carbon capture, most CCU applications such as urea, SAF, ethanol, and DME production will become commercially viable. It is also evident from our analysis that despite utilising CO<sub>2</sub> in the production of chemicals and fuels, a significant amount of CO<sub>2</sub> will still need sequestration.

For instance, out of the 297 and 218 MtCO<sub>2</sub> emitted by the steel and cement industries, approximately 288 MtCO<sub>2</sub> needs to be abated by CCUS alone, with 229 MtCO<sub>2</sub> to be addressed by CCU and 59 MtCO<sub>2</sub> by CCS exclusively. Based on our analysis, we recommend the following:

- **Develop favourable policies to build a CCU ecosystem in the country.** As evident from the research, most CCU applications require green hydrogen. Therefore, the next phase of the NGHM should focus on creating an environment that enables the development of the CCU ecosystem in India.
- **Develop a CCS ecosystem in the country:** While there is significant potential for abating emissions through CCU pathways, CCS is indispensable for a carbon-neutral steel and cement industry. Therefore, India should prioritise designing a CCS policy for developing the ecosystem.
- **Develop and update existing standards and regulations to incorporate CCUS:** A thorough assessment of safety standards is required to identify and develop the necessary safety standards, definition and regulations for the entire CCUS value chain. The environmental impact assessment must have provisions for clearing CCUS projects, especially in the hard-to-abate sectors.
- **Indigenous technology development and piloting:** In the short term, the research, development and demonstration (RD&D) fund under the NGHM should include the development of indigenous technologies for all CCU applications as a priority research area. Furthermore, the government should support pilot demonstrations of all CCU pathways in the medium term.
- **Build a collaborative research network:** The Department of Science and Technology (DST) should build a domestic research network that facilitates collaboration between academia, government institutes, policy think tanks, and industry. It should also establish networks for knowledge transfer with other countries that have successfully implemented CCUS projects at a pilot or commercial scale.

## Acronyms

<b>CAPEX</b>	capital expenditure
<b>CCS</b>	carbon capture and sequestration
<b>CCU</b>	carbon capture and utilisation
<b>CCUS</b>	carbon capture, utilisation, and storage
<b>DME</b>	dimethyl ether
<b>EE</b>	energy efficiency
<b>H<sub>2</sub></b>	hydrogen
<b>MAC</b>	marginal abatement cost
<b>MMBtu</b>	million British thermal units
<b>MT</b>	million tonnes
<b>MtCO<sub>2</sub></b>	million tonnes of CO <sub>2</sub>
<b>MTPA</b>	million tonnes per annum
<b>NDC</b>	Nationally Determined Contributions
<b>NGHM</b>	<i>National Green Hydrogen Mission</i>
<b>OPEX</b>	operating expenditure
<b>RD&amp;D</b>	research, development and demonstration
<b>RE</b>	renewable energy
<b>tcs</b>	tonne of crude steel
<b>TRL</b>	technology readiness level
<b>SNG</b>	synthetic natural gas
<b>SAF</b>	sustainable aviation fuel

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