ASIA INVESTOR GROUP ON CLIMATE CHANGE

Carbon Capture and Storage in the decisive decade for decarbonisation

- The case for Asia

Acknowledgement

About AIGCC

The Asia Investor Group on Climate Change (AIGCC) is an initiative to create awareness and encourage action among Asia's asset owners and financial institutions about the risks and opportunities associated with climate change and low carbon investing.

AIGCC provides capacity for investors to share best practice and to collaborate on investment activity, credit analysis, risk management, engagement and policy. With a strong international profile and significant network, AIGCC represents the Asian investor perspective in the evolving global discussions on climate change and the transition to a greener economy. AIGCC has over 50 members from 13 markets representing over USD26 trillion in assets under management.

www.aigcc.net

About Wood Mackenzie

Wood Mackenzie, a Verisk business, is a trusted source of commercial intelligence for the world's natural resources sector. For nearly 50 years, we have been providing quality data, analytics, and insights, establishing us as the global research and consultancy business powering the natural resources industry. We empower clients to make better strategic decisions, by arming them with objective analysis and advice on assets, companies and markets. Our dedicated oil, gas & LNG, power & renewables, chemicals, metals & mining sector teams are located around the world, and deliver research and consulting projects based on our assessment and valuation of thousands of individual assets, companies, and economic indicators such as market supply, demand, and price trends. We partner with our customers to provide the analytics solutions they rely on to inspire their decision making and, ultimately, accelerate the world's transition to a more sustainable tomorrow.

www.woodmac.com

This report is written by AIGCC and leverages findings and figures from an independent report by Wood Mackenzie, which was commissioned by AIGCC.

Lead authors from AIGCC

Firdaus Anuar
Project Manager

Yong-liang Por
Research Manager

Valerie Kwan
Director, Engagement

With contribution from Wood Mackenzie

Joshua Ngu
Vice President

Allen Chan
Principal Consultant

Reviewers and acknowledgement of individuals

The feedback provided by these individuals does not represent an investment endorsement or recommendation and does not reflect any policies or positions of their firms. With grateful thanks:

All supportive colleagues of AIGCC and IGCC, Karen Wu and team (Cathay Financial Holdings), Courtney Foster, Josh Lowell, Laetitia Pirson, and Tracey Cameron (Ceres), Jose Lazuen (IIGCC), Eric Nietsch (Manulife Investment Management), Ben Pincombe (Principles for Responsible Investment), and Jacqueline Tao (TransitionZero).

TABLE OF CONTENTS

GLOSSARY

Term	Description
AET-1.5	Accelerated Energy Transition -1.5, Wood Mackenzie's 1.5 °C scenario
AET-2	Accelerated Energy Transition -2, Wood Mackenzie's 2°C scenario
AIGCC	Asia Investor Group on Climate Change
AUD	Australian Dollar
bcfd	Billion cubic feet per day
BF	Blast Furnace
BOF	Basic Oxygen Furnace
CAPEX	Capital Expenditures
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CN	China
CSP	Crude Steel Production
DAC	Direct Air Capture
DRI	Direct Reduced Iron
EAF	Electric Arc Furnace
EOR	Enhanced Oil Recovery
ETO	Energy Transition Outlook, Wood Mackenzie's base case scenario based on current policies
EUR	European Euro
GBP	British Pound
GCCSI	Global CCS Institute
GHG	Greenhouse gas
Gt CO_2e	Gigaton (billon tons) of CO_2 Equivalent
IEA NZE	International Energy Agency Net Zero Emissions by 2050 Scenario
IEA SDS	International Energy Agency Sustainable Development Scenario
IGCC	Integrated Gasification Combined Cycle
IN	India
IPCC	Intergovernmental Panel on Climate Change
JKIC	Japan, South Korea, India, China
JKT	Japan, South Korea, Taiwan

Term	Description
JP	Japan
KR	South Korea
LCOE	Levelized Cost of Electricity
MENA	Middle East and North Africa
METI	Ministry of Economy, Trade and Industry, Japan
Mt CO_2e	Megatons (million tons) of CO_2 Equivalent
Mtpa	million tons per annum (year)
N/A	Not Applicable
NDC	Nationally Determined Contribution
NGCC	Natural Gas Combined Cycle
NPC	National Petroleum Council
O&M NPC	Operations and Maintenance National Petroleum Council
OPEX O&M	Operational Expenditure Operations and Maintenance
PCI OPEX	Pulverized Coal for Injection Operational Expenditure
ROW PCI	Rest of World Pulverized Coal for Injection
ROW	Rest of World
SCPC	Supercritical Pulverized Coal
T&D SCPC	Transmission and Distribution Supercritical Pulverized Coal
USD	United States Dollar
WM T&D	Wood Mackenzie Transmission and Distribution
ZEP WM	Zero Emissions Platform Wood Mackenzie
ZEP	Zero Emissions Platform

Executive Summary

The large-scale adoption of carbon, capture and storage (CCS) continues to be a key assumption underlying major decarbonization pathways as a means to bridge the emissions gap[1], resulting in projected CCS capacity requirements that are an order of magnitude greater than present capacity.

To date, there have been few challenges to this assumption despite the significant obstacles that CCS faces, including high operational costs, complex technical challenges, a myriad environmental risk and societal opposition, resulting in a total of only 27 operating CCS facilities worldwide[2] with a capture capacity of 40Mtpa/year-to-date versus projections of up to 6 Gt/year by 2050 in some assessments.

In the decisive decade for decarbonization, the prospect of CCS deployment has become a discussion of critical importance. To validate whether such capacity projections for 2050 are plausible in the Asian context, AIGCC has commissioned Wood Mackenzie to assess the drivers of CCS feasibility, consisting of cost competitiveness to alternatives, policy and regulatory support and storage availability, to assess the competitiveness of CCS in the power generation and steel sectors of China, India, Japan and South Korea (simplified as JKIC onwards).

AIGCC leverages upon selected findings and figures from Wood Mackenzie's report in its analysis which has drawn the following conclusions:

- Deploying CCS capacity in the power generation sector:
  - Will depend on total generation capacity required from gas and coal, and incentives to deploy CCS in these plants
  - Will need to reach 2.8 Gt by 2050 in the Wood Mackenzie 2°C scenario if climate targets of below 2°C are to be met
  - Will require right combination of policy support and technology, which are currently not in place

However, weighing the prospect of lowering costs of renewable energy, there exists a potential risk in CCS implementation resulting in a prolonged transition process away from fossil fuel use.

Detailed analysis of levelised cost of electricity across different scenarios are available in *Appendix B1*.

- Deploying CCS capacity in the steel sector:
  - Is more probable as there are no viable low-carbon alternatives in the short-to-medium term for blast furnace applications
  - Will need to reach 500 Mt by 2050 in the Wood Mackenzie 2°C scenario if climate targets are to be met
  - Is dependent on adequate policy support to allow CCS to compete in blast furnace applications.

1 Emission gap is defined as the difference between the business-as-usual scenario (noted as ETO scenario in Wood Mackenzie analysis) and the 2°C scenario (noted as AET-2 in Wood Mackenzie analysis)

2 The Global Status of CCS 2021 report: https://www.globalccsinstitute.com/resources/global-status-report/

However, for some lower carbon production methods such as Scrap EAF and Biomass BF-BOF in China and India, even with the implementation of carbon tax, steelmaking processes with CCS retrofits significantly fall short in its cost competitiveness. Blast furnace will still be required as it will not be fully displaced by scrap and other options. However, as fuels such as hydrogen become viable, it will also compete with CCS as a decarbonisation solution. Detailed analysis of the cost competitiveness of various steel production methods across different scenarios are available in *Appendix B2*.

At the time of this report's release, granular data within the 1.5°C scenario (referred onward as AET-1.5 scenario) is yet to be made available for application in the analysis. It is therefore important to note that Wood Mackenzie's analysis was based on the 2°C scenario of the decarbonization pathway. It is expected that the direction and feasibility of CCS will broadly remain the same in the 1.5°C pathway, but will see the following nuances:

- **Global energy demand and mix:** Efficiency gains reduce fossil fuel demand while electricity demand grows even more strongly
- **Pace of transition:** Accelerated actions in the near term; negative emissions in long term required to meet the carbon budget
- **Technology:** Low carbon technologies such as renewables, nuclear and hydropower will be deployed more rapidly and in greater volumes
- **Policy:** Aggressive global policies to incentivize action in hard to abate sectors and target carbon budget

AIGCC's research further examines additional obstacles to the large-scale implementation of CCS, including:

- **Environmental risks** from potential leakages that are hazardous to human health and ecosystems and may also lead to water stress given the high water intensity of carbon capture processes. This also creates the prospect of financial liabilities for this leakage.
- **Technical challenges** arising from a lack of scalability owing to the different technical specifications required for different CCS projects, significant research needed to assess the suitability of storage formations and difficulty in establishing a network of pipelines required for large scale transport of CO_2.
- **Financing dearth** as commercial banks remain reluctant to finance CCS projects due to a lack of revenue stream and high commercial failure rate, and we judge public funding for globalized CCS adoption to be unlikely.
- **Societal opposition** appears likely owing to the probable large expansion of industrial sites to accommodate CCS equipment, large-scale use of hazardous chemicals and its transportation and the siting of CO_2 pipelines.
- **Competitive deployment** of resources into ensuring a smooth transition into net zero will affect the overall level of support for CCS deployment. Policies and the different levels of international cooperation to address climate change and its impact to commodity prices, capital investments, sharing of capabilities and export policies may have an indirect impact on the level of attractiveness of large-scale CCS deployment.

This analysis highlights the numerous and deep-seated obstacles facing the widespread adoption of CCS. Combined with the improving economics of renewables in the power generation sector, AIGCC believes that current projections of CCS capacity are likely to substantially undershoot, which in turn, has significant implications for decarbonization pathways of climate models and strategies of industries, governments and companies.

The following are key recommendations for various stakeholders:

Investors

- Engage with companies where CCS implementation is relied upon as a solution to decarbonize business operations rather than an option to prolong the transition away from fossil fuel, and to understand the extent of which CCS is being considered as a decarbonization strategy.
- As part of corporate engagement, gain deeper understanding of sector relevance of CCS implementation for the company's operations, while ensuring that other options to reduce emissions at source are being fully considered and that CCS is only used to neutralize residual emissions where no other technologies exist to decarbonize.
- Engage with policy makers to understand CCS infrastructure support, requirements, and pre-requisites necessary to enable the deployment of CCS.

Companies

- Acknowledge that for some sectors, a credible decarbonization pathway will require the phasing out of high-carbon assets, and that the implementation of CCS is only to be used to neutralize residual emissions and as a bridging technology in a carbon-constraint world for sectors that are hard to abate.
- Deployment of CCS should be supported by detailed disclosure of expected contribution of CCS to carbon emissions reduction targets. Relevant feasibility studies and contingency planning in the event of shortfall to carbon captured through CCS project deployed at asset level should be conducted to justify the scope and scale of CCS strategy to support the company's decarbonization.

In conclusion:

- The attractiveness of CCS deployment is lower when other cost competitive low or zero carbon options are available
- In the steel sector, competition from the cost of fossil fuel-powered feedstocks and other emerging technologies such as hydrogen as the zero-carbon feedstock will influence the level of attractiveness of CCS deployment.
- It is critically important for investors to carefully evaluate companies' decarbonization strategies that are reliant on CCS. Proper due diligence is needed as each CCS project tends to have specific technical characteristics with different types of risk
- CCS technology and economics, including issues on leakage and liability, continue to be a prominent issue
- Carbon pricing and policies will create a better financial position to spur CCS retrofits, but will test consumer tolerance to higher prices

1. Introduction and Purpose of Report

Introduction

Climate change risk and greenhouse gas emissions reductions are now at the top of many investors' agendas. The noticeable increase of net zero emissions commitments from large corporate emitters over the past two years have signaled some progress across Asia through the mainstreaming of climate change issues. To further support investors engaging with portfolio companies, a deeper understanding of decarbonization pathways presented by portfolio companies is necessary for investors as for many sectors, the pathways to decarbonization are not always straightforward. Regional policies, technologies and investments available will affect the trajectory of change. There still exists great uncertainty on the trajectory of limiting temperature rise in line with the Paris Agreement, which requires a complex mix of policies, technologies, and investments.

For many industrial sectors with heavy carbon emissions, such as thermal power and steel, the large-scale deployment of CCS is a key assumption underlying these sectors decarbonisation pathways, and its validity or invalidity would have significant consequences. To bridge the emissions gap, the projected CCS capacity requirements are normally presented in an order of magnitude greater than the present capacity.

Climate Action 100+, a global investor initiative currently with more than 615 investors, responsible for over USD60 trillion in assets under management and engaging on climate change, have launched global sector strategies featuring different sector papers on decarbonization expectations. The papers for the steel[3] and power[4] sectors were released in Q3 and Q4 2021 respectively, with a view to map the transition to net zero and identify priority actions required. In both papers, CCS and carbon capture, utilization and storage (CCUS) were referenced as early-stage technologies that companies would consider as part of their decarbonization strategy. For steel companies, any opportunities and scale of CCS and CCUS identified to be deployed for the company should come with specifications in as much detail as is practically possible the role expected of the emerging technology. For power companies, there are clear expectations for companies to map out a clear decarbonization strategy that minimizes reliance on CCS and CCUS.

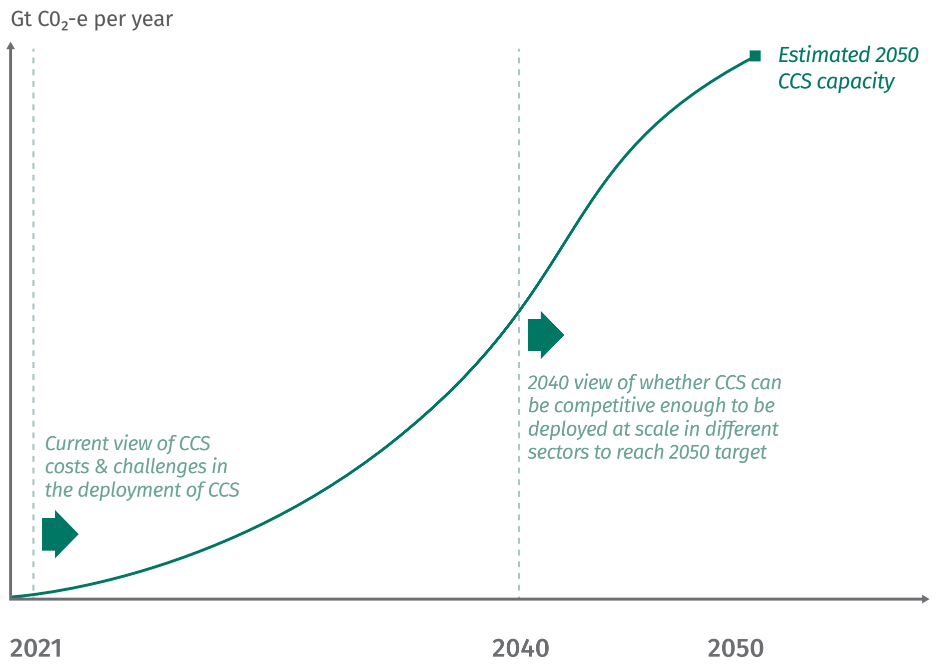
This report aims to triangulate the reasoning of narratives where assumptions for CCS are being deployed to varying extents as part of corporate decarbonization strategies. By providing a sector-level analysis of the prospect of CCS deployment, complemented with country perspectives, the report examines the cost competitiveness of CCS and seeds questions for investors to ask of companies with regards to their approach with CCS deployment. This is increasingly relevant as engagements in the region begin to deepen into the understanding of decarbonization pathways set out by companies and the role of various technologies such as CCS. With the backdrop of increasing commitments to phase down coal as codified in the Glasgow Climate Pact in COP26, and eventually to phase out of coal and other fossil fuels, the role of CCS in the decisive decade to decarbonize has become a discussion of critical importance.

3 Climate Action 100+ Global Sector Strategies: Investor Interventions to Accelerate Net Zero Steel, https://www.climateaction100.org/wp-content/uploads/2021/08/Global-Sector-Strategy-Steel-IIGCC-Aug-21.pdf

4 Climate Action 100+ Global Sector Strategies Investor Interventions to Accelerate Net Zero Electric Utilities, https://www.climateaction100.org/wp-content/uploads/2021/10/Global-Sector-Strategy-Electric-Utilities-IIGCC-Oct-21.pdf

To validate whether current capacity projections are plausible in the Asian context, especially in competition with other low-carbon alternatives in various industries, AIGCC has commissioned Wood Mackenzie to evaluate CCS' cost competitiveness under Wood Mackenzie's 2°C (referred as AET-2 scenario onwards). This is to understand if and how CCS will fit into the low-carbon future, through an evaluation of the cost competitiveness of CCS for the power generation and steel sectors for China, India, Japan and South Korea in 2021 and 2040 respectively. Other qualitative factors which could influence the competitiveness of CCS, and other relevant conclusions on conditions required for the technology will also be covered in the report.

Exhibit 1: Wood Mackenzie Scenario Requirement of CCS Capacity (Illustrative)



Source: Wood Mackenzie

Purpose of the report

This report is intended to support investors in corporate engagement but is also of value for multiple audiences in supporting the understanding of the feasibility of large-scale CCS implementation in the power and steel sector in key Asian markets.

Carbon capture and storage, or simply known as CCS, comprises a group of technologies that prevent carbon dioxide (CO_2) from being released into the atmosphere, by capturing the CO_2 emitted by an industrial process (e.g., burning gas or coal for electricity, or in cement and steel production), and permanently keeping it out of the atmosphere by storing it underground. CCS can be divided into three major parts: 1) Capture and Separation, 2) Transport, and 3) Storage and End-Uses.

CCS has been seen as a core part of most decarbonization scenarios, usually to bridge the emissions gap to the end goal. As a result of such methodologies, projected CCS capacity requirements are often an order of magnitude greater than present capacity. CCS projects to date have faced significant challenges and remain a pure cost in absence of policy support. The CCS value chain is complex and requires a comprehensive set of capabilities and technologies for safe operation.

The following are key recommendations for various stakeholders:

Investors

- Engage with companies where CCS implementation is relied upon as a solution to decarbonize business operations rather than an option to prolong the transition away from fossil fuel, and to understand the extent of which CCS is being considered as a decarbonization strategy.
- As part of corporate engagement, gain deeper understanding of sector relevance of CCS implementation for the company's operations, while ensuring that other options to reduce emissions at source are being fully considered and that CCS is only used to neutralize residual emissions where no other technologies exist to decarbonize.
- Engage with policy makers to understand CCS infrastructure support, requirements, and pre-requisites necessary to enable the deployment of CCS.

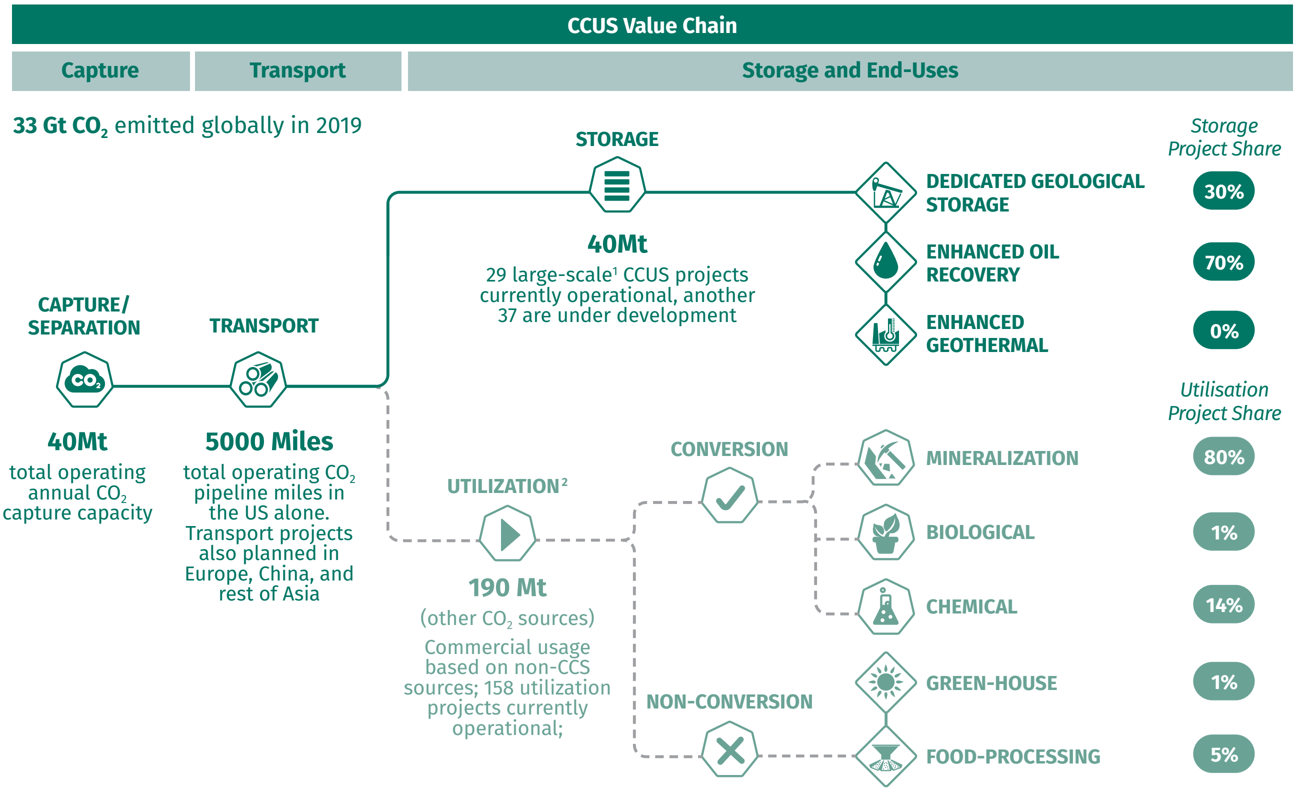
Companies

- Acknowledge that for some sectors, a credible decarbonization pathway will require the phasing out of high-carbon assets, and that the implementation of CCS is only to be used to neutralize residual emissions and as a bridging technology in a carbon-constraint world for sectors that are hard to abate.
- Deployment of CCS should be supported by detailed disclosure of expected contribution of CCS to carbon emissions reduction targets. Relevant feasibility studies and contingency planning in the event of shortfall to carbon captured through CCS project deployed at asset level should be conducted to justify the scope and scale of CCS strategy to support the company's decarbonization.

Context of study

The CCUS value chain is complex and requires a comprehensive set of capabilities and technologies for safe operation. It is therefore crucial to note that this report will not cover analysis on the utilization of CO_2, based on the assumption that current major end-use of captured CO_2 is CO_2-EOR (enhanced oil recovery). As noted from the IEA report, there is a limited role of CO_2 usage by industries and a large majority of captured CO_2 of up to 95% captured in 2050[5] will be in geological storage.

Exhibit 2: The complexity of CCUS value chain



Notes: 1. Large-scale: >0.8 Mt per year of CO_2 for a coal-based power plant and >0.4 Mt per year for other emissions-intensive industrial facilities
2. CO_2 utilization is not covered in this report
Source: Wood Mackenzie, IEA, The Global CCUS Institute, Third Way

For details on Wood Mackenzie's assessment of storage availability in China, India, Japan and Korea, please refer to *Appendix A: Storage availability in focus countries*.

5 The CCUS chapter within the IEA NZ by 2050 Roadmap for Global Energy Sector provides detailed estimates on the marginal increment of capture volumes over the next five years followed by more rapid expansion thereafter, with most of the CO_2 captured being stored in permanent geological storage.

Scenarios and assumptions

Wood Mackenzie has used the AET-2 scenario as the basis of the analysis. This scenario considers significant changes to the energy mix and demand to limit temperature rise from pre-industrial levels.

The business-as-usual scenario for Wood Mackenzie analysis is called Energy Transition Outlook (ETO), which is based on current policies. The ETO scenario is a present-day view based on Wood Mackenzie's models, commodity prices and cost estimates. It also reflects estimates of carbon taxes based on prevailing policies in targeted countries. The cost analysis was conducted at two points in time for the ETO scenario (2021 and 2040) to provide a view of the current trajectory and to provide a basis of comparison against the AET-2 scenario. For the purposes of the report, the ETO 2021 scenario is useful in mapping the current state of play, whilst the AET-2 scenario in 2040 serves as the basis of the analysis as we continue to explore into the feasibility of CCS deployment in industrial decarbonisation pathways.

This report aims to explore the challenges towards large-scale deployment of CCS in Asian markets, together with how cost-competitive CCS will be in the power and steel sectors in Wood Mackenzie's 2°C scenario. Wood Mackenzie has yet to conduct a full quantitative analysis under a AET-1.5 scenario. However, the direction and feasibility of CCS is unlikely to radically change in the 1.5°C pathway. Whilst this is not directly comparable to the IEA's Net Zero Emissions (IEA NZE) scenario nor a critique of plausibility of other scenarios, more details are be available in *Chapter 3: A qualitative comparison of conclusions if extended to a 1.5°C pathway*.

For more detail on scenarios applied and the assumptions of the scenario, please refer to *Appendix C: Scenarios Used by Wood Mackenzie in the Analysis*.

2. Wood Mackenzie's assessment of CCS Cost Competitiveness by Sector and Country

Wood Mackenzie's study relies on its tracking of CCS costs from literature review and the use of sensitivity analyses. The cost competitiveness analysis evaluates the relative position of different options from the present day to a 'transition' state in 2040. For the purposes of the study, a common set of CCS costs based on published literature are applied across all country comparisons with adjustments made based on country-specific parameters such as onshore or offshore storage. A sensitivity analysis was further conducted to evaluate the potential impact of upper/lower bound assumptions on cost, carbon prices and other parameters. Detail of the sensitivity analysis of cost competitiveness of CCS through the entire value chain in the respective markets for power generation and steel sectors are available *Appendix B-1 and B-2* respectively.

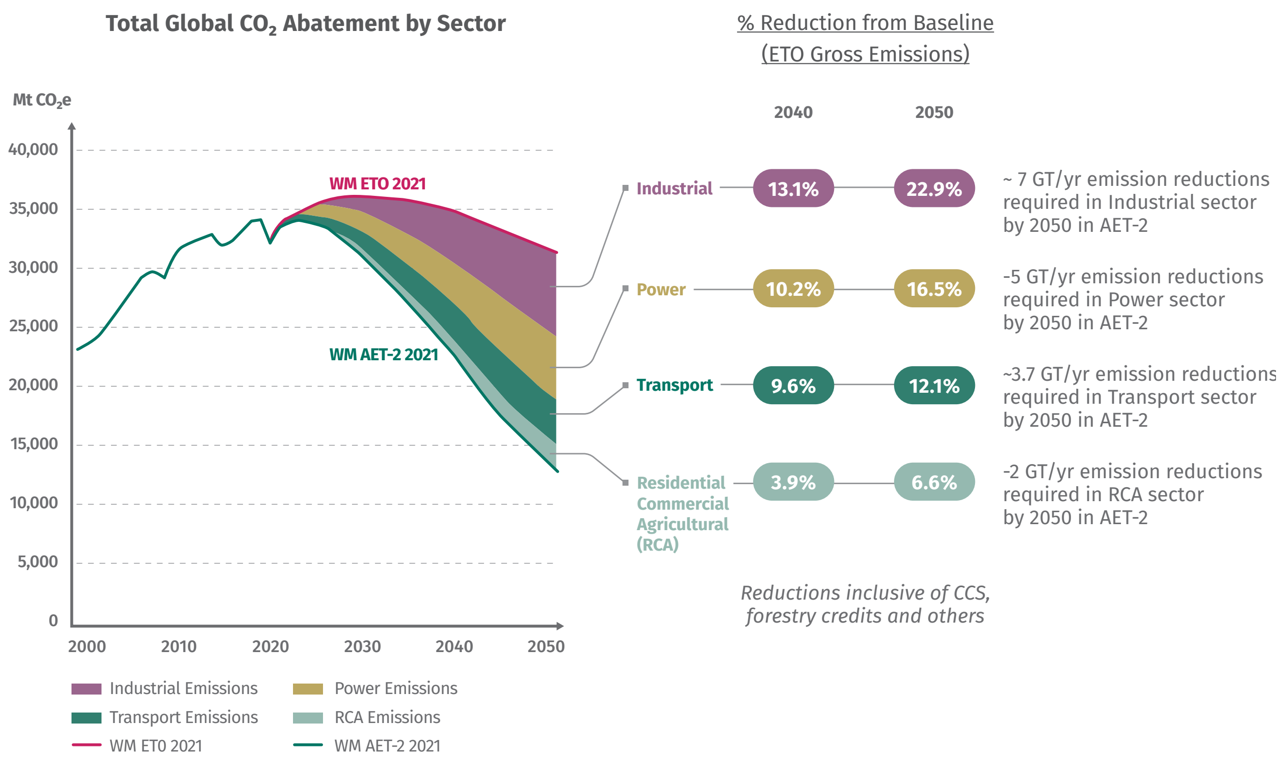
Power generation sector

Reduction in emissions associated with the generation of electricity is central to any plan to reach net zero. The power sector is a large source of emissions today and decarbonisation is needed, not just to address these emissions, but to support the transition of other sectors to net zero like transport. It also plays a central role in economic activity and everyone's daily lives. The need for a secure supply of low-cost electricity is a strategic imperative for most national governments and actions to decarbonize power, and can have widespread implications. The power sector accounts for 13.5 Gt per annum, which is about 40%[6], from a total of 33.9 Gt of global CO_2 emissions in 2020.

According to Wood Mackenzie's AET-2 scenario, the power sector is estimated to account for an approximately 10% gross reduction from baseline global CO_2 emissions (current emissions trajectory in the Energy Transition Outlook [ETO], Wood Mackenzie's base case scenario based on current policies) in 2040 and an approximately 16% reduction in 2050. As a result, significant reductions will be required from the industrial and power sectors to meet 2°C targets as outlined in Exhibit 3 below.

6 Net Zero by 2050, International Energy Agency (IEA)

Exhibit 3: Total Global CO_2 Abatement by Sector



Source: Wood Mackenzie;
Note: ETO = WM's Energy Transition Outlook Scenario, AET-2 = WM's Accelerated Energy Transition - 2 °C Scenario;

High level evaluation of technologies considered for the analysis

Options considered for cost competitive analysis of the power generation sector are as follow:

- Fossil fuel-based (coal and gas) option, without CCS
- Fossil fuel-based (coal and gas) option, with CCS
- Renewables based (solar and wind) option, including battery and storage options

Exhibit 4: Summary of power generation options evaluated in analysis (fossil fuel-based options)

Options	Current Status	Future Trends	Current Maturity	% Capacity Share 2040[1]
Coal Fired Power	• Coal still dominates ~44% share of JKIC generation capacity in 2021 • Remains critical to grid stability as base load • Advancements in supercritical & 'ultra'-supercritical plants have improved efficiencies • Financing will be challenging given climate change concerns	**Will decline given environmental concerns and retirements, although improvements are possible:** • **Integrated Gasification Combined Cycle:** Convert coal to syngas prior to combustion for greater efficiency & lower emissions • **Oxy-fuel Combustion:** Use of pure O_2 in combustion to improve efficiency & create CO_2 rich flue gas for capture • **CCS retrofit:** Retrofit of brownfield plants to capture CO_2 pre or post combustion	Supercritical Coal (Fully commercial) IGCC/ Oxyfuel (Pilot/Demo only)	14%
Gas Fired Power	• Accounts for ~8% of JKIC generation capacity • Remains critical to grid stability as dependable dispatch capacity • Plant economics supported by price surges even at low utilisation	**Market share to remain steady as cleaner option to maintain grid stability Potential improvements include:** • **Hydrogen:** H_2 blending / substitution as feed gas to reduce emissions • **Allam cycle:** Use of pure O_2 in combustion price surges even at low utilisation to generate CO_2 as working fluid • **CCS retrofit:** Retrofit of brownfield plants to capture CO_2 pre or post combustion	NGCC (Fully commercial) Allam Cycle (Pilot/Demo only) H_2 blending (Concept only)	7%

Notes: (1) Capacity share In Japan, South Korea, China, India in AET-2 scenario (2) IGCC: Integrated Gasification Combined Cycle (3) NGCC: Natural Gas Combined Cycle

Concept only | Pilot/Demo only | Fully commercial

Source: Wood Mackenzie

Exhibit 5: Summary of power generation options evaluated in analysis (renewables options)

Options	Current Status	Future Trends	Current Maturity	% Capacity Share 2040[1]
Solar	• Accounts for 15% of JKIC power generation capacity • Utility PV expected to reach parity with coal in mid-2020s across APAC	• Largest capacity growth projected given supportive policy & economics • Rate of cost reduction will slow but cost improvements will continue via higher efficiencies & utilisation, increasing unit sizes, modularisation & further economies of scale	● Utility PV	34%
Wind	• Accounts for 12% of JKIC power generation capacity • Onshore wind expected to reach parity with coal in mid-2030s	• Sizeable capacity growth but slower than solar given higher costs • Onshore wind capacity factors will continue to improve with larger turbines & advanced dispatch models • Offshore wind will also improve with larger turbines & more high speed wind sites to be developed	● Onshore Wind ◕ Offshore Wind	20%
Battery Storage (with renewables)	• Storage paired with renewables account for 2% of JKIC capacity • WM projections based on coupling of Li-Ion batteries with 4-hr duration at 50% MW rating • Critical to reduce curtailment risk	• Share of capacity will rise 6x with improving battery costs & policy support – may be competitive vs gas by mid-2020s • Improvements expected to module costs, storage efficiency & higher capacity factors	◕ Battery Storage	12%

Notes: Capacity share in Japan, South Korea, India and China (JKIC) in AET-2 scenario
Source: Wood Mackenzie

○ Concept only ◐ Pilot/Demo only ● Fully commercial

Exhibit 6: Options considered for cost competitiveness analysis for power generation (USD/MWh)

	2021				2040			
	China	India	Japan	South Korea	China	India	Japan	South Korea
Gas (No CCS)	○	○	○	○	○	○	○	○
Coal (No CCS)	○	○	○	○	○	○	○	○
Gas + CCS	○	○	○	○	○	○	○	○
Coal + CCS	○	○	○	○	○	○	○	○
Utility Solar	○	○	○	○	○	○	○	○
Onshore Wind	○	○			○	○		
Offshore Wind			○	○			○	○
Utility Solar + Battery[1]	○	○	○	○	○	○	○	○
Onshore Wind + Battery[1]	○	○			○	○		
Offshore Wind + Battery[1]			○	○			○	○

Note: (1) Assumes lithium-Ion battery of 4-hr duration with 50% MW rating
Source: Wood Mackenzie

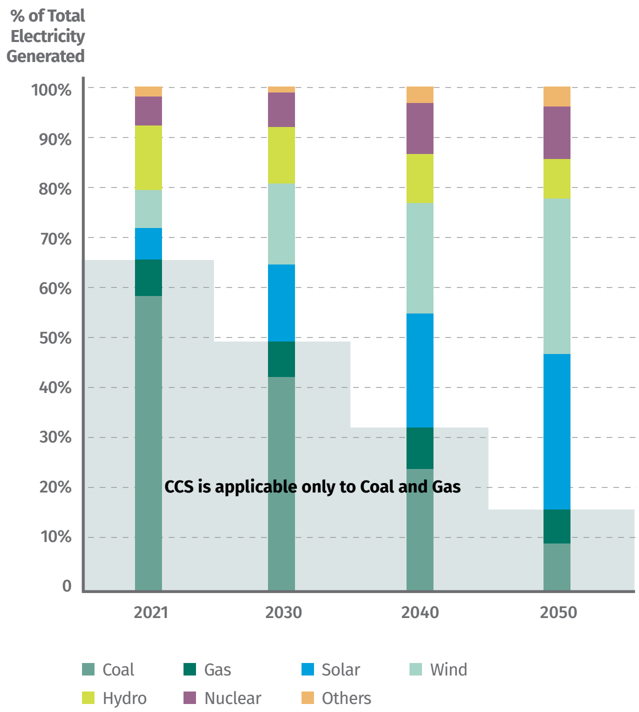
For an overview of levelized cost of electricity (LCOE) competitiveness across the four countries in the power sector, please see Exhibit 15 in page 25.

Findings and analysis

- In Wood Mackenzie's 2°C scenario, CCS is expected to play a niche role in decarbonising dependable[7] capacity to support grid stability. Renewables face increasing system costs[8] to address grid reliability at high penetration rates thus other dependable options are needed, while further development of battery and storage are taking place. Cost competitiveness analysis supports a transition to renewables, but CCS retrofits only become competitive in AET-2 to provide dependable capacity.

Exhibit 7: Power Generation Output by Type and Outlook for Power Generation Options

JKIC[1] Power Generation Output by Type



Outlook for Power Generation Options

Renewables (including storage)
- Dominant by 2050 accounting for more than 60% of output
- Low-carbon & scalable choice for new capacity
- Grid reliability remains a concern thus there is a continued need for dependable capacity

Gas-fired Power
- Provides ~ 7% of power output by 2050
- Retains niche as dependable[2] dispatchable[3] capacity in lieu of other flexible options

Coal-fired Power
- Generates 10% of power output by 2050
- Still plays key role as dependable[2] capacity where renewables are not sufficient or coal fleet is young

Nuclear & Hydro Power
- Maintains ~20% share through to 2050
- Low-carbon & reliable but faces environmental issues or safety concerns hence cannot fully substitute gas & coal

Other Technologies
- Other options such as biomass, geothermal, H_2
- Share of total output by 2050 is small

Source: (1) Japan, South Korea, India, China
(2) Dependable refers to capacity with high availability during peak demand over long duration
(3) Dispatchable refers to capacity that is adjustable per grid requirements over long duration
Note: Wood Mackenzie

- Renewables will be cheapest by 2040 but fossil fuels with CCS retrofits could play a role in supporting grid reliability in AET-2
- Generation capacity in Japan, South Korea, India and China is estimated to grow by a compound annual growth rate (CAGR) of 4.4% in AET-2 with fossil fuels declining to 21% of the capacity mix by 2040.
- Power generation sector emissions are expected to decline sharply even without CCS as coal capacity retires.

7 Dependable refers to capacity with high availability during peak demand over long duration

8 System costs refer to additional transmission & distribution infrastructure investments required to accommodate incremental renewable projects. These costs are not reflected in the LCOE of individual projects but will increase with more intermittent capacity in order to maintain the same level of reliability.

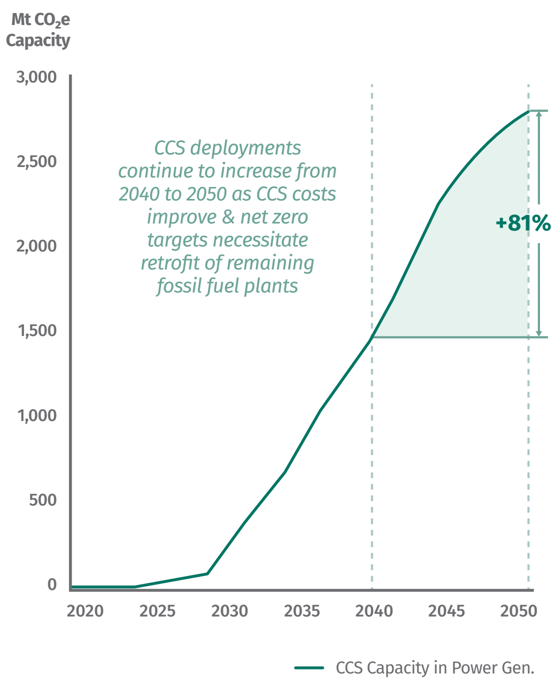
- Fossil fuel power generation will decline due to costs and emissions concerns but will still play a role to maintain grid stability.
- Low carbon options (renewables) are well understood, highly competitive and already deployed at scale in China and India.

Future trajectory for CCS in remaining fossil fuel plants for dependable capacity

In the 2°C scenario, Wood Mackenzie estimates that CCS deployment will continue to increase from 2040 to 2050 as costs improve and net zero targets necessitate retrofit of remaining fossil fuel plants.

Exhibit 8: Projected deployment for CCS in power generation post- 2040 under AET-2

Global Power Sector CCS Capacity[1] in AET-2



Notes: (1) Please refer footnote 9
Source: Wood Mackenzie

Key CCS Drivers from 2040 AET-2 Analysis

Trend	Key Conclusions in AET-2	Trend
Cost	**Vs. non-CCS fossil fuels:** Emerging cost advantage due to carbon prices to widen with CCS cost improvement	⬆
	Vs. renewables: Cost gap too wide to bridge; CCS remains as backup	⬌
Policy	Carbon prices unlikely to fall given continuing focus on net zero	⬆
	National net zero targets in some countries necessitate CCS retrofit on remaining fossil fuel plants unless other options are available	⬆
Technology	Long duration batteries still limited (~8 hrs) by 2050, thus CCS with fossil fuels is unlikely to be displaced	⬌

<u>Implications for 2050 (AET-2 Scenario):</u>

- If the world is to meet its 2°C target, CCS capacity is expected to continue to grow until alternatives for dependable capacity emerge - trajectory depends on technology readiness

⬆ Supports CCS Growth ⬇ Reduces CCS Growth ⬌ No Change

9 Notes: (1) Includes significant CCS deployment for biomass power generation (BECCS) in Europe and US. BECCS, or Bioenergy with Carbon Capture and Storage, is one of carbon removal technique where biomass (organic material) is converted into heat, electricity, or liquid or gas fuels (the bioenergy step), and the carbon emissions from this bioenergy conversion are captured and stored in geological formations or embedded in long-lasting products (the CCS step)

Key trends and conclusions for CCS in the Power Generation Sector as observed by Wood Mackenzie

CCS in Power Generation Sector

Implications on CCS Deployment

- Global CCS capacity needs to reach ~2.8 Gt by 2050 in WM's AET-2 scenario if targets are to be met
- Achieving the required CCS capacity will be more challenging as it depends on the continued use of gas & coal power for dependable capacity, but more importantly it requires the incentivisation of CCS. Bio energy (BECCS) plants also contribute to negative emissions
- The right combination of policy support & technology may put the capacity estimate within reach - but policies are not yet in place and uncertainty is high
- However, CCS is still expected to play a key role as
  - Decarbonisation targets cannot be achieved with renewables alone
  - High renewables penetration reduces grid reliability & increases total system costs
  - Other low carbon alternatives such as hydro & nuclear cannot fully replace gas & coal

For more detail on the country-level analysis on levelized cost of electricity (LCOE) with or without CCS retrofits for different power generation options compared against renewable energy, please refer to *Appendix B-1*.

Steel sector

Steel is a metal alloy formed from iron ore, carbon, and other elements depending on the final properties desired. Its strength and low cost make its use widespread across the construction, transport, and industrial sectors. Steel is currently produced by two main methods. The Blast Furnace and Basic Oxygen Furnace (BF-BOF) method (comprises of approximately 70% of total production) are typically used to make virgin (or 'primary') steel. In this process, a high grade (metallurgical) coal is used as both an energy and heat source and as a reduction agent to remove oxygen from the iron ore.

The second method uses an Electric Arc Furnace (EAF), fed by either scrap steel or by Direct Reduced Iron (DRI), also known as "sponge iron." It is estimated that approximately 500 Mt of steel is recycled every year and that 83% of the steel produced is recycled at the end of its life[10]. Feeding this steel "scrap" into the EAF makes "secondary" steel, which currently accounts for 23% of the total steel produced with EAF method.

According to IEA[11], steel production emitted 3.6 Gt CO_2 in 2019. The sector is currently responsible for about 8% of global final energy demand and 7% of energy sector CO_2 emissions (including process emissions). Steel's direct (Scope 1) emissions, largely released by the burning of coal, accounted for the largest share (62%) followed by indirect (Scope 2) emissions (27%) from imported and onsite electricity and heat generation. The BF-BOF process is responsible for about 85% of these emissions with the majority released during the BF stage.

More detail about the steel industry and its climate impact are available in the Climate Action 100+ global steel sector paper[12].

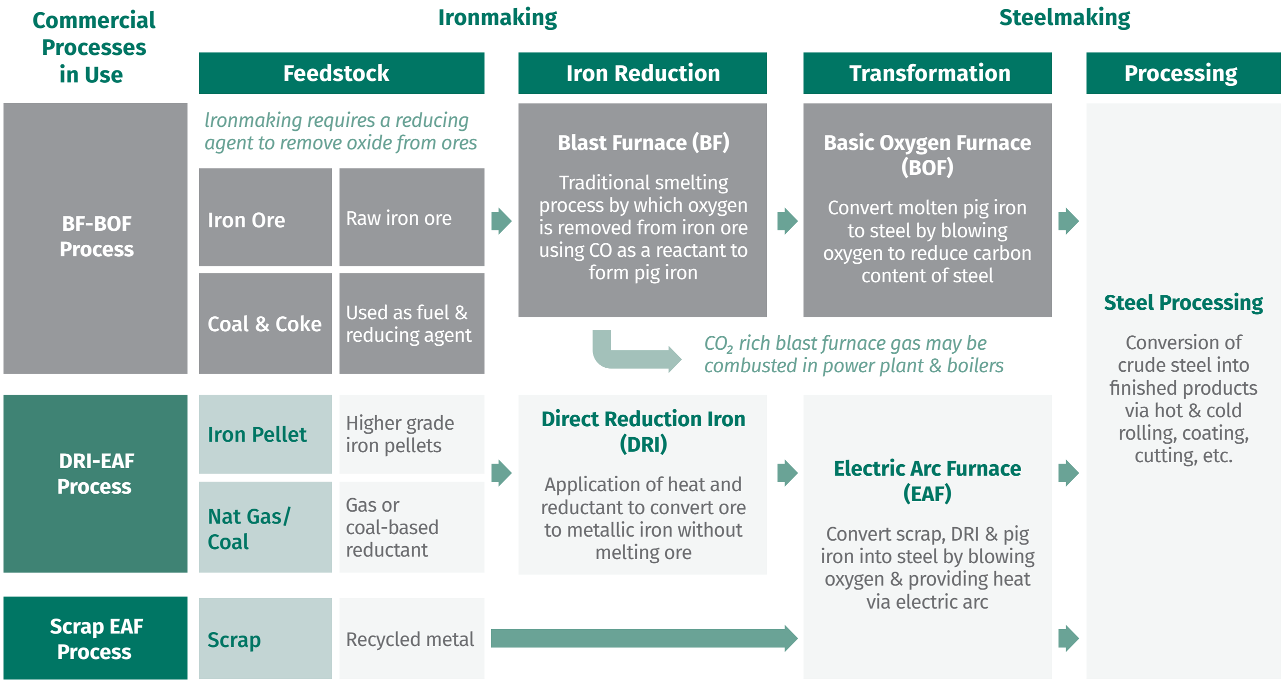
Below is an illustration from Wood Mackenzie outlining the conventional iron and steel making processes.

10 Material Economics, The Circular Economy a Powerful Force for Climate Mitigation Transformative innovation for prosperous and low-carbon industry. https://materialeconomics.com/publications/the-circular-economy-a-powerful-force-for-climate-mitigation-1

11 IEA Energy Technology Perspectives, Iron and Steel Technology Roadmap, https://www.iea.org/reports/iron-and-steel-technology-roadmap

12 Climate Action 100+ Global Sector Strategies: Investor Interventions to Accelerate Net Zero Steel, https://www.climateaction100.org/wp-content/uploads/2021/08/Global-Sector-Strategy-Steel-IIGCC-Aug-21.pdf

Exhibit 9: Introduction to conventional iron and steel making processes



Note: Blast furnace processes where there are use for CCS retrofits are indicated as grey boxes
Source: Wood Mackenzie

High level evaluation of technologies considered for the analysis

The options considered for Wood Mackenzie’s cost competitiveness analysis for the steel sector are as follow:

- Blast furnaces options, including with CCS
  - Basic Oxygen Furnace (BOF)
  - Electric Arc Furnace (EAF)
- Coal, gas, and hydrogen with Direct Reduced Iron (DRI) options
- Scrap EAF, Biomass BF-BOF and Hydrogen BF-BOF options

Exhibit 10: Summary of steelmaking options evaluated in the analysis

Options	Current Status	Future Trends	Current Maturity	% Capacity Share 2040[1]
BF-BOF Process	• Conventional BF-BOF dominates more than 70% share of global production due to legacy plants	**Share to decline given environmental concerns but 2040 share is still sizeable** **Potential improvements include:** • **Process improvements:** Modifications (i.e. top gas recycling) to improve efficiency • **CCS** can be retrofit to existing plants • **Feedstock substitution:** Low-carbon feed-stock can partially substitute coal by 2030s	● Conventional ◔ Hydrogen/ Biofuel	**Conventional Process: 42%** **Hydrogen/ Biofuel: 6%**
DRI-EAF Process	• Only ~6% of current market share • Production is led by India which comprises of very small coal-based DRI-EAF mini mills • Other countries use gas-based DRI which is less CO_2 intensive	**Share to increase given cleaner process** **Potential improvements include:** • **Low carbon reductants:** Increased usageof gas in near term & H_2 in long term; use of H_2 in DRI is more complex thus will only be deployed in advanced countries by 2040	● Gas/ Coal ○ H_2 based	**Gas/Coal Based: 11%** **H_2 Based: 2%**
Scrap EAF Process	• ~21% of current market • Well established in developed countries (Japan, S Korea) with ample domestic scrap recycling	• Expected to grow as more countries including China increase scrap recycling • Subject to availability and quality of scrap	●	**39%**

Notes: (1) In Japan, South Korea, China, India in AET-2 scenario
Source: Wood Mackenzie

○ Concept only ◑ Pilot/Demo only ● Fully commercial

The following steel production options have been selected based on the expected prevailing technologies in each country in 2021 and 2040.

Exhibit 11: Options to be considered in analysis for steel

	2021			
	China	**India**	**Japan**	**South Korea**
BF-BOF (No CCS)	○	○	○	○
BF-BOF + CCS	○	○	○	○
BF-EAF (No CCS)	○	○		
BF-EAF + CCS	○	○		
Scrap EAF	○	○	○	○
Biomass BF-BOF	○	○		
Green H_2 BF-BOF	○	○	○	○
Coal DRI-EAF		○		
Natural Gas DRI-EAF		○		
Green H_2 DRI-EAF	○		○	○

	2040			
	China	**India**	**Japan**	**South Korea**
Gas (No CCS)	○	○	○	○
Coal (No CCS)	○	○	○	○
Gas + CCS	○	○		
Coal + CCS	○	○		
Utility Solar	○	○	○	○
Onshore Wind	○	○		
Offshore Wind	○	○	○	○
Utility Solar + Battery[1]		○		
Onshore Wind + Battery[1]		○		
Offshore Wind + Battery[1]	○		○	○

Note: DRI = Direct Reduced Iron; BOF = Blast Furnace; EAF = Electric Arc Furnace
Source: Wood Mackenzie

Findings and analysis

There are broadly three types of processes in use today, with the traditional blast furnace process being the most carbon intensive. While conventional BF-BOF retains the largest market share in 2040, cleaner processes and feedstock substitution will grow steadily.

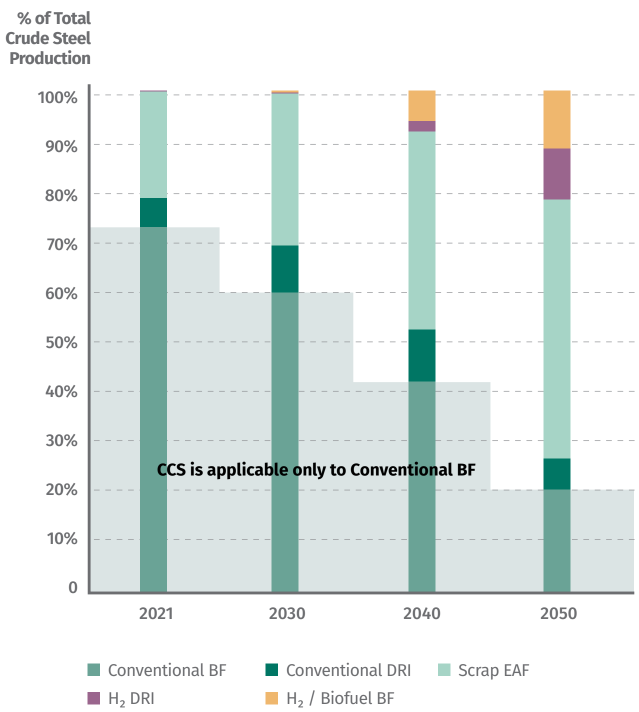
It is anticipated that the market share of conventional BF-BOF will fall from approximately 80% in 2021 to approximately 50% by 2040 as cleaner processes and feedstock substitution grow steadily. While BF-BOF applications will decline in market share, it will not currently be feasible to fully displace BF-BOF processes with current alternatives as BF remains the only option to convert raw iron ore of any quality into high grade steel. It therefore remains to be the best scalable option available to create high-grade steel. In addition to the quality of steel output, other factors such as sunk capital already invested in blast furnaces also add to the challenge of displacing BF-BOF application. Wood Mackenzie's assessment is that steel produced with DRI methods are currently only competitive in mid to low grade steel and the developmental trajectory of the technology for high grade DRI steel is not expected until the 2040s.

As discussed in the previous section, most emissions come from the BF process and thus CCS is most applicable to BF applications. Based on Wood Mackenzie's analysis, CCS will be an attractive 'lower carbon' option for BF applications in the AET-2 scenario as BF cannot be fully substituted in the near to mid term. Zero-carbon feedstock options such as hydrogen will only become viable by 2040 to start decarbonising BF applications.

Global steel capacity is expected to grow steadily but the biggest change will come from a shift in production process and feedstock. Despite global capacity growth, steel sector emissions are expected to decline by approximately 33% from 2021 levels by 2040 in the AET-2 scenario due to growth in scrap EAF and DRI and emergence of hydrogen-based options. An additional 20% of remaining steel sector emissions in 2040 are expected be captured via CCS in this scenario.

Exhibit 12: Steel Output by Type and Outlook for Steel Options

JKIC[1] Steel Output by Option



Source: (1) Japan, South Korea, India, China
(2) Excluding BF with low carbon feedstock
Note: Wood Mackenzie

Outlook for Iron & Steel Making Options

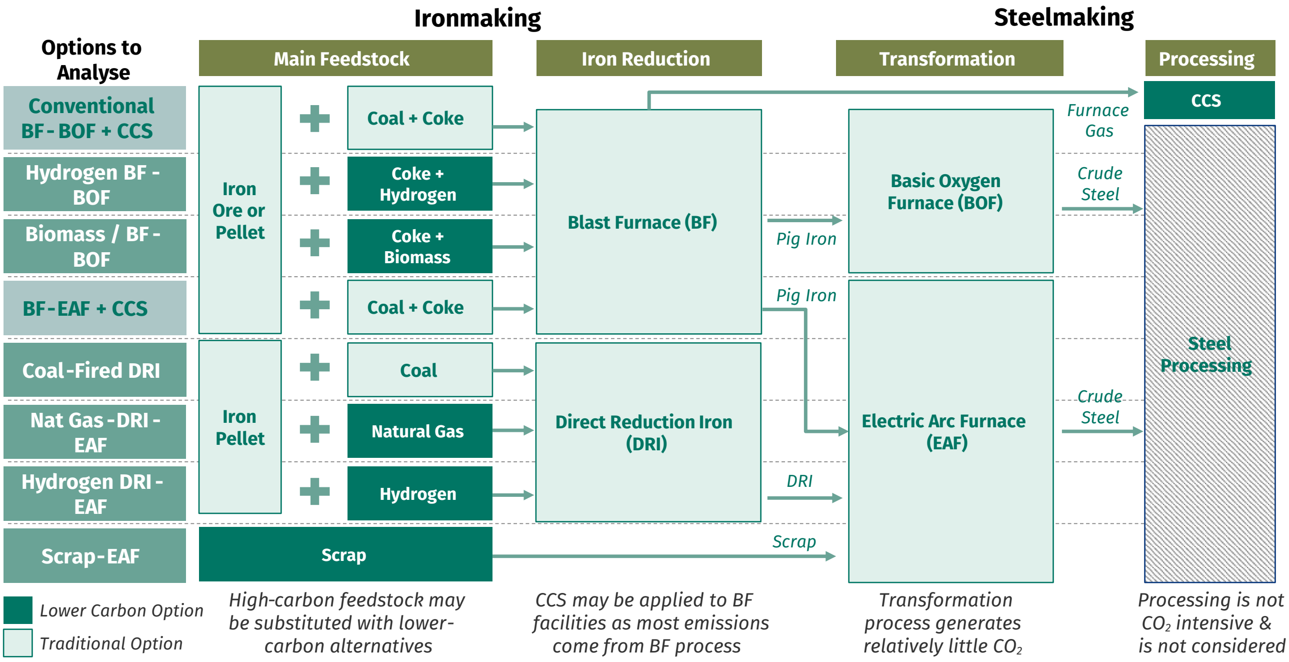
Conventional Blast Furnace (BF)
- Declines from 73% to 20%[2] of output by 2050
- Continued deployment expected despite high emissions as it is not fully interchangeable with DRI
- Remains only option for low grade ore inputs or for developing countries with limited feedstock options

Conventional Direct Reduced Iron (DRI) Options
- Increases to 10% of output by 2040 but drops to 6% as it is displaced by H_2-DRI towards 2050
- Gas-based options see increased deployment to 2040 given lower emissions & energy requirements

Scrap Electric Arc Furnace (Scrap EAF)
- Scrap usage increase more than double to 52% share by 2050
- Driven by greater availability of scrap recycling in developing countries & low emissions/high quality output

Low Carbon Feedstocks and Reductants
- Accounts for 22% of output by 2050
- Expected to present competitive low-carbon option to BF & DRI facilities though significant technical & economic challenges remain - deployment expected in mid-2030s to 2040s

Exhibit 13: Steelmaking options to be applied by 2040

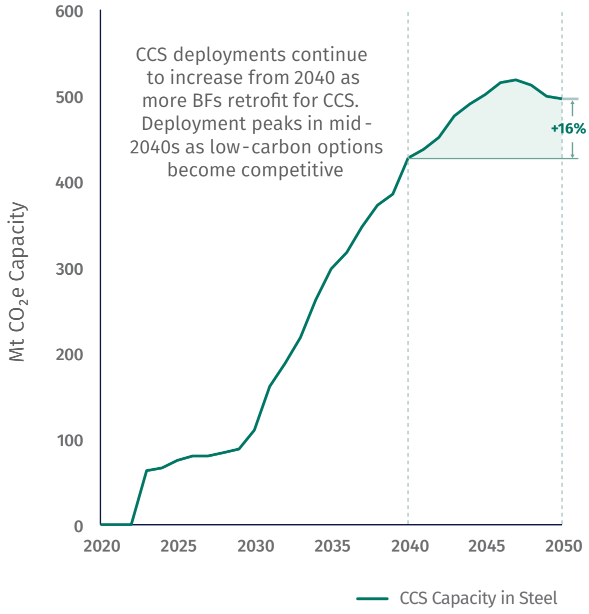


Source: Wood Mackenzie

CCS will need to compete against low carbon feedstock options and scrap by 2040. CCS deployments continue to increase from 2040 as more BFs retrofit for CCS. Deployment peaks in the mid- 2040s as low-carbon feedstocks become competitive.

Exhibit 14: Projected deployment for CCS in steel post-2040 under AET-2

Global Steel Sector CCS Capacity in AET-2



Source: Wood Mackenzie

Key CCS Drivers from 2040 AET-2 Analysis

Trend	Key Conclusions in AET-2	Trend
Cost	**Vs. conventional BF/DRI:** Marginal advantage for CCS from carbon price	▲
	Vs. scrap: Scrap usage will grow but is still limited by availability and quality	◆
	Vs. low carbon feedstock: Highly dependent on H_2 availability & price	▼
Policy	Carbon prices unlikely to fall given continuing focus on net zero	▲
	National net zero targets in some countries necessitate CCS retrofit, shift to low-carbon feedstock or shutdown of remaining mills	▲
Technology	H_2 -BF/DRI becomes commercial in advanced countries by 2040 and will compete as H_2 costs drop	▼

Implications for 2050 (AET-2 Scenario):

- Policy will continue to drive CCS retrofits but capacity is expected to peak as low-carbon feedstocks become increasingly competitive towards 2050

▲ Supports CCS Growth ▼ Reduces CCS Growth ◆ No Change

Key trends and conclusions for CCS in the Steel Sector as observed by Wood Mackenzie

CCS in Steel Sector

Implications on CCS Deployment

- Global CCS capacity needs to reach ~500 Mt by 2050 in WM's AET-2 scenario if targets are to be met
- Achieving required CCS capacity is more probable as there are no viable low-carbon alternatives in the short-to-mid term
- High emission blast furnaces cannot be fully substituted by 2050 and will require CCS to decarbonise
- However CCS deployment also requires sufficient policy support to incentivise CCS retrofits and avoid carbon leakage
- Zero-carbon feedstock such as H_2 are expected to become viable by 2040s and can potentially displace CCS in the long run - but outlook is still uncertain

Source: Wood Mackenzie

Country level summary - further analysis by AIGCC

Wood Mackenzie's analysis in power generation and steel covered the following four markets: China, India, Japan, and South Korea[13] , all major GHG emitters in Asia and users of fossil fuel-based power generation and steel producers in the region. For the power sector, market-level analysis was conducted to compare the levelized cost of electricity in the 2021 ETO scenario with that of 2040 in the AET-2 scenario. For the steel sector, market-level analysis was conducted to compare cost competitiveness of various steel production options in the 2021 ETO scenario with that of 2040 in the AET-2 scenario. Detailed cost competitive comparisons for the power and steel sector are available in *Appendix B1 and B2* respectively.

For an overview of LCOE competitiveness across the four countries in the power sector, please see Exhibit 15.

13 Although Indonesia is also a major GHG emitter in Asia, it is not one of major steel producing country. Thus, in order to provide fair comparison with other focus countries for steel sector, Indonesia is not covered in this report.

Exhibit 15: Overview of LCOE Results by Country, USD/MWh Real 2021

Options	2021	2040[1]	2021	2040[1]	2021	2040[1]	2021	2040[1]
Coal	49	134	66	129	72	147	78	154
Gas	95	140	110	144	104	144	102	125
Coal + CCS	112	92	138	112	161	128	165	133
Gas + CCS	131	127	158	142	161	142	154	123
Solar	50	25	38	19	135	68	84	42
Wind [2]	56	21	56	21	175	67	169	64
Renewables + Storage [3]	111	37	100	33	268	88	190	62

Decrease by 2040 Increase by 2040 Cost Competitive vs Hydrocarbon (avg)

Key Observations on Cost Competitiveness

- Coal & gas LCOE become uncompetitive to renewables despite lower commodity prices
- However, a sizeable proportion (>20%) of capacity will remain in place given continuing need for dependable dispatchable power
- CCS retrofits become economically viable for gas & coal plants to meet this niche
- Carbon pricing & subsidy will play a major role in enabling CCS viability

- Renewables develop sizeable LCOE advantage as cost improvements continue
- Deployment is dependent on proximity to demand, infrastructure, land availability, etc.
- Grid volatility & overall system costs may increase with higher renewables penetration thus dependable capacity is still important
- Battery storage costs improve but long duration storage not yet practical by 2040

Note: (1) In AET-2 (2 °C Scenario) only; (2) Refers to Onshore Wind for China & India, Offshore Wind for Japan & South Korea ; (3) Average of Wind + Battery and Solar + Battery Options
Source: Wood Mackenzie

For an overview of steel production costs and its competitiveness across the four countries in the steel sector, please see Exhibit 16.

Exhibit 16: Overview of steel production cost results by country, USD/ton Crude Steel Production Real 2021

Options	2021	2040[1]	2021	2040[1]	2021	2040[1]	2021	2040[1]
BF-BOF	510	558	372	492	537	600	525	599
BF-EAF	547	635	447	591	N/A	N/A	N/A	N/A
BF-BOF + CCS	604	526	491	487	629	578	616	577
BF-EAF + CCS	641	600	564	586	N/A	N/A	N/A	N/A
Coal – DRI - EAF	N/A	N/A	319	530	N/A	N/A	N/A	N/A
Gas – DRI - EAF	N/A	N/A	374	414	N/A	N/A	N/A	N/A
H_2 – DRI - EAF	657	495	N/A	N/A	919	637	864	564
Scrap EAF	513	409	428	479	597	692	559	641
Biomass BF-BOF	572	507	450	466	N/A	N/A	N/A	N/A
H_2 - BFBOF	585	494	559	514	768	604	689	495

Key Observations on Cost Competitiveness

- BFs are still required due to its versatility
- Conventional BF becomes uncompetitive due to higher feedstock cost & carbon price
- CCS options become competitive vs conventional BF options in all countries
- Although CCS is not zero-carbon, it remains the main option until H_2 options emerge

- H_2 DRI is technologically challenging hence deployment will be later in India, but will be competitive in other markets by 2040
- Dependent on availability of green H_2

- Low carbon technologies likely to be competitive vs conventional steel and CCS
- Scrap steel is commercial but subject to availability – high quality scrap costs will rise
- H_2-based BF options will be attractive under projected prices but outlook still uncertain

Note: (1) In AET-2 (2 °C Scenario) only
Source: Wood Mackenzie

N/A Decrease by 2040 Increase by 2040 Cost Competitive vs Conventionals (avg)

China

China is highly dependent on coal to generate electricity and is the world's largest steel producer. According to Wood Mackenzie's assessment of the current state, utility PV and coal is the most competitive for power generation in 2021. In the current scenario, gas with CCS and coal with CCS are on the highest end of the spectrum and are uncompetitive on a cost basis compared to renewables in China. However, there continues to be a role for fossil fuel capacity due to intermittency challenges. Similarly for steel, traditional options such as scrap EAF or BF-BOF are the most competitive.

However, projecting on to 2040 using the AET-2 scenario, renewables with the advantage of improvements in short term battery storage will have clear LCOE competitiveness over CCS supported options for gas and coal in the power sector, even with the support of stronger carbon price. CCS supported options for fossil fuels are only marginally increasing LCOE cost competitiveness of fossil fuel energy in China through savings in carbon tax. By 2040, in the steel sector, Scrap EAF is expected to remain the lowest cost option by 2040. High carbon prices will support the development of H_2-BOF options. CCS retrofits for BF options are viable but have decreased in relative cost positioning with respect to 2040 ETO.

India

India is highly dependent on coal for power generation and is the third largest steel producer in the world. At COP26, the country has committed to increasing non-fossil fuel installed electricity capacity to 500GW by 2030 indicating a trajectory to transition into low carbon energy. Based on Wood Mackenzie's analysis for power generation in 2021, renewables such as onshore wind and utility PV already have the lowest LCOE, and fossil fuel-based power generation coupled with CCS option is currently uncompetitive in terms of cost in India. In the steel sector, coal-based DRI-EAF is currently the most cost competitive while CCS retrofits are not yet competitive.

By 2040 in the AET-2 scenario, renewables continue to maintain competitiveness and the reduction in capital for storage technologies have increased competitiveness and the reduction in capital for storage technologies have increased competitiveness of onshore wind and solar with storage retrofits. Gas & coal LCOE continue to increase especially with the introduction of a carbon tax. CCS retrofits will be marginally more competitive compared to conventional gas & coal but will still be significantly more expensive than renewables. In the steel sector, a carbon tax will change the competitiveness landscape and enable natural gas DRI-EAF and Biomass BF-BOF to become the most competitive. CCS retrofits for BF-BOF will also be competitive due to savings from the carbon tax vs traditional BF options.

In the AET-2 scenario, a high carbon tax landscape in India would make CCS a viable option in steel where other options continue to be in close competition, but it will remain uncompetitive in the power sector.

Japan

Japan is reliant on coal in the power generation sector, especially since the Fukushima nuclear incident in 2011, where strong opposition against nuclear power narrows down Japan's options in its energy mix. In Wood Mackenzie's analysis, the 2021 ETO scenario indicate gas and coal to be the most cost competitive. For the steel sector, conventional BF-BOF and scrap EAF remains the most cost competitive option in 2021. Due to primary options for steel being not fully interchangeable, BF-BOF is considered necessary in the long term for the production of high quality products.

By 2040 in the AET-2 scenario, renewables and storage continue to be at the more competitive end of the spectrum enjoying lower LCOE compared to other options. High carbon prices support CCS retrofit, but CCS options remain more expensive than renewables and thus will only fulfil the role of providing dependable capacity. In the steel sector, BF-BOF with CCS retrofits will have better cost competitiveness but hydrogen options are also closely competitive. Momentum from the development of hydrogen as the zero-carbon feedstock and as a decarbonisation solution for the steel industry will continue to compete with CCS deployment.

South Korea

South Korea has approved a plan to phase out all coal power by 2050 to support the newly proposed NDC targets and is amongst the few Asian countries that have made the most significant upgrade of their targets in the lead up to COP26. With the backdrop of a nationally approved roadmap for 2050 carbon neutrality, utility PV is nearing LCOE parity with coal in 2021, while wind and CCS is at the high end of the cost spectrum rendering those option uncompetitive. In the steel sector, conventional BF and scrap EAF are the most competitive, while the CCS retrofitted BF-BOF option is positioned to be more competitive than options deploying hydrogen feedstock.

By 2040 in the AET-2 scenario, renewables and short duration storage are significantly cheaper compared to fossil fuels with CCS retrofits. Offshore wind with storage will also see significant improvement in relative LCOE positioning with respect to a 2040 ETO scenario owing to decreased capital costs. In the steel sector, hydrogen and CCS-based BF options become more competitive than conventional BF, whilst hydrogen options gain the most significant relative improvement in cost positioning with respect to a 2040 ETO scenario.

In the AET-2 scenario, there is limited competitiveness for CCS deployment in power generation and a decarbonization roadmap complemented with strong supporting carbon policies will result in increased competitiveness of hydrogen options and to some extent CCS-based BF options.

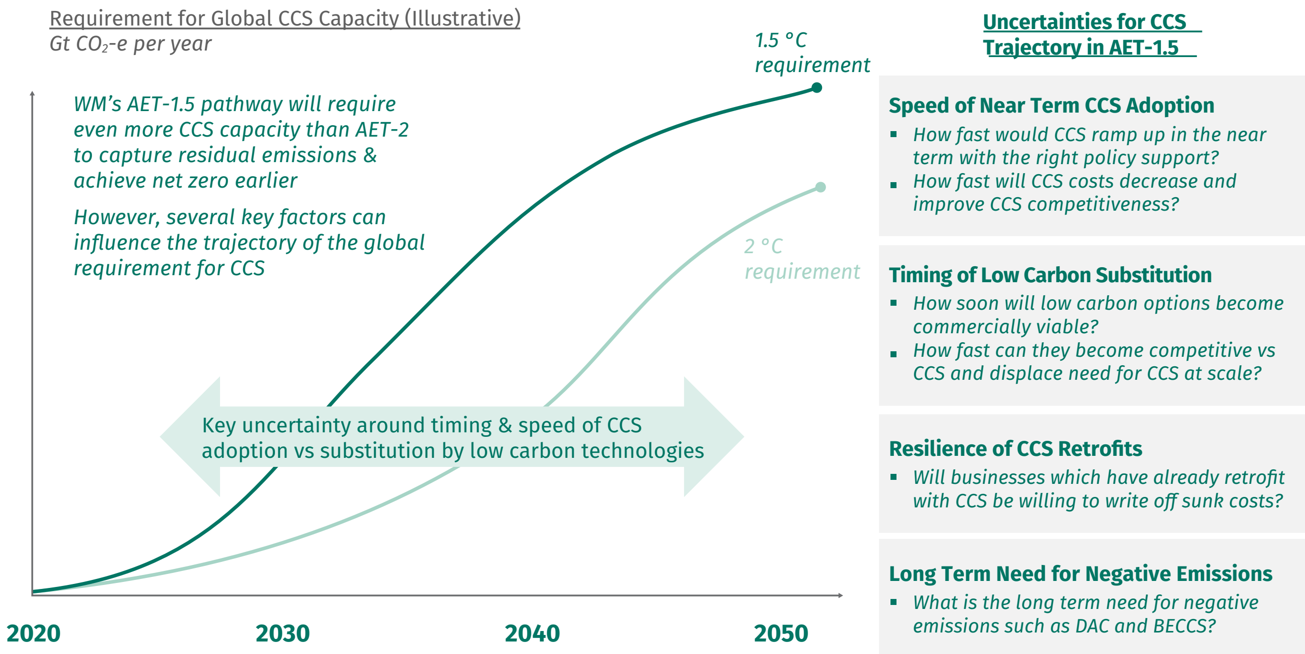
Detailed cost competitive comparisons for the power and steel sector are available in *Appendix B1 and B2* respectively.

3. A qualitative comparison of conclusions if extended to a 1.5°C pathway

In July 2021, the International Energy Agency published its first comprehensive energy roadmap, Net Zero by 2050 (NZE), outlining an energy pathway requiring unprecedented transformation to bring global energy-related CO_2 emissions to net zero by 2050 and to allow the world to limit global temperature rise to 1.5°C. Whilst Wood Mackenzie's analysis based on an in-house 2°C scenario will have variations in the pace and scale of the transformation, the underlying conclusions are broadly consistent. The relevant qualitative differences of Wood Mackenzie's AET-2 scenario with IEA's NZE are as follows:

- **Different end goals**: NZE represents a much more rapid transition to net zero than AET-2:
  - NZE reflects a 1.5°C pathway[14] to reach global net-zero by 2050
  - AET-2 reflects a 2°C pathway, which assumes developed countries reach net zero by 2050 and global net zero is reached by 2070
- **Pace of change**: NZE assumes faster deployment of CCS as well as nascent technologies such as hydrogen and Direct Air Capture (DAC)[15] thus changing the trajectory of the transition
- **CCS deployment**: NZE projects up to 7.6Gt of CCS/DAC capacity by 2050 while AET-2 projects only up to 4.6Gt by 2050

Exhibit 17: Key Uncertainties for the CCS Cost Competitiveness under Wood Mackenzie's 1.5 °C Pathway



Source: Wood Mackenzie

14 AET-1.5 scenario by Wood Mackenzie noted throughout the report is aligned with IEA NZE 2050, thus aligned with 1.5°C pathway.

15 Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere. According to IEA, two technology approaches are being used to capture CO_2 from the air currently: liquid and solid DAC.

Implications for power generation sector

The IEA's NZE envisions faster decarbonization of the power sector supported by rapid innovation and deployment of hydrogen. It also has a smaller role for fossil fuels. CCS requirement for the power sector in AET-2 is higher due to several factors:

- Higher global electricity demand by 2050 in AET-2
- Lower proportion of generation output from hydro, nuclear, hydrogen blending by 2050
- More aggressive carbon prices in NZE drives faster phase-out of fossil fuels

Exhibit 18: High Level Comparison of IEA's NZE scenario conclusions to Wood Mackenzie's analysis for power sector

CCS in Power Generation Sector

- **Faster transition with additional options for dependable capacity:** Reniewables still expected to lead sector decarbonisation, with nuclear, hydro & bioenergy playing a sizeable role in providing dependable capacity
- **Gas & coal diminished but in a similar role:** Thermal power maintains role for dependable capacity but gas & coal will also be displaced by biomass, ammonia & battery storage; thus only ~1.4Gt of CCS1 is expected in power by 2050.
- **Conclusions are consistent:** Gas & coal power still needed for dependable capacity, but accelerated transition leads to faster demand shift & new technology which reduce but does not eliminate deployment of CCS in power

Notes: (1) IEA projection includes CCS for power from fossil fuels as well as for power from bioenergy

Source: Wood Mackenzie

Key differences in assumptions in the power sector for demand, technology, policies and emissions between the WM AET-2 and IEA NZE scenarios are outlined below. In both scenarios, wind and solar energy penetration are expected to be at comparable levels by 2050. However, in a 1.5° C pathway, other zero carbon technologies will assume a stronger role with more aggressive carbon pricing accelerating the phasing out of fossil fuels.

Exhibit 19: Comparison of AET-2 Assumptions to IEA NZE Assumptions for Power Generation

	WM AET-2 Assumptions	IEA NZE Assumptions
Electricity Mix	**Larger electricity demand & share met by fossil fuels** ▪ ~70,000 TWh demand by 2050 ▪ Low carbon[1] has 81% share in 2050 but wind/PV is comparable with NZE	**Bullish nuclear & hydro growth** ▪ ~60,000 TWh demand by 2050 ▪ Hydro & nuclear capacity doubles by 2050 – much faster than AET-2 ▪ Low carbon has 90% share in 2050
Technology	**Hydrogen has limited power role** ▪ H_2 production drives power demand but plays small role in power gen. via blending in gas turbines	**Hydrogen plays large role** ▪ Hydrogen co-firing will address 2.5% of power output by 2050 ▪ 100% blending of H_2/ammonia in unabated coal plants by 2050
Policy	**Relatively moderate policies** ▪ Global carbon price is set at level to incentives CCS in hard-to-abate sectors (~USD110/t)	**Aggressive carbon policies** ▪ Carbon price rises to USD250/t, pushing phase out of fossil fuels ▪ Further support for grid reliability & nuclear life extensions/additions
Emissions	**Not fully decarbonised** ▪ Advanced economies decarbonised by 2050, global net zero by 2070	**Decarbonised by 2040** ▪ Power sector decarbonised by 2035 for advanced economies, by 2040 for others

Source: Wood Mackenzie, IEA NZE Scenario;
Note: (1) Low carbon includes wind, PV, nuclear, hydro & other low carbon options

Implications for steel sector

IEA's NZE relies more heavily on the use of CCS and slightly less on scrap EAF in the steel sector to meet a lower carbon budget. CCS requirement in steel under AET-2 is lower than NZE due to:

- Higher use of Scrap EAF in AET-2 (as % of market share)
- Less aggressive decarbonization trajectory in AET-2
- Lower carbon prices in AET-2, which resulted in lower CCS capture rates

In both scenarios, CCS and hydrogen-based options are needed.

Exhibit 20: High-level comparison of IEA's NZE scenario conclusions to Wood Mackenzie's analysis for steel sector

CCS in Steel Sector

- Aggressive decarbonisation with similar options: High carbon price (up to \$250/tCO_2 by 2050) spur greater CCS deployment and aggressive substitution of coal by EAF, electrolysis and H_2-based options by 2050 (up to ~70% of demand)
- Coal use not fully substituted: Coal still provides ~30% of steel energy demand by 2050 & is mostly abated by CCS with 670Gt of capacity by 2050
- Conclusions are consistent: Policy, subsidy & global trade agreements are necessary to allow sector to decarbonise. Coal is not fully substitutable thus CCS is required to abate emissions in order to meet emissions targets

Source: Wood MacKenzie

Key differences in assumptions in the steel sector for demand, technology, policies and emissions between the WM AET-2 and IEA NZE scenarios are outlined below. In both scenarios, the pace of emergence of hydrogen-based options are critically important. Both scenarios will also require international policies in place to establish a level playing field for export.

Exhibit 21: Comparison of AET-2 Assumptions to IEA NZE Assumptions for Steel

	WM AET-2 Assumptions	IEA NZE Assumptions
Sector Demand	**Greater use of scrap EAF** ▪ Higher steel demand growth met by comparatively larger proportion of scrap EAF (~52%) by 2050 ▪ Low carbon [1] share is similar (~22%)	**Greater reliance on CCUS** ▪ Lower use of scrap EAF (~46%) results in higher reliance on CCUS with conventional options by 2050
Technology	**Slower emergence of hydrogen** ▪ H_2-based BF & DRI become viable in mid-2030s in advanced economies but accelerates from 2040-50 ▪ Electrolysis is not viable before 2050	**Faster emergence of technology** ▪ H_2-based options begin deployment in mid-2020s ▪ Iron ore electrolysis emerges as option in addition to hydrogen
Policy	**Moderate carbon prices** ▪ Relatively moderate carbon price (USD110/t) support CCS retrofits ▪ Similar policies will be required to support trade of low-carbon exports	**Aggressive carbon prices** ▪ Very high carbon prices (USD250/t) drive higher CCS capture rates ▪ International policies required to establish level playing field for export
Emissions	**Not fully decarbonised** ▪ 46% of gross residual emissions are captured via CCS ▪ Net emissions fall to 0.8 Gt by 2050	**Nearly decarbonised by 2050** ▪ Emissions fall to 0.2 Gt by 2050 ▪ ~90% of non low carbon production is equipped with CCS

Note: (1) Low carbon includes wind, PV, nuclear, hydro & other low carbon options

Source: Wood Mackenzie, IEA NZE Scenario

4. AIGCC's additional assessment of challenges and other considerations to large-scale deployment of CCS

Other than the economic competitiveness analysis provided by Wood Mackenzie mentioned in previous chapters, AIGCC's own research further examines additional obstacles to the large-scale implementation of CCS.

Significant environmental risks

The most substantial risk associated with CCS is the leakage of CO_2 from storage sites. The Intergovernmental Panel on Climate Change (IPCC) predicts with 90-99% certainty that well-designed reservoirs will hold 99% of CO_2 injected for 100 years. However, there are many technological unknowns such that the risks of leakages cannot be externalized nor discounted[16]. There are two types of CO_2 leakages: **abrupt leakages** that could result from naturally occurring events or equipment fault; and **gradual leakages** that could occur because of incorrect site selection and inadequate preparation.

In particular, there are concerns over the common choice of depleted oil and gas fields as storage sites as the area could potentially contain geological fracture and risk of natural fissures, hence more comprehensive geological site selection or seabed screening is needed before captured CO_2 can be safely stored. For example, in 2012, scientists found a fracture close to Statoil's North Sea Sleipner CCS site. Although Sleipner CCS project is a saline aquifer, it is located on an oil and gas production area where natural fissures pose risk for CO_2 leakage.

Seepage of CO_2 from long-term CCS projects may lead to delayed global warming unless this seepage can be tightly controlled. A Nature Geoscience report concluded that unless the seepage rate of sequestered CO_2 can be held to 1% every 1,000 years, the overall global temperature increase could still reach dangerous levels that cause some of the worst sea-level rise and ocean acidification projections.

Furthermore, CO_2 leaks can result in the following hazards:

- **Human health**: CO_2 is benign and non-toxic at low concentrations, but at high concentrations and in confined space it can cause asphyxiation. CO_2 is denser than air, so when released, it tends to accumulate in shallow depressions, a risk that increases in confined spaces close to the ground.
- **Contaminate groundwater**: According to this report by Environmental Management, the primary concern of leakage of CO_2 into a groundwater resource is that the increased acidity of these fluids could increase the absorption of commonly occurring minerals such as lead and arsenic, which could exceed maximum concentration limits.

16 Estimating geological CO_2 storage security to deliver on climate mitigation (12 June 2018) https://www.nature.com/articles/s41467-018-04423-1#Abs1

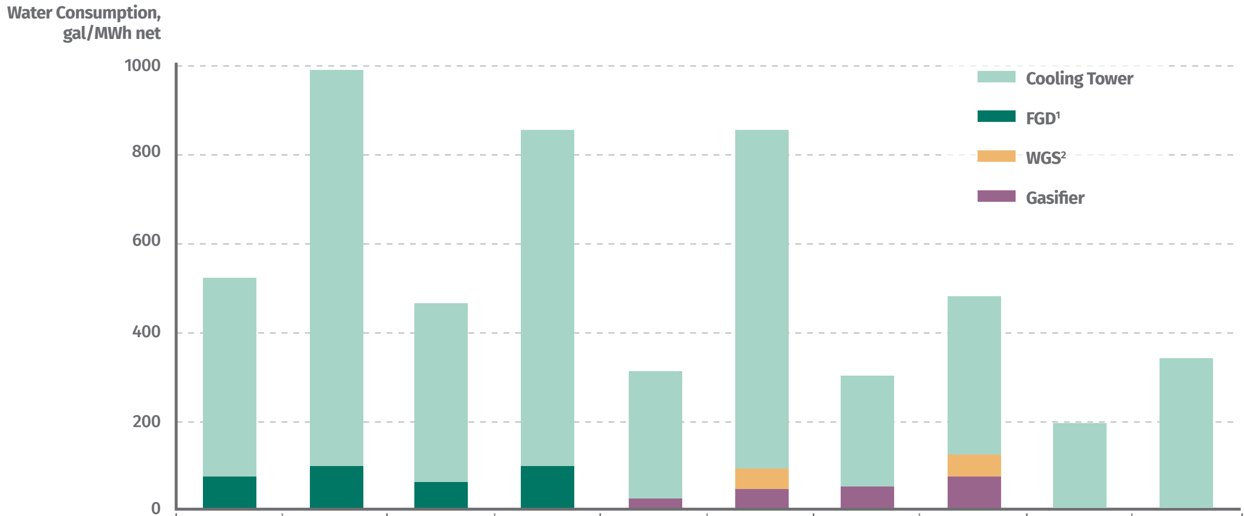
- **Damage terrestrial and marine ecosystems**: A Environmental and Experimental Botany report concluded that crop root and shoot growth and crop yield were significantly lower in cases of elevated soil CO_2, demonstrating the severity of damage to terrestrial vegetation from CO_2 leakage. This Marine Environmental Research report concluded that seawater acidification induced by CO_2 emissions was responsible for the loss of diversity of bacterial organisms, reducing community stability and harming ecosystem resilience.
- **Induce seismicity**: A National Academy of Sciences report concluded that earthquakes can be triggered by the injection of large volumes of CO_2 if the local geology is not suitable for injection. Local geological characteristics need to be appraised carefully.

The widespread deployment of CCS may also lead to water stress as:

- CCS technologies typically involve large water consumption during their energy-intensive capture process[17]. Most CCS projects currently in operations use absorption technologies, with common absorbents consisting of aqueous bases that contain amine groups that bind CO_2. The circulation of large quantities of solvents results in significant water loss by evaporation, leading to a maximum water consumption increase of 90%.
- A Nature Sustainability report concluded that certain geographies lack sufficient water resources to meet the additional water demands of CCS technologies, with 43% of global coal-fired power plants experiencing water scarcity for at least one month a year and 32% experiencing scarcity for five or more months per years. Further research to develop new absorption technology, such as membrane separation that may require less water, is needed to minimize this risk.

17 The nexus of water and CCS: A regional carbon sequestration partnership perspective. https://cyberleninka.org/article/n/965321.pdf

Exhibit 22: Comparison of water consumption per net power using wet recirculation tower



	Subcritical PC		Supercritical PC		IGCC(slury-fed)		IGCC(dry-fed)		NGCC	
	No CC	CC	No CC	CC	No CC	CC	No CC	CC	No CC	CC
Total	517	985	452	844	309	452	295	475	192	338
Cooling Tower	449	884	392	759	290	355	243	355	192	338
FGD	68	101	59	86						
WGS						52		49		
Gasifier					19	45	53	71		

Source: Gerdes K, Nichols C. Water requirements for existing and emerging fossil fuel-based plant technologies. Office of Systems, Analyses and Planning, National Energy Technology Laboratory, DOE/NETL-402/020108 (2009)

Notes: [1] FGD: flue gas desulfurization
[2] WGS: water-gas shift reactor

Based on an assessment by the Global CCS Institute on geological studies done to date on CCS storage potential, the focus countries in this report (Japan, South Korea, India and China) have conducted some studies into geological storage potential but all will require further assessment to improve confidence in the certainty of storage potential estimates (please refer to *Appendix A*).

The cost of ramifications for the above risks outlined could far outweigh the benefits of GHG emissions abated or other relevant benefits from an economic perspective given the potential compounded effect in terms of potential impact. Even if there is a low likelihood of occurrence, a substantial leakage in a worst-case scenario could have an impact that is outsized in terms of affecting climate change or neighboring communities and would therefore warrant a comprehensive and detailed assessment of the impact of all risks by various multi-disciplinary expertise.

Technical challenges facing CCS

A key challenge facing CCS is to reduce costs so that it is competitive with other low carbon technologies. However, we believe this understates the significant technical barriers that large-scale projects would encounter, including:

- **Scalability –** equipment needed for CCS projects differ widely depending on the source of CO_2. For example, the gas composition in gas separation plants have different properties from the exhaust gases at a power plant. Gas produced from a deep-sea gas field arrives at the surface under high pressure and low temperature, so the separation of CO_2 from natural gas needs to be tailored for this. The complexity and customization of the required equipment make it difficult to quickly scale up.

- **Suitability –** According to the Society of Petroleum Engineers, a major difference between CO_2 injection into underground saline aquifers compared to depleted oil and gas fields is that the former requires injected CO_2 to be accommodated by compression of the formation and formation water. The resultant increase in pressure limits the injection rate and total amounts that can be stored. Appraisal of the suitable CO_2 injection into the subsurface and significant research and development in subsurface modelling are required.

- **Transport -** the scaling up of CCS is likely to require the construction of a pipeline network to transport CO_2 as the most efficient mode of CO_2 transport. Such a network would require multiple CO_2 streams which are characterized by varying impurity levels and handled by individual operators to be linked to the pipeline, posing additional corrosion and safety challenges, as detailed in this Renewable and Sustainable Energy Review. Identifying the appropriate size of the pipelines required for a CO_2 transportation network is a challenging task that has to balance a wide range of factors whilst ensuring assets are not under or over-utilized.

Case study: Chevron Gorgon LNG CCS in Western Australia

The Gorgon LNG project is one of the world's largest LNG projects with a production of 2.3 billion cubic feet per day (Bcf/D) and a lifespan of 40 years, located off the northwest coast of Western Australia.

This project includes a commercial-scale CCS project which is:

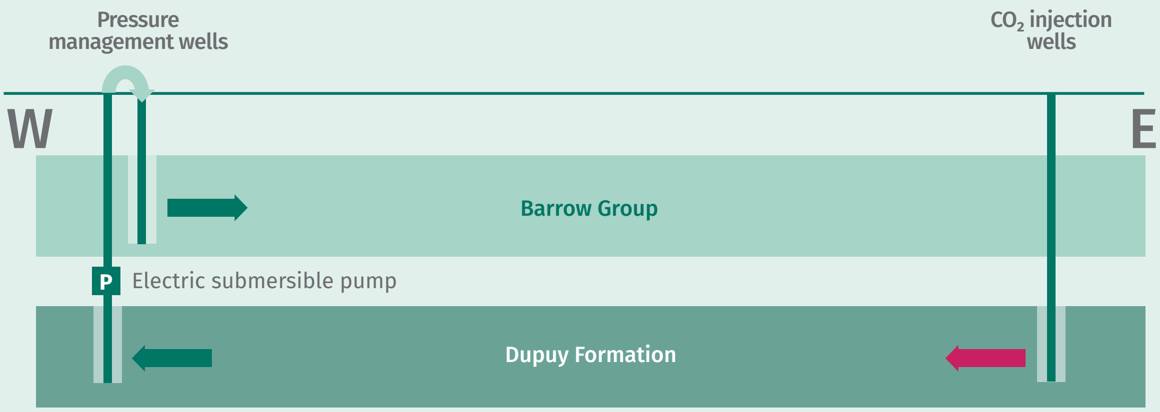
- Designed to store 3.4 – 4 Mtpa of CO_2 and a total of 120 Mt over the project's lifetime equivalent to at least 80% of reservoir emissions as part of the project's environmental approval.
- CO_2 will be captured directly from the gas field, liquefied and transported by a 7 km pipeline to be injected into the Dupuy saline aquifer, located 2.3km beneath Barrow Island.
- Originally estimated to cost a total of AUD 2 billion (about USD 1.5 billion), of which AUD 60 million (about USD 45 million) was funded by the Australian government and includes AUD 150 million (about USD 112 million) of storage appraisal costs and AUD 415 million (about USD 311 million) for the development of six CO_2 injection compressor trains.

In January 2021, independent energy news outlet, Boiling Cold, published reports obtained under Freedom of Information laws revealing that:

- Chevron and its main partners, Shell and ExxonMobil, had spent a total of AUD 3.1 billion (about USD 2 billion) to mid-2020, a significant escalation in costs.
- Chevron had started injecting CO_2 underground in August 2019 despite its pressure management system not working and that the regulator had issued multiple extensions for Chevron to keep operating despite this issue.
- CO_2 injection started more than three years after Gorgon first produced LNG because the water in the CO_2 corroded pipework, resulting in an additional 7 Mt of CO_2 vented into the atmosphere.

This project highlights that burying up to 4 million tons per annum (Mtpa) of CO_2, in this case, is a complex task. Here, CO_2 is injected into a layer of sandstone 400 m thick and more than 2000 m underground, and about 4km away, water is pumped to the surface from the same layer to make room for the CO_2. This water is then pumped into a different layer of rock above the CO_2. If the water is not moved, the pressure required to inject the CO_2 will rise, reducing the amount that can be stored and eventually risk fracturing the rock around the CO_2 injection wells.

Exhibit 23: Gorgon CO_2 pressure management system



Source: Chevron

The performance of the Gorgon CCS project is to be assessed on a five-year average and if targets are not met, approval conditions state that Chevron will be obliged to offset the emissions. This review is due later in 2021. The difficulties faced by this project could therefore also result in substantial financial penalties for the project sponsors.

In July 2021, Chevron confirmed that it was not going to meet its promised injection rates, with the project only capturing a fraction of the carbon dioxide expected during its first five years of operation, where only 5 million tons of CO_2 had been injected since the August 2019 start-up[18]. Chevron later announced that it will have to resort to purchase of offsets to make up for the deficit over a five-year period to July 2021 and to ensure that the facility meets regulatory requirements[19].

CCS projects are difficult to finance commercially

To date, there are no examples of commercial banks financing CCS projects outside of the USA due to the considerable uncertainties facing the financial viability of CCS projects including:

- Difficulty in assessing earnings since projects outside the US do not generate any apparent revenue stream.
- High historical failure rate, for example, under the European Energy Programme for Recovery (EEPR) that ran from 2008-2017, six CCS projects that were sponsored at a cost of EUR 424 million were either cancelled or wound up, without ever having become operational, except for a pilot plant in Spain, which did not demonstrate the use of CCS on a commercial scale.

The deployment of CCS in the USA has been relatively more successful, with the US hosting 10 of the 19 operating CCS plants globally. We attribute this to the introduction of CCS-specific values for carbon through a tax credit known as the 45Q, which was significantly expanded in 2019 and provides up to USD35/t for CO_2 used for EOR and USD50/t for CO_2 stored in dedicated geologic storage[20].

This allowed CCS projects in the US such as Petra Nova and Lake Charles Methanol to secure financing based on revenues that are reliant on the sale and use of CO_2 for EOR and tax credits. We note that there remains a degree of commercial risk, as we detail in our case study on the recent closure of the Petra Nova CCS plant due to the fall in oil prices.

Other recent examples of the reliance on government support can be seen in:

- the Norwegian government's decision in 2020 to fund the scale-up of a CCS project for EUR 2 billion or 80% of the total costs of the project, which would transport liquified CO_2 from a cement factory and waste-to-energy power plant to undersea storage carried out by the Northern Lights CCS project.
- the Dutch government's grant of EUR 2 billion in May 2021 to a consortium including Shell and ExxonMobil to capture CO_2 from the Port of Rotterdam and store it in empty Dutch gas fields in the North Sea.
- the UK government's launch in May 2021 of a plan to develop industrial CCUS clusters and projects which will be supported from the GBP 1 billion Carbon Capture and Storage Infrastructure Fund, which will primarily support capital expenditure on transport and storage networks and industrial CCS.

18 https://www.upstreamonline.com/energy-transition/blow-for-ccs-chevrons-giant-carbon-capture-project-falling-short-of-targets/2-1-1041696

19 https://www.energyvoice.com/renewables-energy-transition/ccs/363627/

20 Meeting The Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage, Chapter 3 – Policy, Regulatory, and Legal Enablers, https://dualchallenge.npc.org/documents/CCUS-Chap_3-030521.pdf?a=1624655845

Case study: Petra Nova CCS project in Texas

Petra Nova was a joint venture CCS project between NRG Energy and JX Nippon which received a USD190 million grant from the US government and started up in 2017. The plant was designed to:

- capture 90% of CO_2 from a 240MW slipstream of flue gas and sequester 1.4 Mtpa of CO_2 at NRG Energy's Unit 8 Parish Generating Station.
- utilize a proven process by Mitsubishi Heavy Industries and Kansai Electric Power that uses a high-performance solvent for CO_2 absorption and desorption.
- compress and transport the CO_2 through a 129 km pipeline to the West Ranch oil field for enhanced oil recovery (EOR) and ultimately sequestered.

The Petro Nova plant was idled on 1 May 2020 and subsequently mothballed in late July 2020, which NRG Energy attributed to a collapse in oil prices and made the project uneconomical. During the period of its operation, we note that:

- according to the Department of Energy (DOE), the facility missed its carbon capture targets by about 17%, succeeding in capturing 3.8Mt of CO_2 during its first three years, short of the 4.6Mt that had been projected.
- utilization rates at the Unit 8 Parish Generating Station were similar to utilization rates before the CCS project coming online, resulting in no benefit to utilization rates at the retrofitted plant.

We believe the failure of this project highlights the manifold technical and economic difficulties that CCS projects face, while a lack of disclosure on this project leaves many unanswered questions, primarily the reasons for the technical difficulties and the actual cost of capture and sequestration.

Societal opposition is likely

There is a lack of publicly available research about community attitudes towards CCS projects in Asia due to a lack of large-scale projects in Asia thus far. Nevertheless, we believe that inferences can be drawn about CCS infrastructure from experience with similar energy infrastructure, which we believe points towards potential societal opposition stemming from:

- **Significant plant site expansion –** Power plants are likely to require significantly larger space to accommodate the additional process facilities, and a study from the Imperial College London suggests that depending on the technology employed, the site area required for CCS equipment could approach the size of the power generating plant itself. This is likely to cause difficulties for existing plants that do not have space available and would entail expansion into adjacent communities, which is likely to face community resistance.
- **Presence of hazardous material –** Certain CCS technologies may use or produce hazardous materials in large quantities. For example, a study in the International Journal of Greenhouse Gas Control concludes that amine-based CCS technologies generate wastes in chemical reclaimers that are toxic, including chemicals such as vanadium, antimony and cyanide.

- **Hazardous chemical transportation –** Large quantities of ammonia, hydrogen sulfide and other chemical solvents are needed for CCS in power plants. These chemicals have never been used in power plants at this scale and would require the construction of chemical delivery pipelines that would require more space while increasing the risks to communities from potential spills.
- **CO_2 pipeline siting –** The scaling up of a CO_2 pipeline network, as discussed above, is also likely to face public opposition. A study in *Energy Policy* highlights the main concerns as being: 1) safe operation of the pipeline; 2) risks to people, livestock and vegetation from leakage; 3) lack of operational pipelines to demonstrate the technology; and 5) disruption to local communities during pipeline construction.

The effects on communities and the environment could potentially impact those living in proximity to the project sites and therefore would be experiencing the impacts of CCS projects the most directly. The climate justice perspective of how projects are being planned is therefore a critically important additional consideration.

Competitive deployment of resources by governments

The pace and magnitude of carbon policies rely on governments' commitment to achieving net zero targets despite socio-economic impacts and cost incurred. In particular, where countries and regions experience power shortages as a result of increasingly higher coal prices, the competitive deployment of resources into ensuring a smooth transition into net zero will affect the overall level of support for CCS deployment. Policies in the forms of subsidies, taxation and caps will incentivize different technologies and outcomes.

Additionally, the different levels of international cooperation to address climate change and its impact to commodity prices, capital investments, sharing of capabilities and export policies may have an indirect impact on the level of attractiveness of large-scale CCS deployment.

5. Conclusion

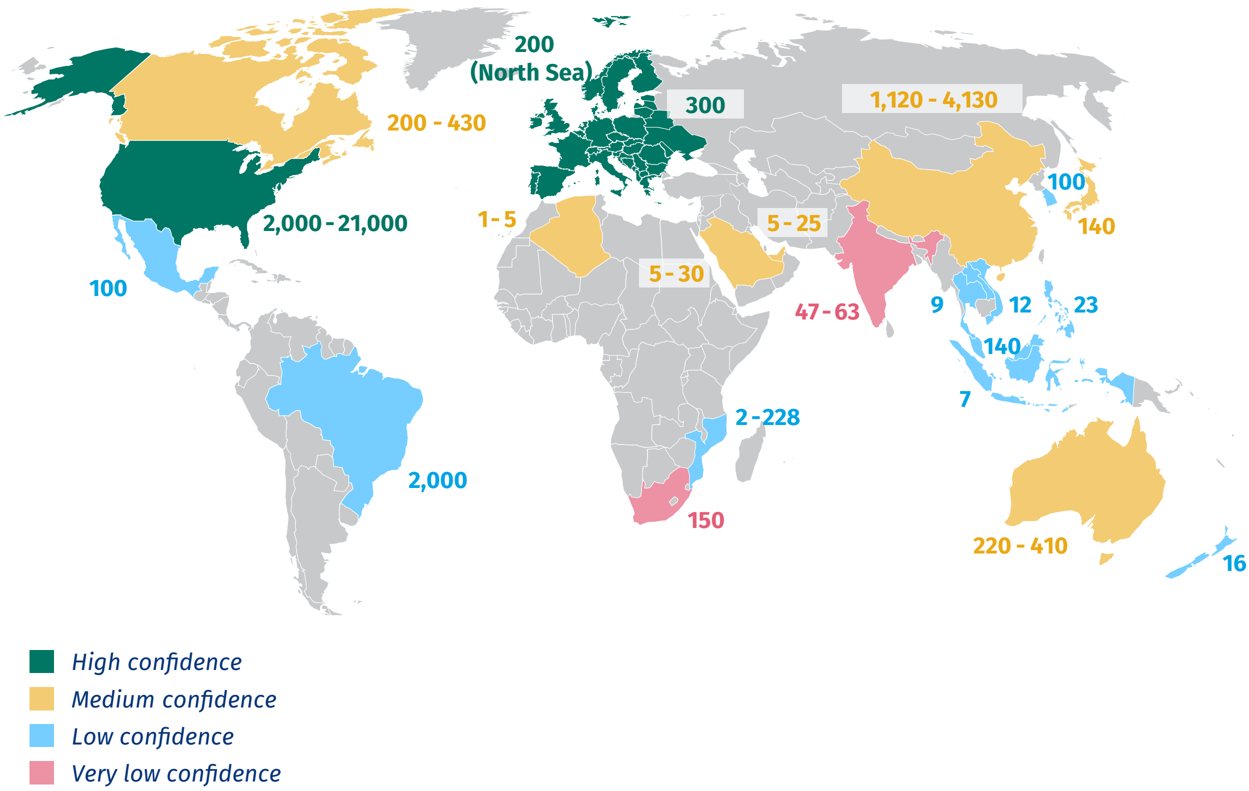
- This report shows that there are a wide range of factors affecting the cost effectiveness of large-scale deployment of CCS technologies. **The attractiveness of CCS deployment decreases where there is the availability of other low carbon alternatives** such as the case in the power sector where renewable energy technologies are well developed.
- On the contrary, where other low carbon options are unclear, as in the case for hard-to-abate sectors such as steel, the attractiveness of CCS deployment increases as more aggressive carbon pricing and relevant policies come in place.
- **In the steel sector, competition from other emerging technologies such as hydrogen as the zero-carbon feedstock, and the cost of fossil fuel-powered feedstocks will influence the level of attractiveness of CCS deployment.** In traditional blast furnace operations, hydrogen cannot eliminate all carbon emissions, due to the presence of process emissions from steelmaking. This to say the attractiveness of CCS will also depend on what share of emissions are under the scope of abatement. Although the study does not cover sectors beyond power and steel, similar conclusions could be drawn for other hard to abate sectors such as cement.
- It is therefore **critically important for investors to carefully evaluate the companies with decarbonization strategies using CCS** as the strategy to transition and request as much detail as practically possible on the planned role of CCS. Proper due diligence is needed as each CCS project tends to have specific technical characteristics with different type of risk.
- For example, with some cases of CCS deployment in the power sector, investors should evaluate the prospect of the deployment despite challenges with cost competitiveness, as CCS may be deployed to further prolong the use of fossil fuels.
- Understanding the barriers and incentives to the deployment of CCS in respective markets and competition from other technologies is critically important for a comprehensive view of the cost effectiveness of CCS deployment.
- **CCS technology and economics, including issues of leakage and the associated liability, continue to be a prominent issue.** The technological unknowns of the risks of leakages cannot be discounted, not only from the perspective of cost-effectiveness, but also for concerns with the impact of leakage to human health, groundwater contamination, damage on terrestrial and marine ecosystems and associated induced seismic activity, all of which will further exacerbate other environmental problems.
- **Carbon pricing and policies will create a 'level playing field' to spur CCS retrofits and will test consumer tolerance to higher prices.** Government's ability to develop well-defined regulations for storage and infrastructure requirements will also have a role to play in the attractiveness of deployment of CCS. It is therefore important to understand that there are geopolitical considerations at play impacting international cooperation and coordination of investments supportive of CCS.

Appendices

Appendix A: Storage availability in focus countries

According to Global CCS Institute, global storage potential is currently estimated at 6,700 – 29,500 Gt, with feasibility dependent on further evaluation of site geology. To date, 260 Mt of CO_2 has been permanently stored. Even with high estimated levels of national or regional capacity, project feasibility and economic viability are both entirely site-specific, depending on seismic activity, soil composition and a variety of other key geological factors.

Exhibit 24: Potential CO_2 Storage Potential by Region (Gt CO_2 Capacity)



Source: Wood Mackenzie, Global CCS Institute

CO_2 is transported and stored as a supercritical fluid due to desirable properties. It transforms from gas to supercritical fluid at high temperature (>31.1°C) and pressure (>72.9 atm). At depths of more than 80 m, CO_2 natural temperature and pressure exceed a critical point and allow denser storage as fluid. Greater depths do not mean greater storage capacity, because fluid density stays constant. Wood Mackenzie also stated that multiple options exist for CO_2 storage with depleted oil and gas reservoirs, with saline aquifers having the highest potential and are the most attractive geological storage options for permanence and scale. Saline aquifers offer the greatest storage potential, but depleted oil and gas reservoirs benefit from better geological understanding, associated infrastructure, and cost synergies.

Exhibit 25: Introduction to CO_2 Storage Options

	Methods	Challenges	Benefits
Oil and Gas Reservoirs	• **Residual trapping** : injected supercritical CO_2 displaces existing fluid in porous rock; small pockets of residual CO_2 trapped between rock grains • Most common application is EOR, where CO_2 is injected to enhance hydrocarbon production by pushing fluids towards producing wells	• EOR and CCUS are perceived as poor solutions for decarbonization as they extend theuse of fossil fuels • EOR project economics are sensitive to oil price	• Most CCUS projects today are linked to EOR • Proven technology • EOR adds economic value via increased recovery of oil & gas • Attracts capital to CCUS & allows greater learning • Required capabilities overlap with oil & gas
Saline Reservoirs	• **Solubility / Mineral trapping**: Portion of injected CO_2 dissolves into the brine water within the porous rock formation. • Some CO_2 combines with available hydrogen atoms to form HCO_3 , which can react with the minerals in the rock to form solid carbonate minerals	• No additional revenue streams • Few developed projects thus limiting operational knowledge base • Requires additional surface infrastructure development	• Large potential for CO_2 storage
Other Options	• Unmineable coal seams • Basalt		

Source: Wood Mackenzie, DOE

Exhibit 26: Comparison of different types of geological storage and the importance to climate goals

Importance to climate goals →

	Percentage of CO_2 Storage	Volumetric Potential	Depth of geological understanding	Geographic distribution	Synergies with existing infrastructure	Proximity to CO_2 emissions sources	Technology Maturity	Additional revenue streams (e.g. through oil and gas production)	Cost advantages	Projected lead time[1]
Depleted oil and gas reservoirs	●	◕	●	◕	●	◕	◕	○	◕	◕
Saline aquifers	●	●	◔	●	◔	●	◕	○	◑	◑
Enhanced Oil Recovery (EOR)	◕	◔	●	◕	●	◕	●	●	◕	●
Unmineable coal / Organic shale	◕	◕	◕	◑	◑	◑	◔	◑	◑	◔
Basalt	●	◔	◔	◕	◔	◔	○	○	○	○

Note: (1) Fuller Harvey Balls denote shorter lead times
Source: Wood Mackenzie

Appendix B-1: Wood Mackenzie's LCOE Competitiveness Analysis Result by Country – Power Generation Sector

Wood Mackenzie has developed three scenarios to test the impact of key variables on CCS cost competitiveness.

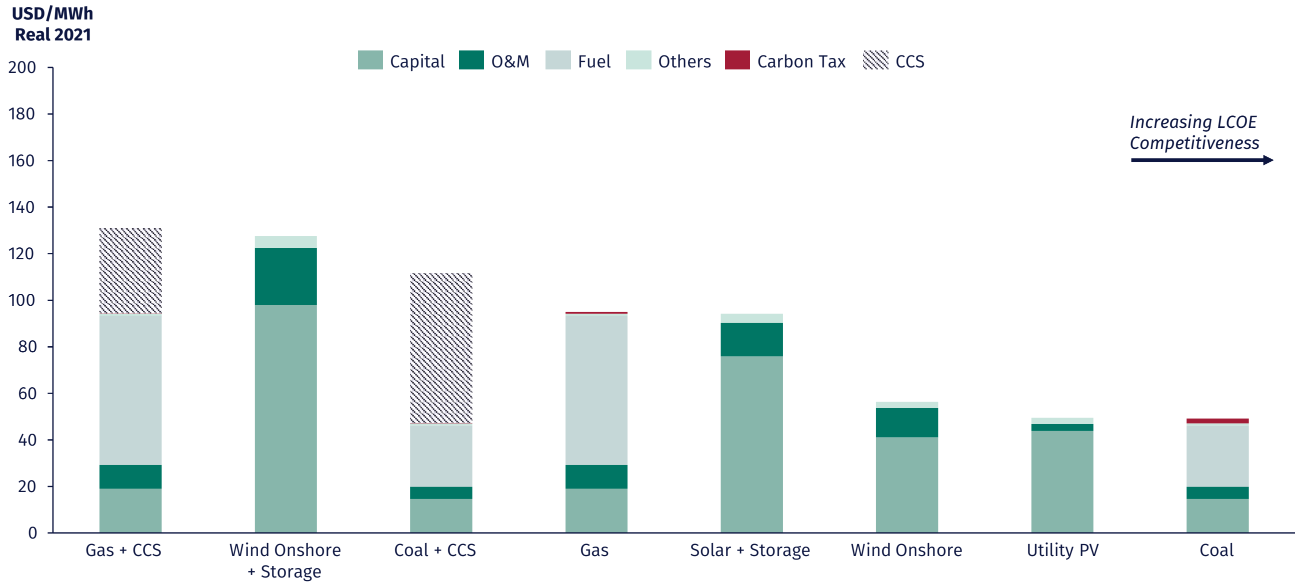
Wood Mackenzie has developed two separate sensitivity cases to test the potential impact of flexing key cost and pricing parameters. The sensitivity cases are a combination of key input parameters including policy (carbon price), technology (cost of CCS and alternatives), and market (commodity prices) which can influence the relative cost competitiveness of various options. To simplify the overall analysis, Wood Mackenzie has defined two cases representing an 'optimistic' case and 'constrained' case for CCS competitiveness to represent the upper and lower bounds of how much these parameters can change cost competitiveness in aggregate.

- 'Optimistic' Case represents a set of parameters which are most favorable for the competitiveness of CCS. This case applies a higher carbon price (consistent with a 1.5 °C pathway), lower estimates for CCS costs and higher costs for non-CCS alternatives and commodity prices.
- 'Constrained' Case represents a set of parameters which are least favorable for the competitiveness of CCS. This case applies a lower carbon price (consistent with current projections), higher estimates for CCS costs and lower costs for non-CCS alternatives and commodity prices.

China

For China, Wood Mackenzie found that renewables are at parity with coal as the lowest LCOE option in 2021, while CCS is much more expensive.

Exhibit 27: 2021 ETO China LCOE Competitiveness Analysis

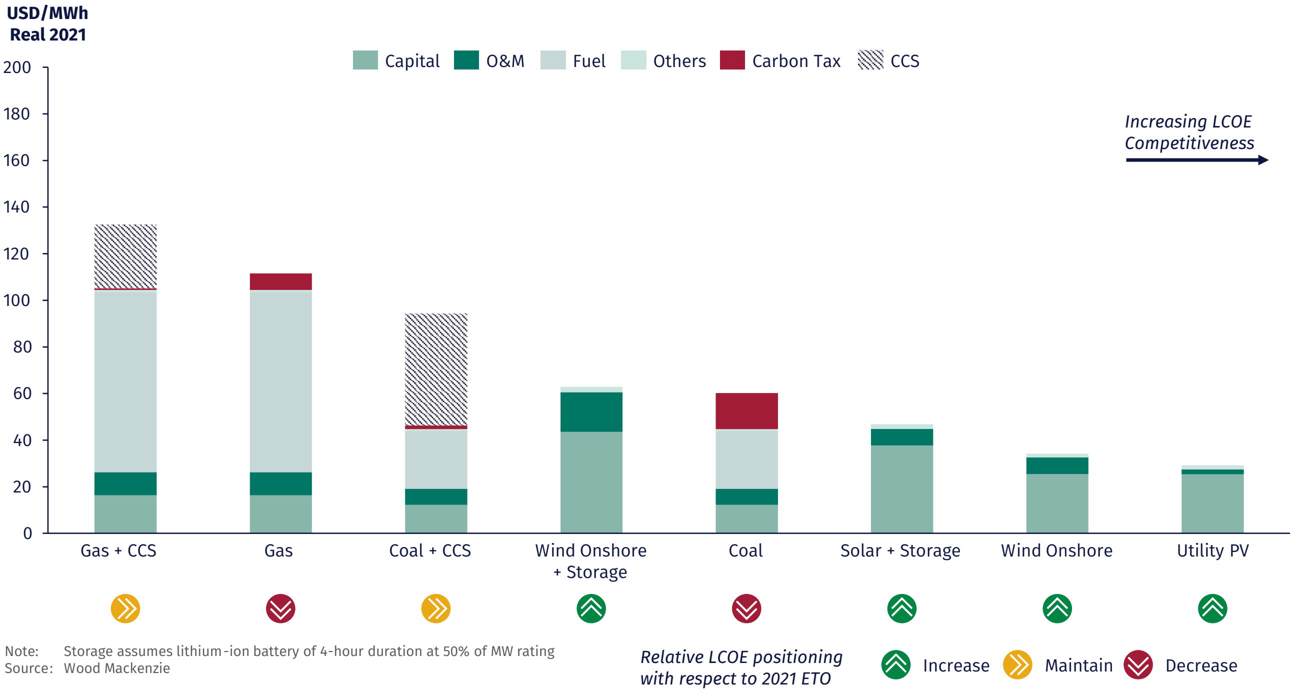


Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating

Source: Wood Mackenzie

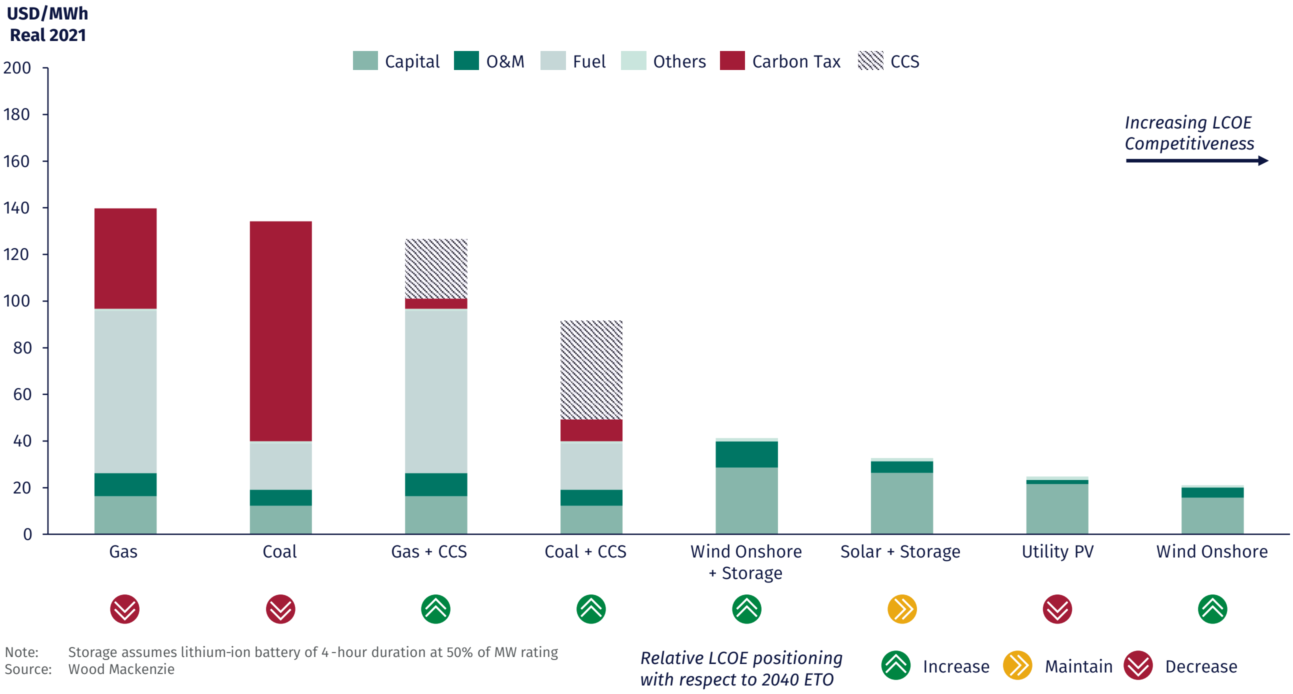
But in 2040, the findings will change. In the ETO scenario, renewables will have a clear advantage while carbon prices are insufficient to spur CCS retrofit. In the AET-2 scenario, renewables and storage extend advantage while high carbon prices support CCS retrofit.

Exhibit 28: 2040 ETO China LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

Exhibit 29: 2040 AET-2 China LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

For LCOE competitiveness sensitivity analysis result, renewables' substantial cost advantage remains even in the most optimistic scenario.

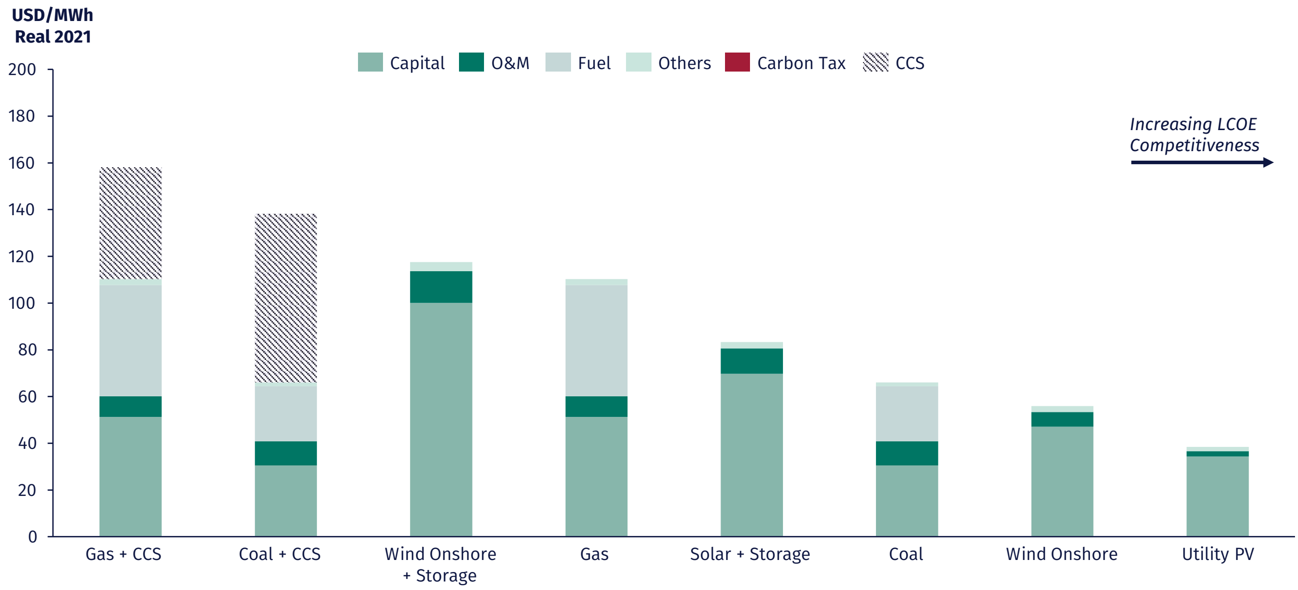
Exhibit 30: 2040 AET-2 China LCOE Competitiveness Sensitivity Analysis

Source: Wood Mackenzie

India

Contrary to China, Wood Mackenzie found that renewables already have the lowest LCOE in India.

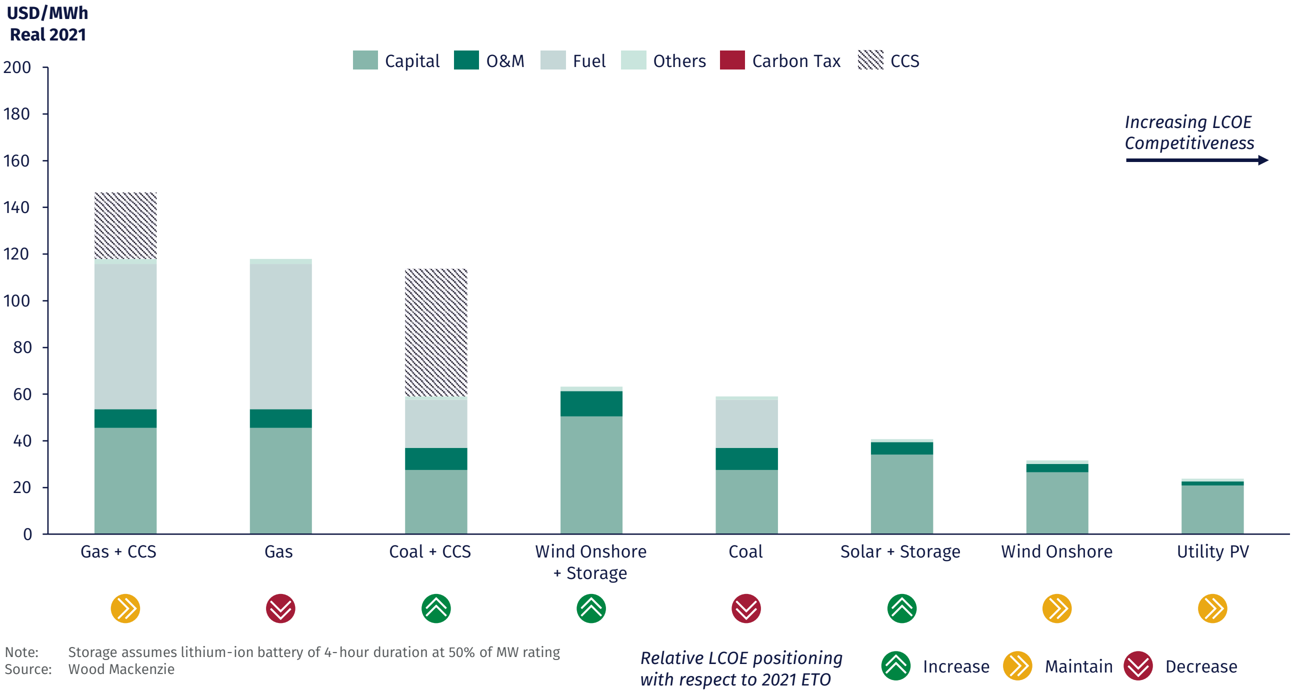
Exhibit 31: 2021 ETO India LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

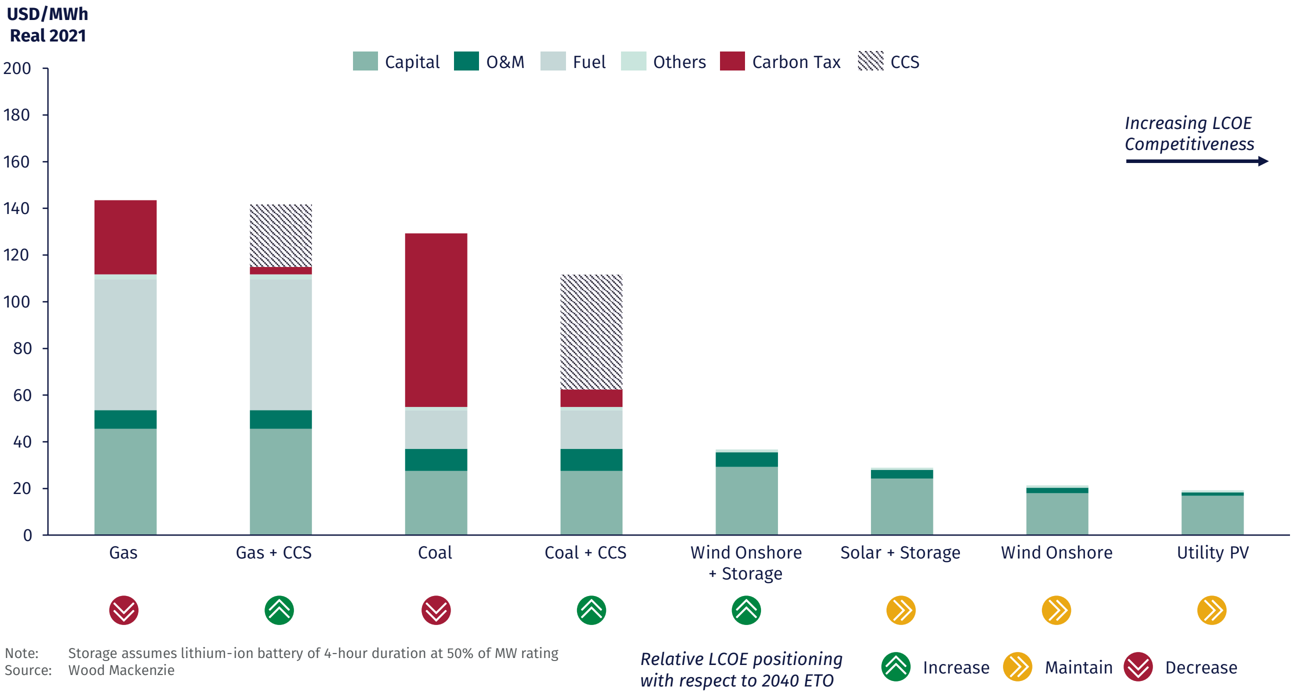
Renewables will continue to be most competitive in the 2040 ETO scenario in India, with renewables plus storage also becoming competitive and CCS remaining uneconomic without carbon pricing. In the AET-2 scenario, CCS options become viable with a high carbon tax, while renewables LCOE will fall even further.

Exhibit 32: 2040 ETO India LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

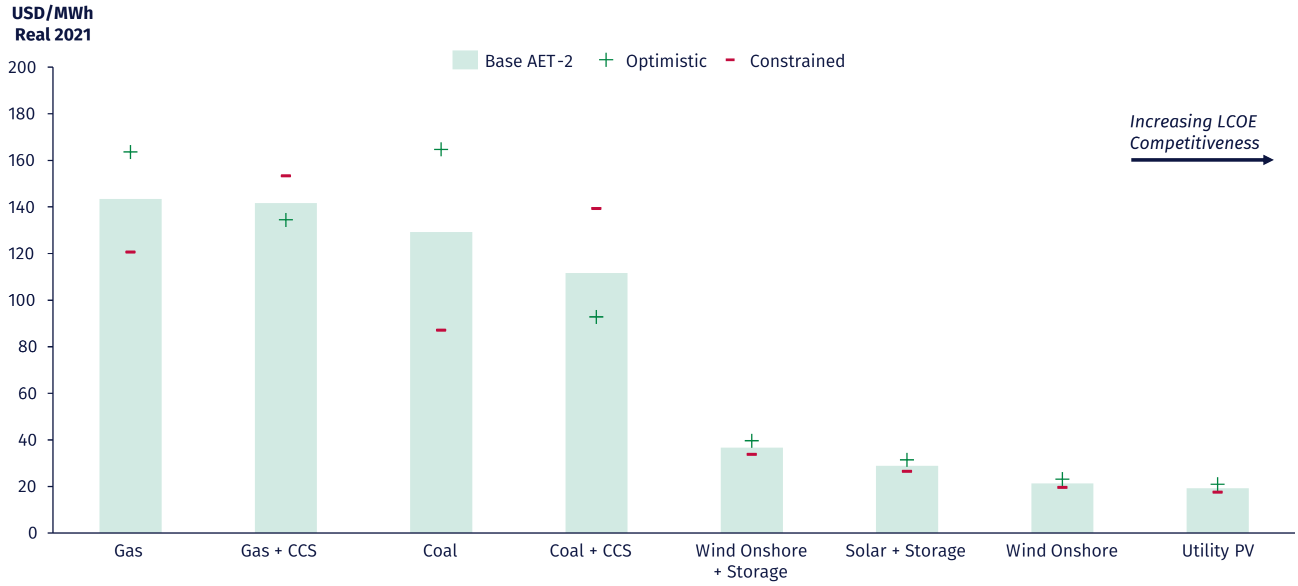
Exhibit 33: 2040 AET-2 India LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

For the LCOE competitiveness sensitivity analysis, results indicate similar sustained cost advantage for renewables across both optimistic and constrained sensitivity cases.

Exhibit 34: 2040 AET-2 India LCOE Competitiveness Sensitivity Analysis

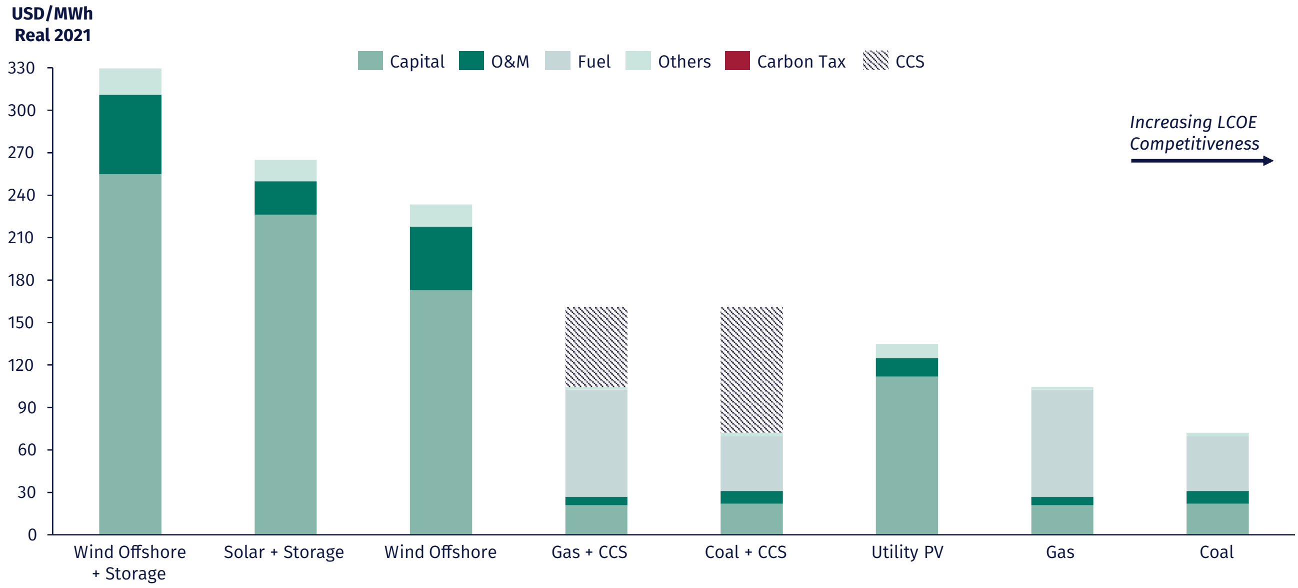


Source: Wood Mackenzie

Japan

In Japan, contrary to more competitive renewables in China and India, Wood Mackenzie found that coal and gas are the lowest cost options in 2021, while renewables still have a sizeable gap in LCOE.

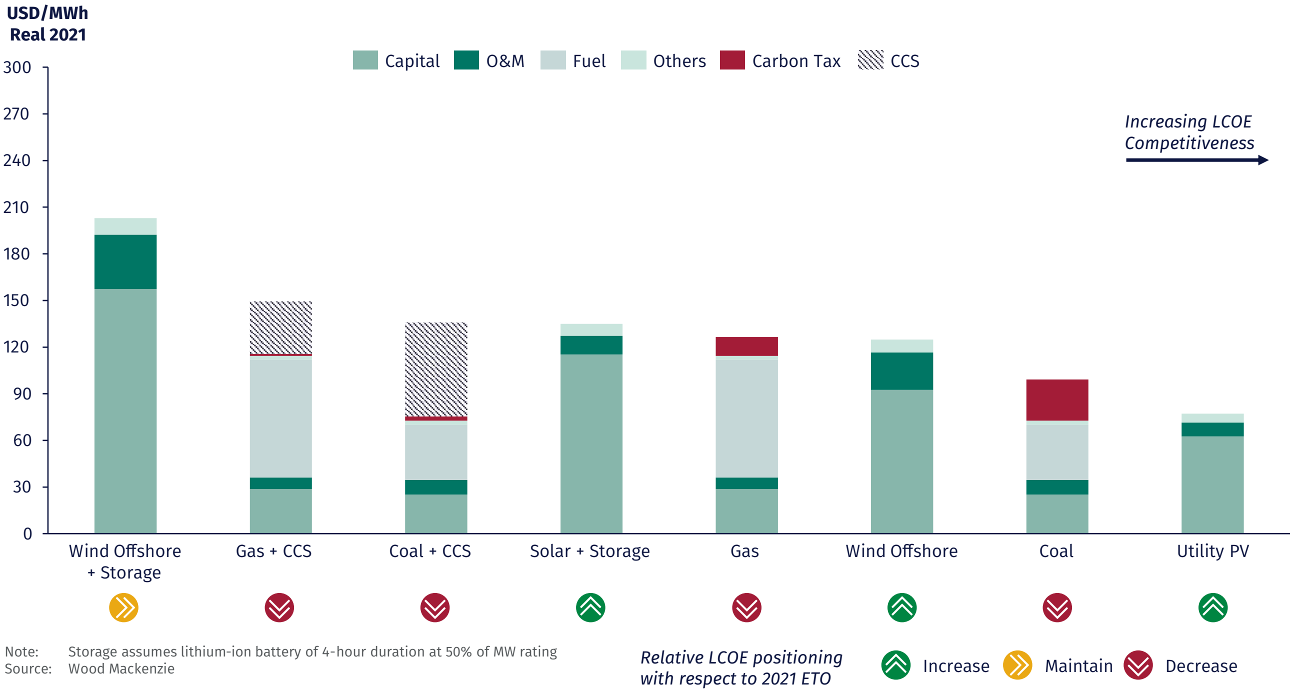
Exhibit 35: 2021 ETO Japan LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

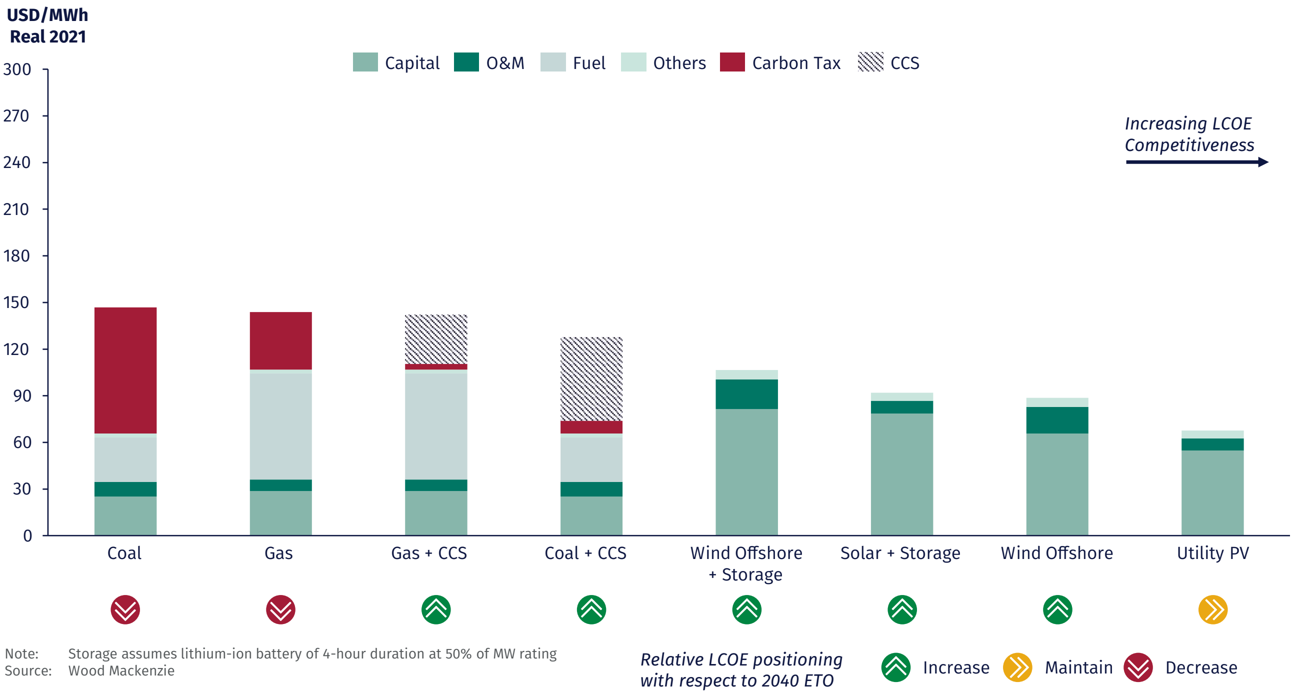
By 2040 in the ETO scenario, utility PV has the lowest LCOE. CCS options are still uneconomical at a USD 40/t carbon price. In the AET-2 scenario, renewables and storage have the lowest LCOE and high carbon prices will support CCS deployment.

Exhibit 36: 2040 ETO Japan LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

Exhibit 37: 2040 AET-2 Japan LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

For the LCOE competitiveness sensitivity analysis, given high renewables with storage costs, coal with CCS costs could be competitive if CCS project characteristics are very favorable.

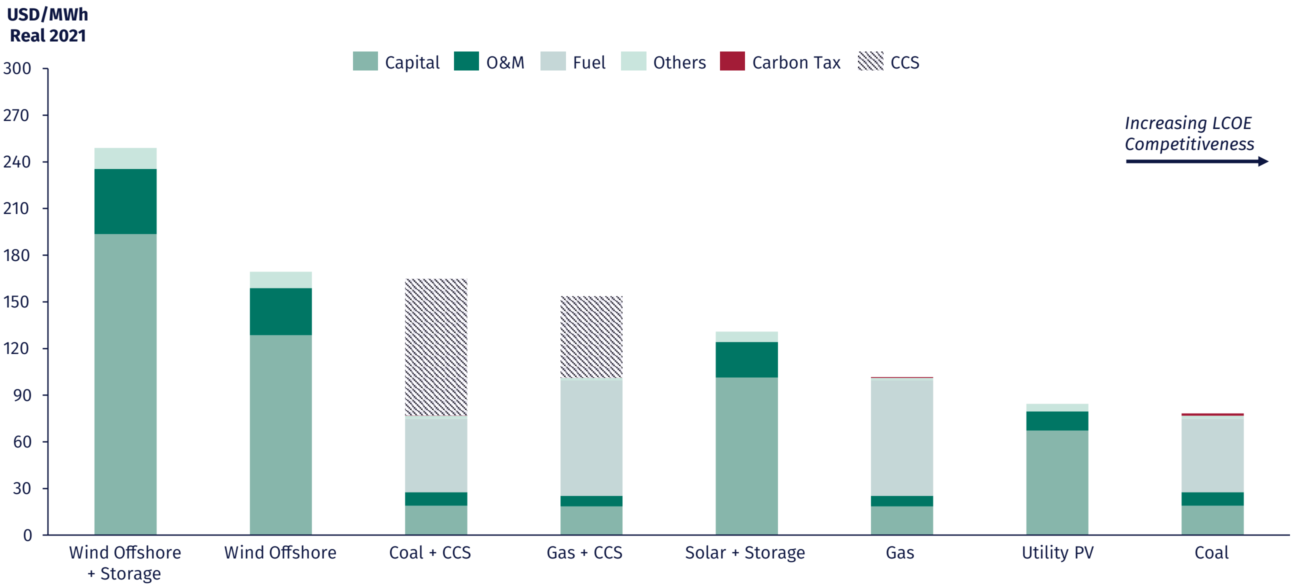
Exhibit 38: 2040 AET-2 Japan LCOE Competitiveness Sensitivity Analysis

Source: Wood Mackenzie

South Korea

Similar to Japan, PV is nearing LCOE parity with coal, but wind and CCS remains a long way off in South Korea in 2021.

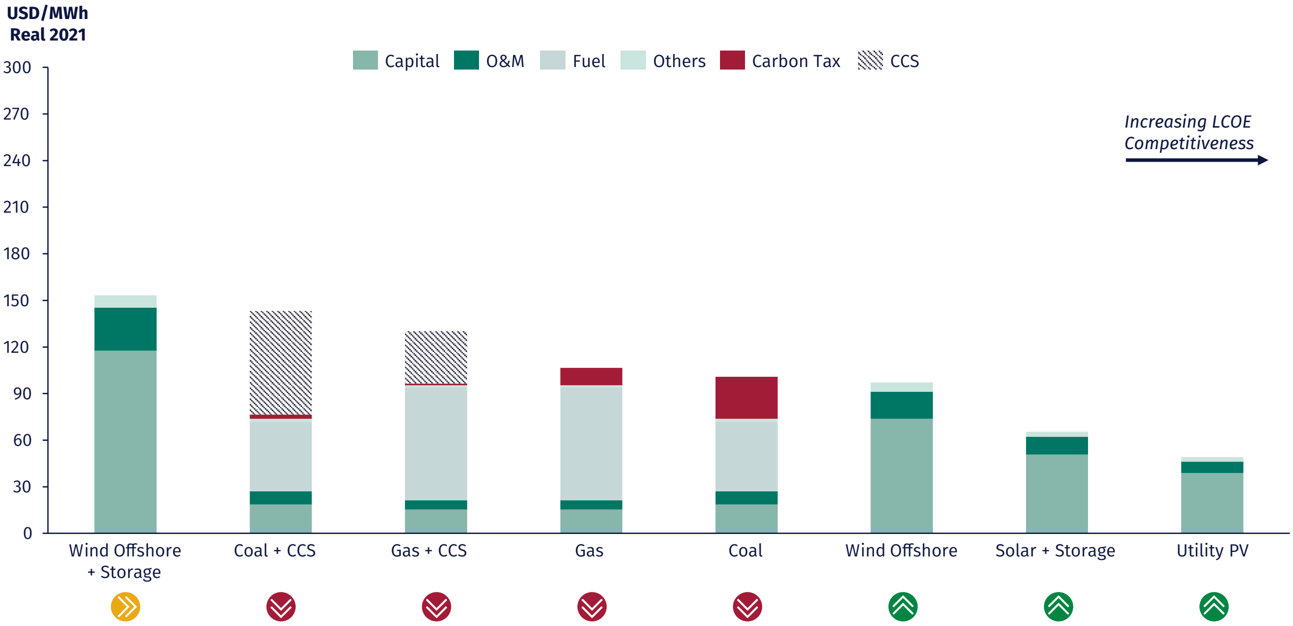
Exhibit 39: 2021 ETO South Korea LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

By 2040 in the ETO scenario, PV and storage have a clear LCOE advantage. A USD 37/t carbon price (cheaper than Japan) is insufficient for CCS. In the AET-2 scenario, renewable and storage LCOE falls further while high carbon prices support CCS deployment.

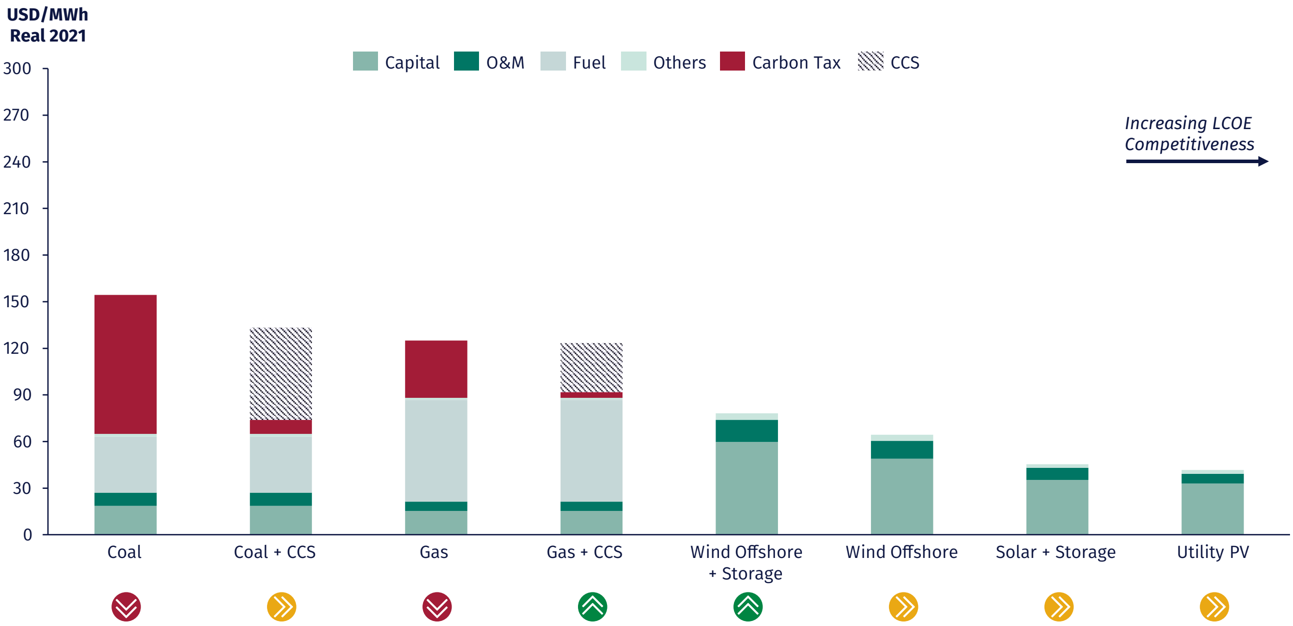
Exhibit 40: 2040 ETO South Korea LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

Relative LCOE positioning with respect to 2021 ETO — Increase, Maintain, Decrease

Exhibit 41: 2040 AET-2 South Korea LCOE Competitiveness Analysis



Note: Storage assumes lithium-ion battery of 4-hour duration at 50% of MW rating
Source: Wood Mackenzie

Relative LCOE positioning with respect to 2040 ETO — Increase, Maintain, Decrease

For the LCOE competitiveness sensitivity analysis, the inherent cost gap between CCS and renewables remains even under an optimistic scenario for CCS costs.

Exhibit 42: 2040 AET-2 South Korea LCOE Competitiveness Sensitivity Analysis

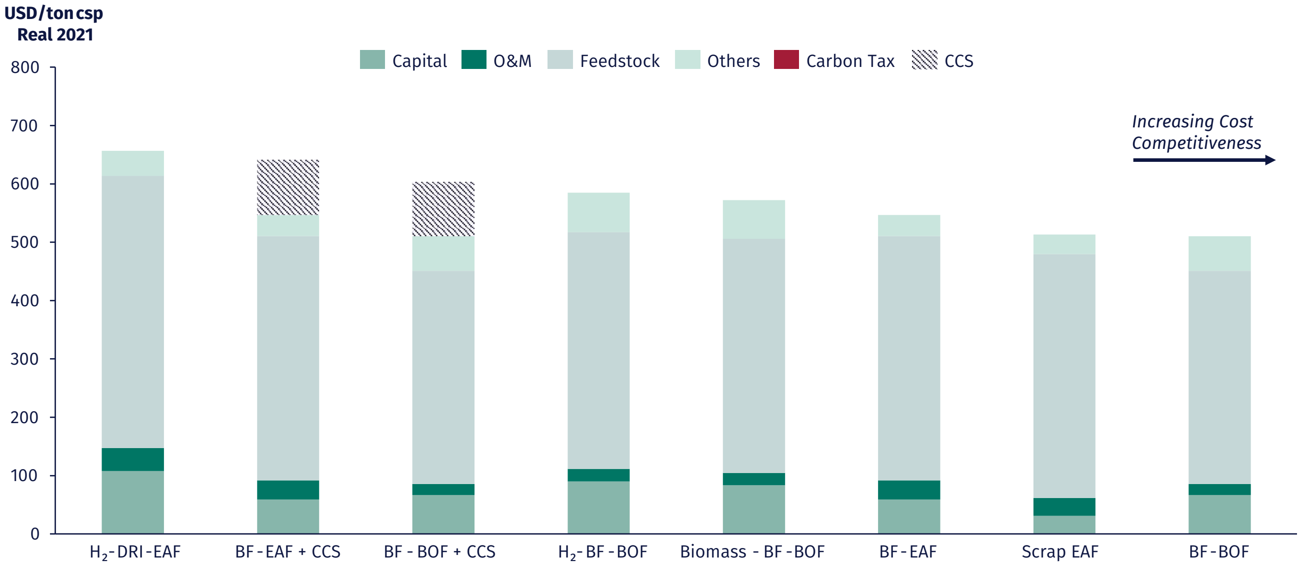
Source: Wood Mackenzie

Appendix B-2: Wood Mackenzie's Steel Production Cost Comparison by Country – Steel Sector

China

For China, Wood Mackenzie found that traditional BF-BOF and scrap EAF options are the most competitive in 2021.

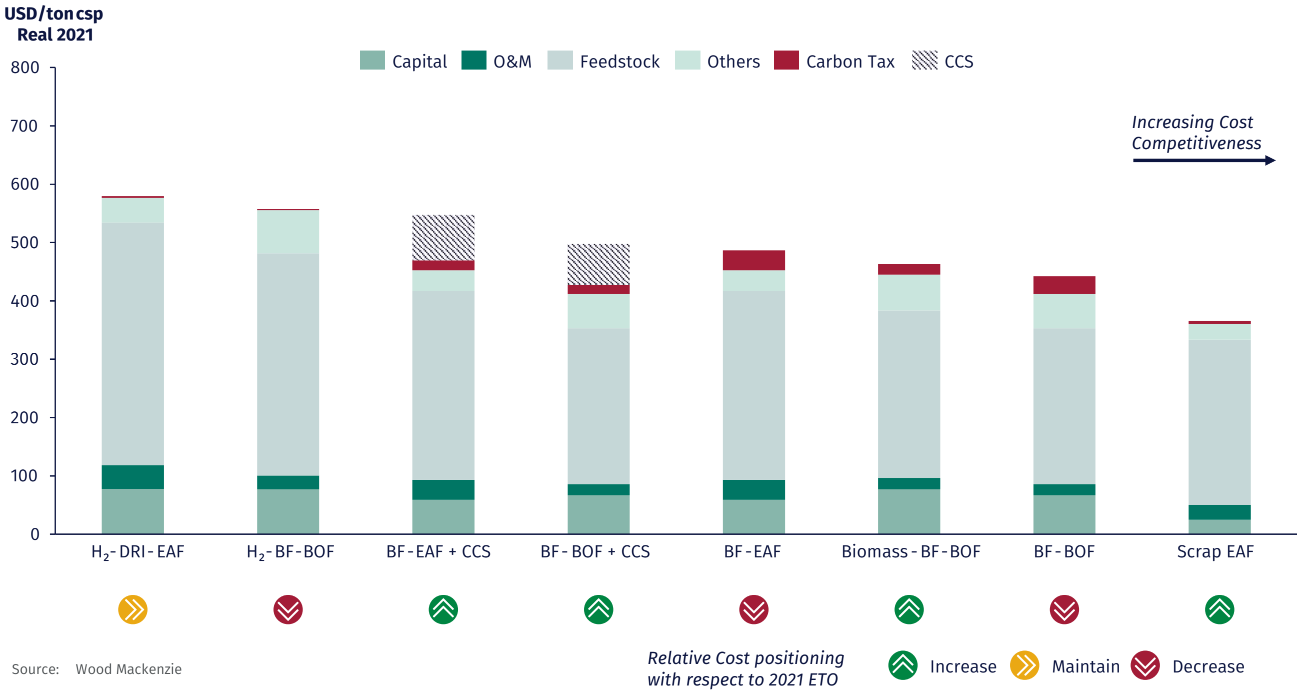
Exhibit 43: 2021 ETO China Steel Production Competitiveness Analysis



Source: Wood Mackenzie

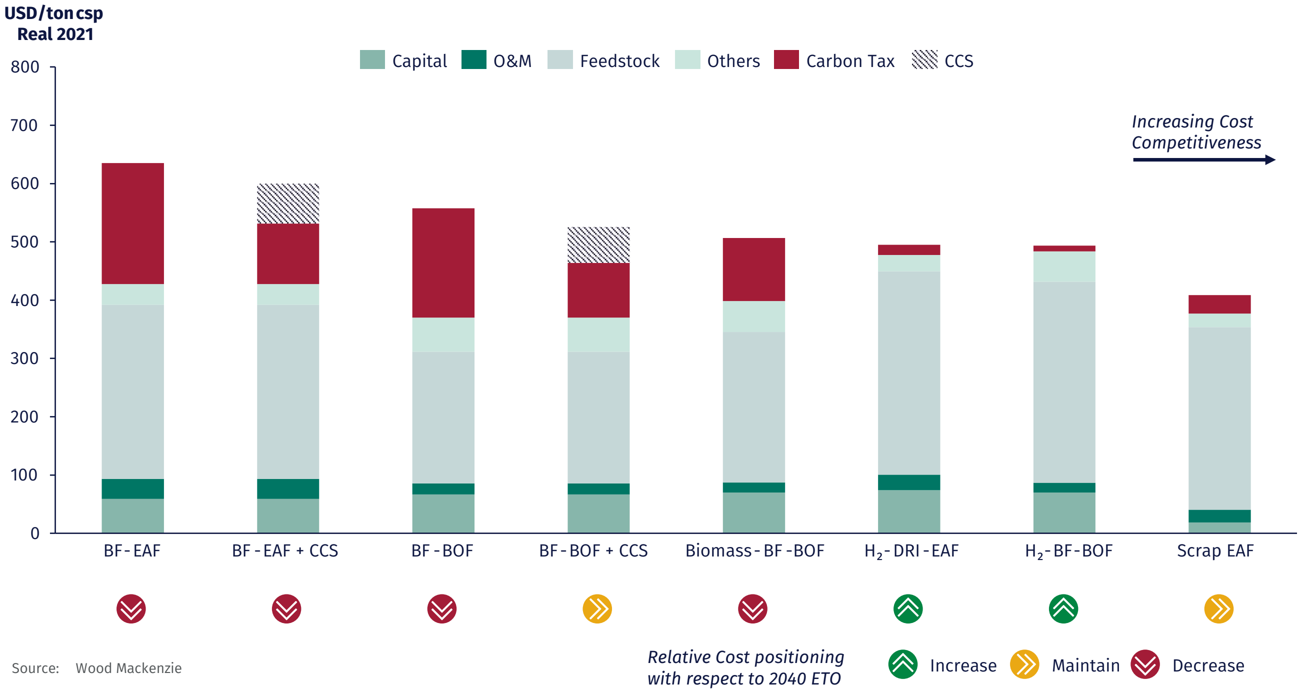
By 2040 in the ETO scenario, scrap EAF has a clear cost advantage, but carbon prices are insufficient to spur CCS or hydrogen use in BF-BOF applications. Traditional BF-BOF is expected to remain in use as scrap EAF is constrained by scrap availability. In the AET-2 scenario, scrap EAF remains the lowest cost option, but high carbon prices mean CCS and Hydrogen-BF options are viable.

Exhibit 44: 2040 ETO China Steel Production Competitiveness Analysis



Source: Wood Mackenzie

Exhibit 45: 2040 AET-2 China Steel Production Competitiveness Analysis



Source: Wood Mackenzie

For the cost competitiveness sensitivity analysis, scrap EAF maintains an advantage across both price sensitivity cases, while all other options are in close competition.

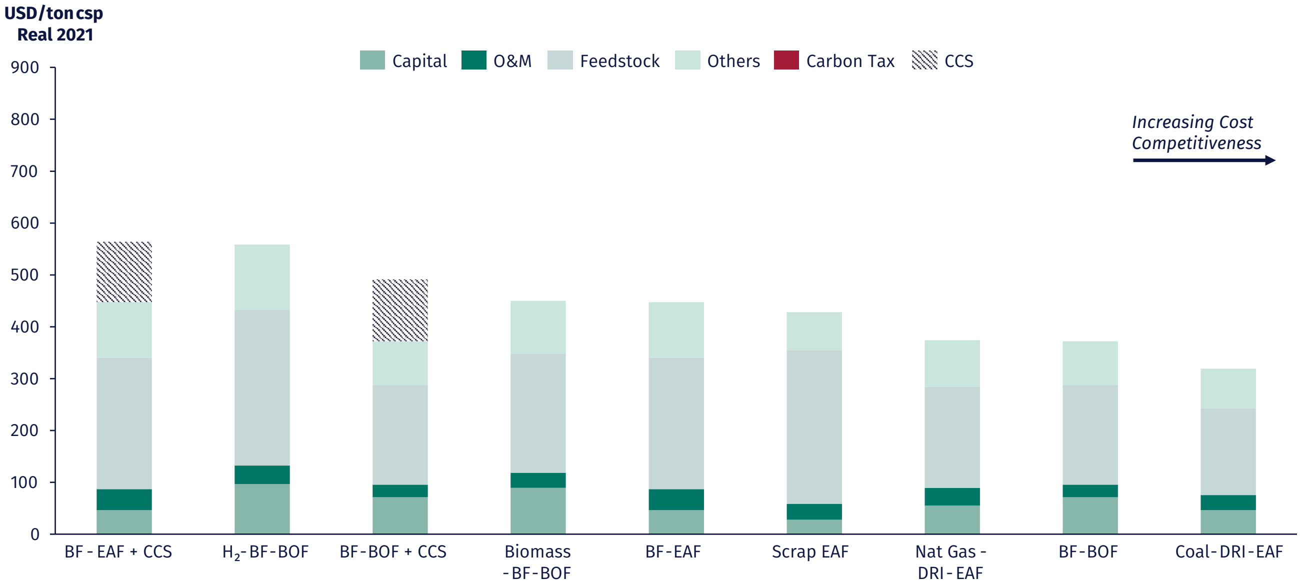
Exhibit 46: 2040 AET-2 China Steel Production Cost Competitiveness Sensitivity Analysis

Source: Wood Mackenzie

India

Slightly different from China, Wood Mackenzie found that conventional BF and DRI options are the clear low-cost options for India in 2021.

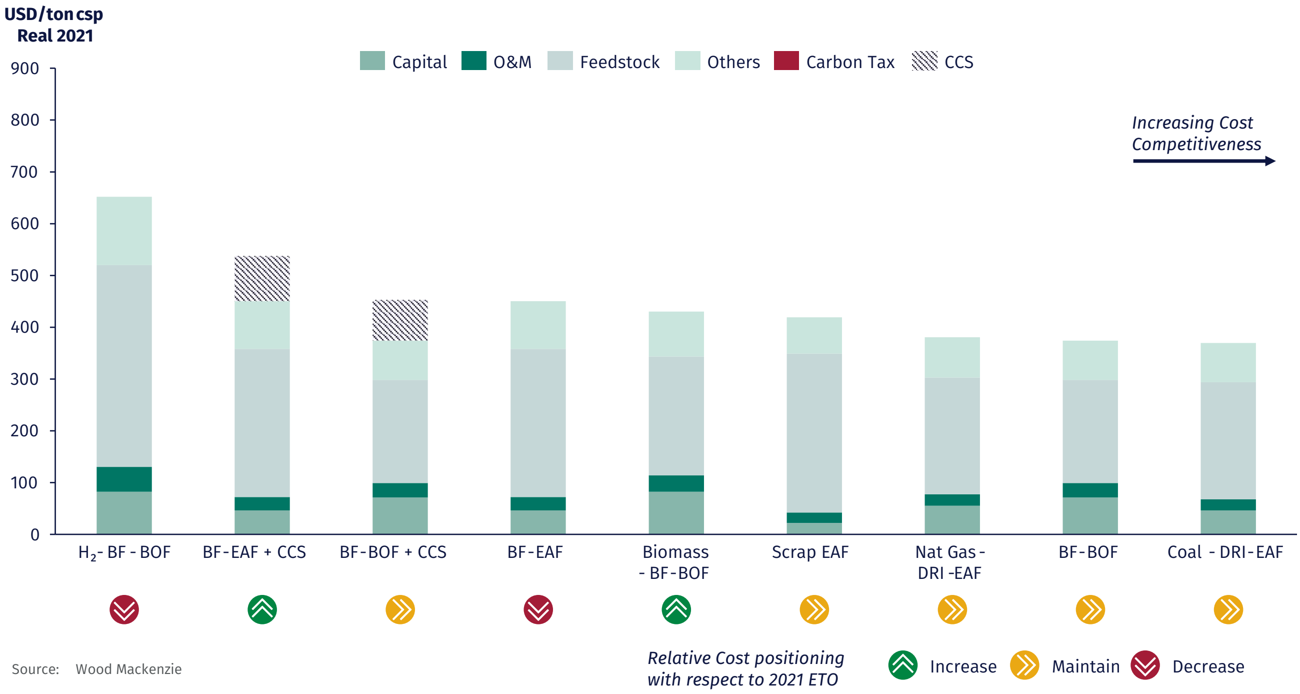
Exhibit 47: 2021 ETO India Steel Production Cost Competitiveness Analysis



Source: Wood Mackenzie

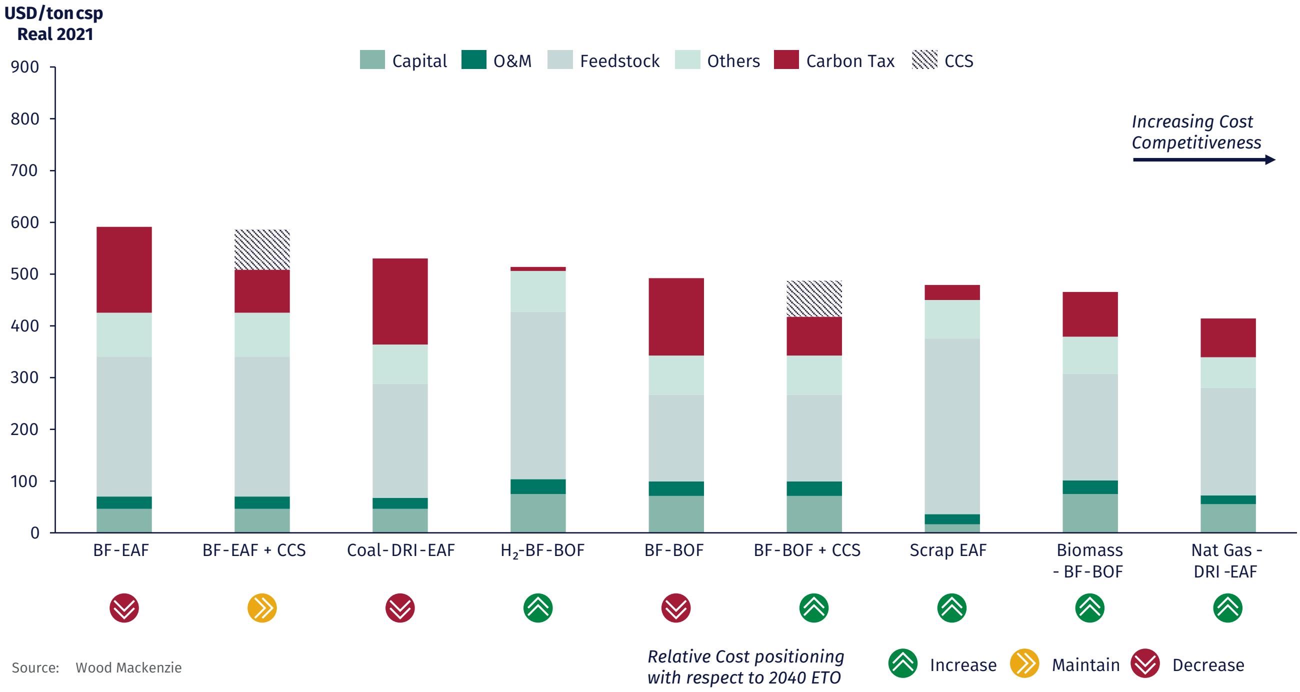
By 2040 in the ETO scenario, the status quo largely remains as traditional BF and DRI remain the most competitive given a lack of carbon pricing. In the AET-2 scenario, a high carbon tax changes the landscape significantly with biomass and CCS based BF becoming competitive.

Exhibit 48 : 2040 ETO India Steel Production Cost Competitiveness Analysis



Source: Wood Mackenzie

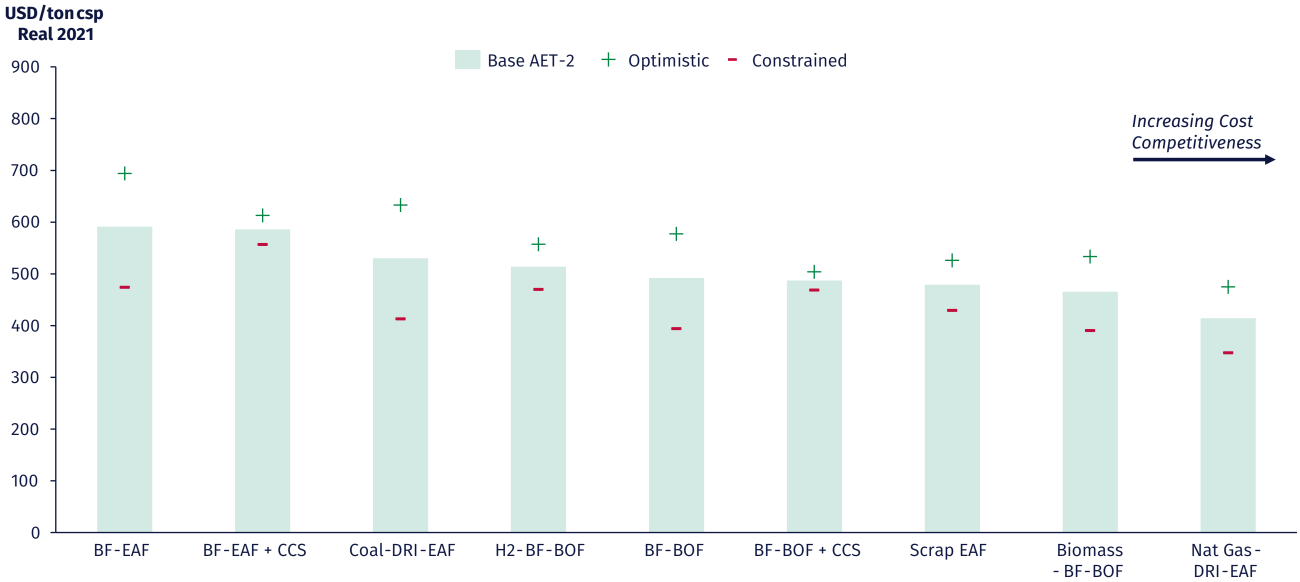
Exhibit 49: 2040 AET-2 India Steel Production Cost Competitiveness Analysis



Source: Wood Mackenzie

For the cost competitiveness sensitivity analysis, in an optimistic case using lower CCS cost estimates and higher carbon prices, BF-BOF with CCS could potentially be even more cost competitive against some low carbon options such as scrap and H_2-BF-BOF.

Exhibit 50: 2040 AET-2 India Steel Production Cost Competitiveness Sensitivity Analysis

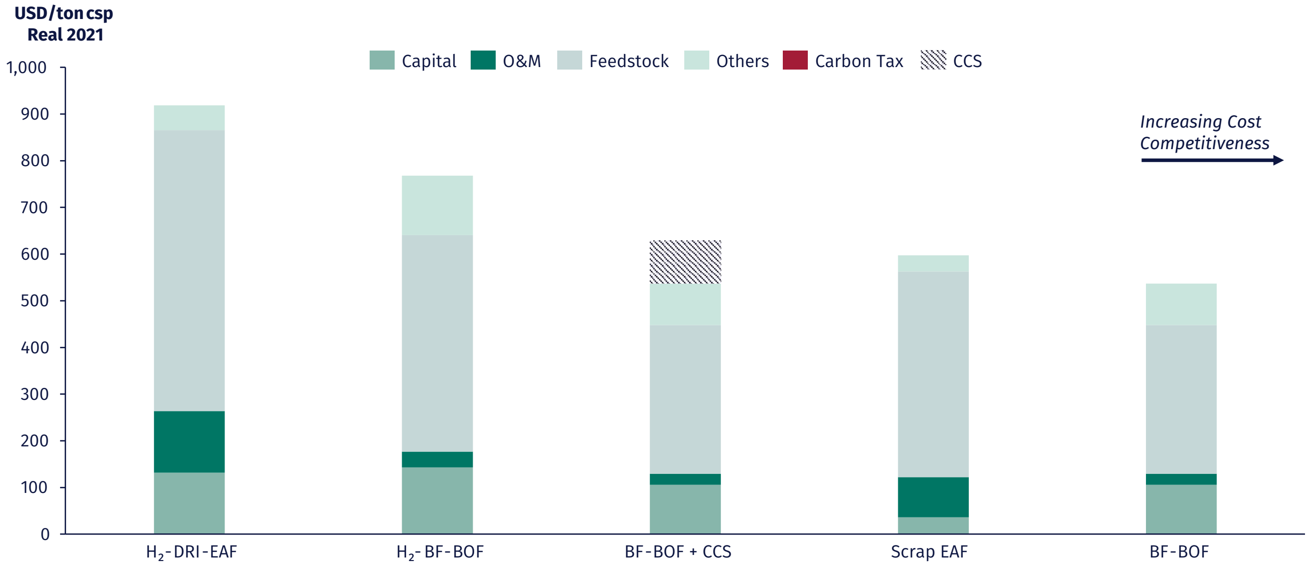


Source: Wood Mackenzie

Japan

In Japan, Wood Mackenzie found that conventional BF-BOF and scrap EAF are the most competitive options in 2021.

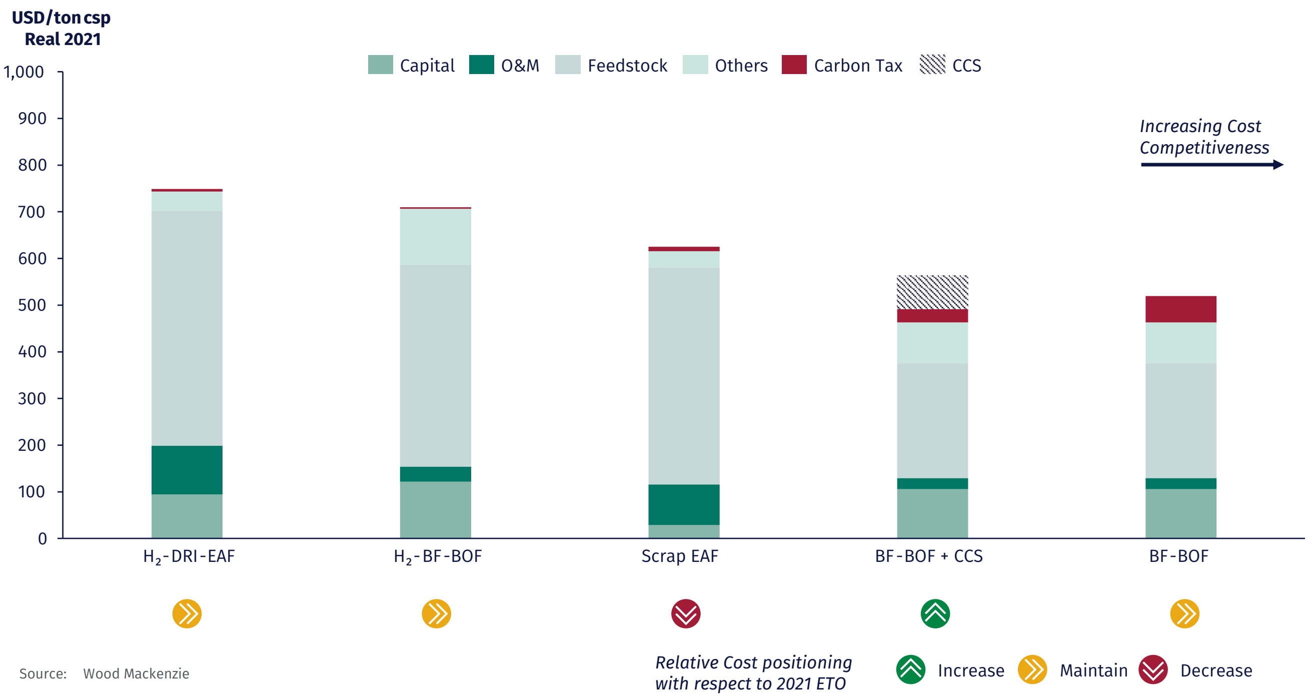
Exhibit 51: 2021 ETO Japan Steel Production Cost Competitiveness Analysis



Source: Wood Mackenzie

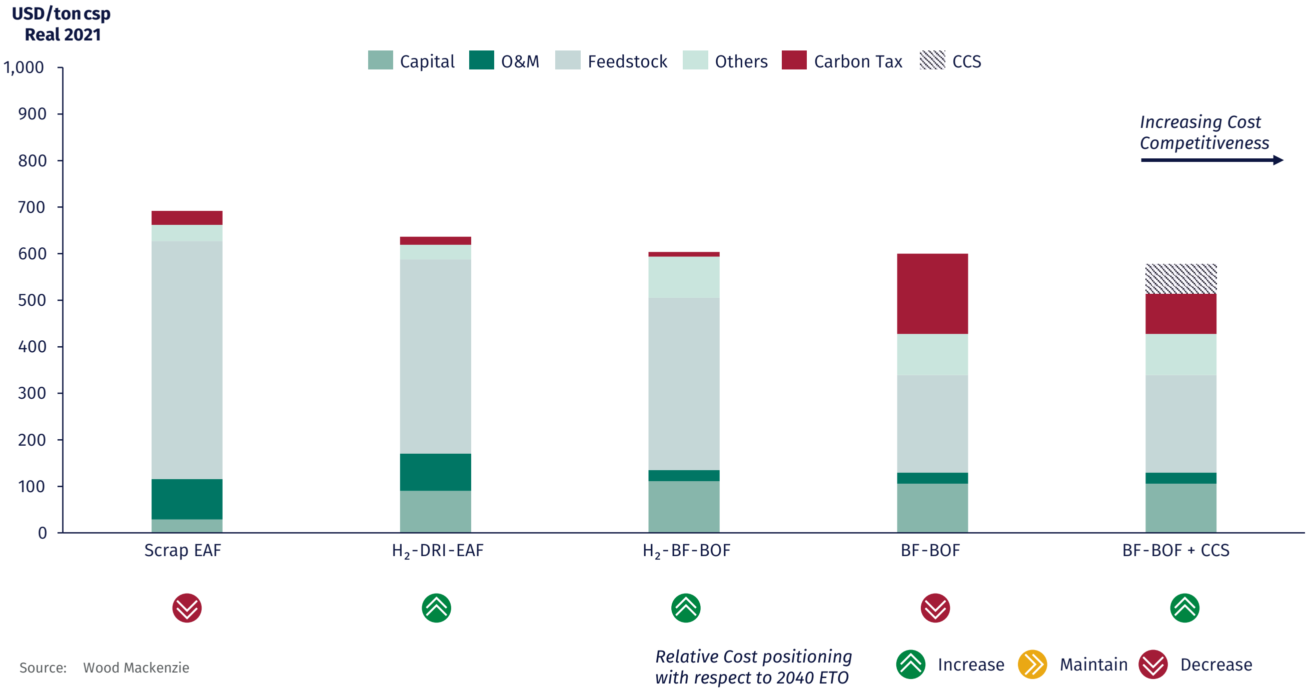
By 2040 in the ETO scenario, conventional BF-BOF remains the lowest cost option, while a carbon price is not sufficient to support low-carbon options including CCS. In the AET-2 scenario, a high carbon price supports the deployment of CCS-based BF-BOF with hydrogen-based options also becoming competitive.

Exhibit 52: 2040 ETO Japan Steel Production Cost Competitiveness Analysis



Source: Wood Mackenzie

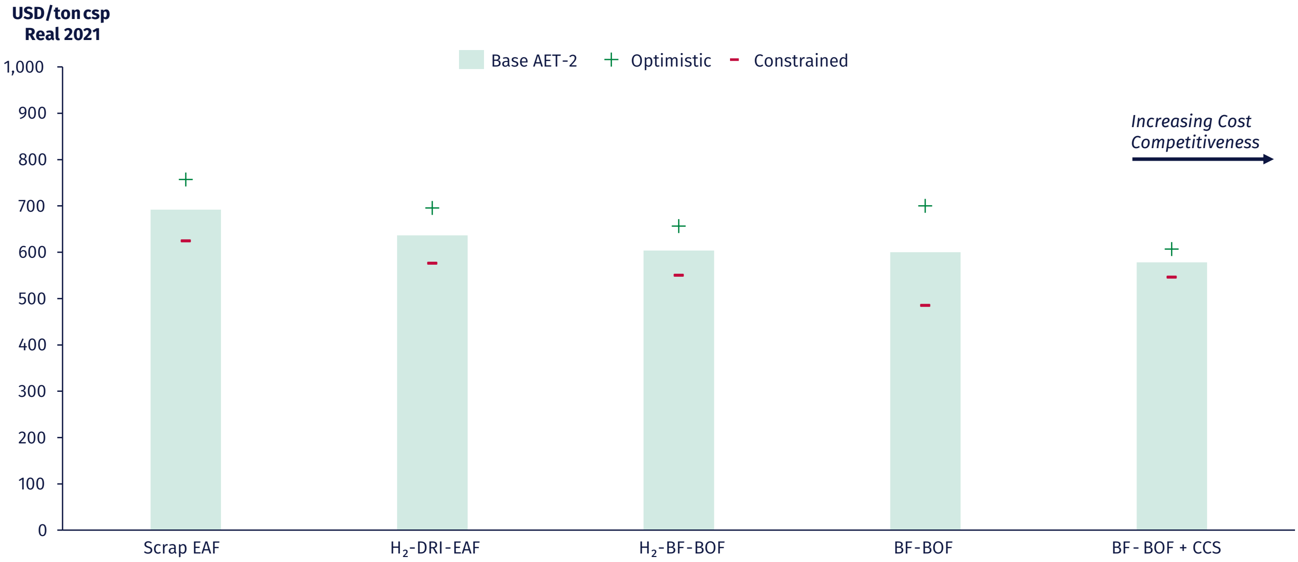
Exhibit 53: 2040 AET-2 Japan Steel Production Cost Competitiveness Analysis



Source: Wood Mackenzie

For the cost competitiveness sensitivity analysis, CCS becomes the most competitive option in the optimistic case, while traditional BF-BOF remains the most competitive in the constrained case.

Exhibit 54: 2040 AET-2 Japan Steel Production Cost Competitiveness Sensitivity Analysis

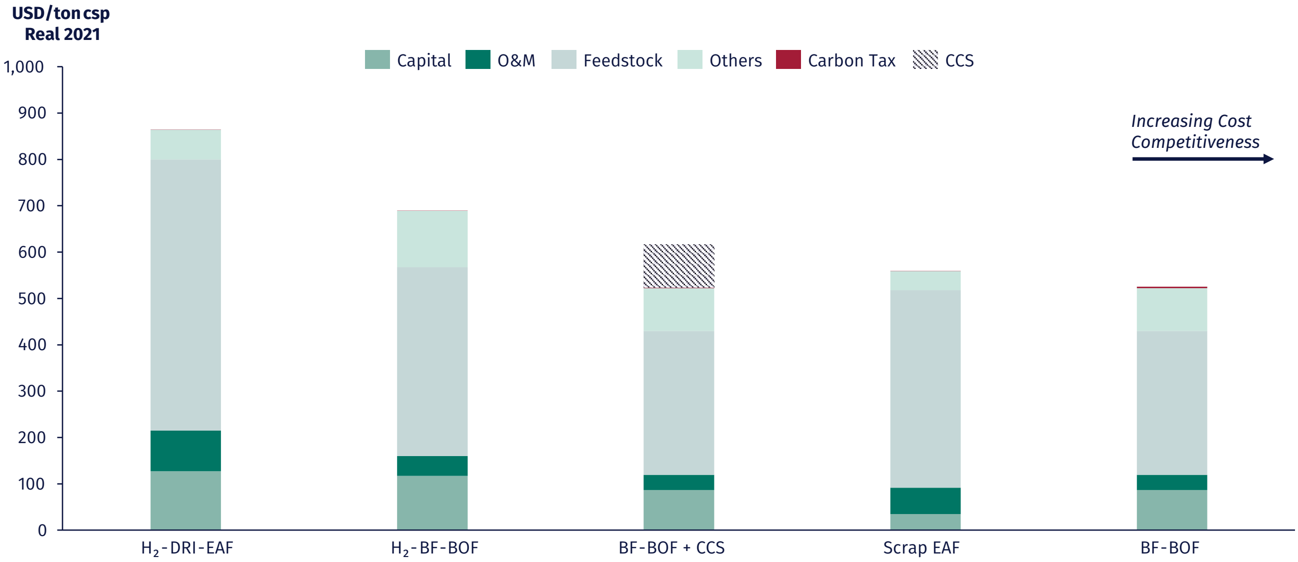


Source: Wood Mackenzie

South Korea

Similar to Japan, conventional BF and scrap EAF are the most competitive options in 2021.

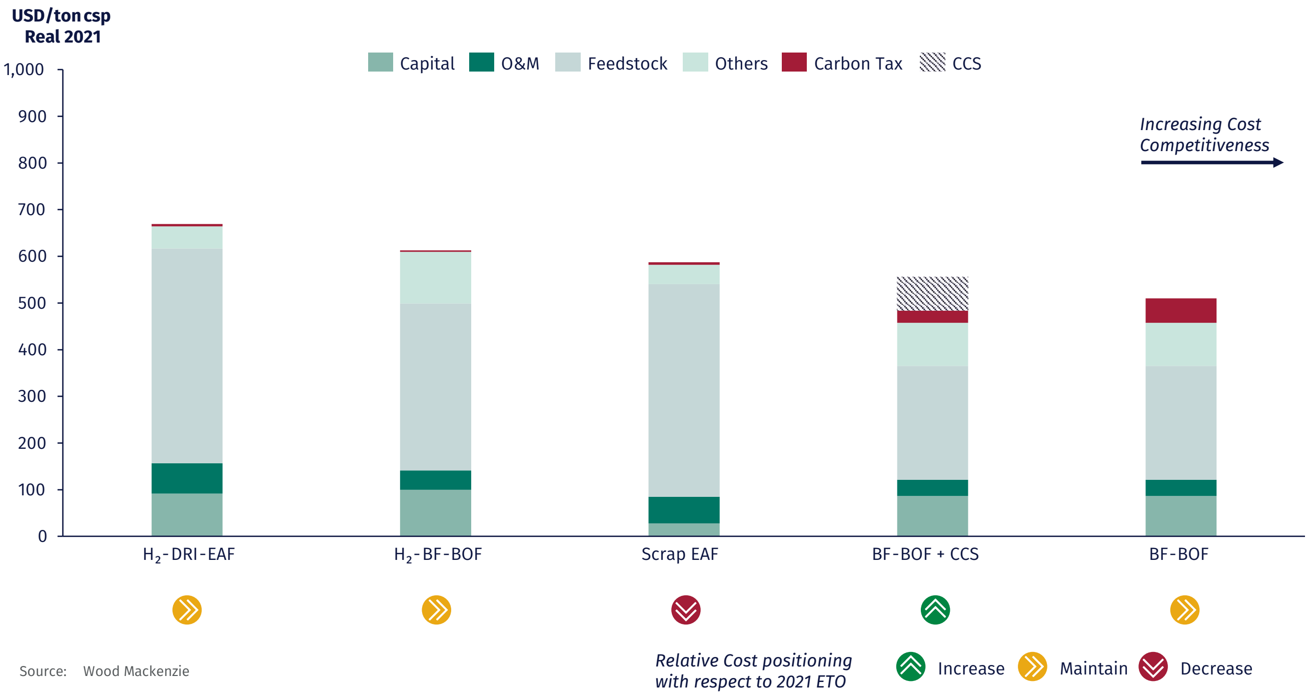
Exhibit 55: 2021 ETO South Korea Steel Production Cost Competitiveness Analysis



Source: Wood Mackenzie

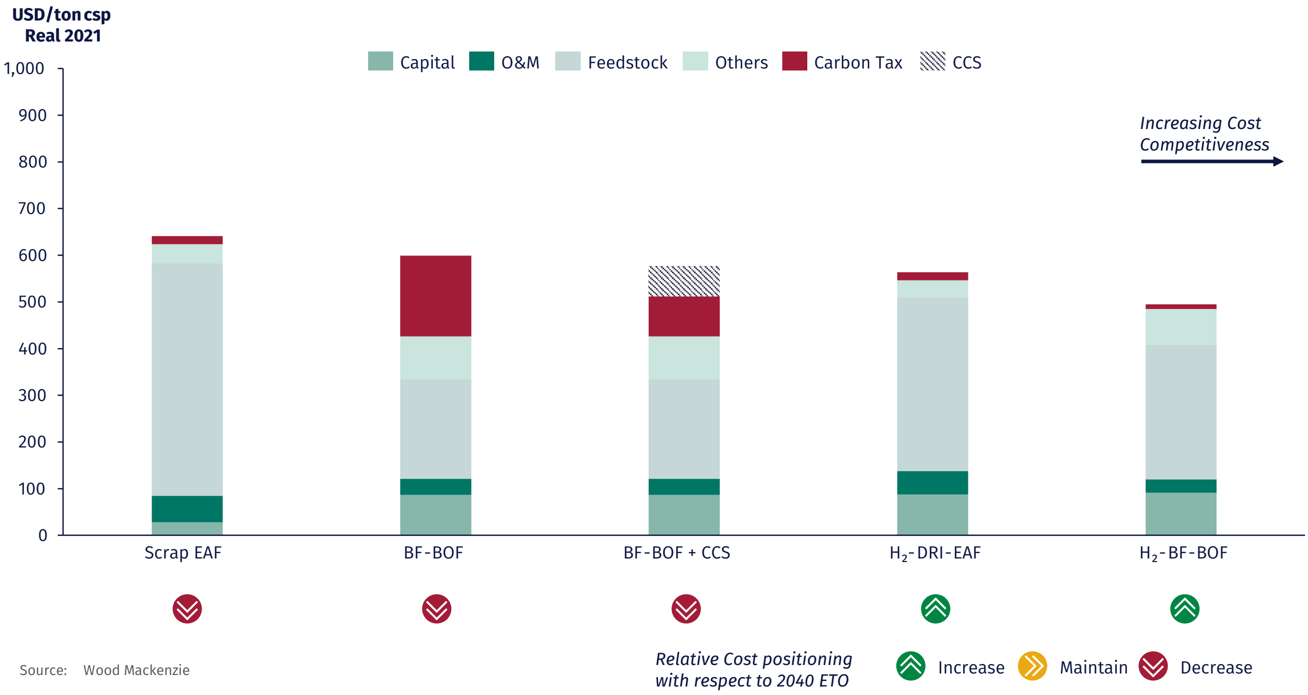
By 2040 in the ETO scenario, conventional BF remains the lowest cost option while scrap costs increase, and carbon prices are insufficient for CCS. In the AET-2 scenario, hydrogen and CCS-based BF options become closely competitive with conventional BF.

Exhibit 56: 2040 ETO South Korea Steel Production Cost Competitiveness Analysis



Source: Wood Mackenzie

Exhibit 57: 2040 AET-2 South Korea Steel Production Cost Competitiveness Analysis



Source: Wood Mackenzie

For the cost competitiveness sensitivity analysis, low-carbon options extend their advantage over conventional options in the optimistic case, with hydrogen alternatives as the most competitive. In the constrained case, traditional BF-BOF will compete against hydrogen-based options.

Exhibit 58: 2040 AET-2 South Korea Steel Production Cost Competitiveness Sensitivity Analysis

Source: Wood Mackenzie

Appendix C: Scenarios Used by Wood Mackenzie in the Analysis

Introduction to Wood Mackenzie's Energy Transition Scenarios (from Energy Transition Service)

	Base Case (3 °C Scenario) (Energy Transition Outlook)	2 °C Scenario (Accelerated Energy Transition – 2)	
Likely outcome based on current trends	• Base Case view across all commodity and technology business units • Incorporates evolution of current policies and technology advancement playing out in the future • Broadly consistent with a 3 ºC global warming view for 2021 (limiting global temperature rise to 3 ºC)	• A scenario developed to show what needs to happen to achieve a 2 °C scenario. • Cumulative emissions trajectory aligns with the upper temperature limit stated in the Paris Agreement • Assumes a rapid decarbonisation of power and other sectors to reduce emissions • Assumes developed countries reach net zero by 2050 & global net zero in 2070	***Accelerating trends in base case outlook to meet 2 °C target***
	Estimated 2050 CCS Capacity: ~0.86 Gt	**Required 2050 CCS Capacity: ~4 Gt**	

Note: Based on H_2 2020 scenario dataset

Boundaries of Wood Mackenzie's Analysis

What this study is	What this study is NOT
• Provides a top-down evaluation & indicative trends of how CCS costs compare to other options in key CO_2 emitting sectors • Focuses mainly on the cost perspective and the role that CCS could play in each sector as a result • Highlights implications on the conditions that would be required to support CCS deployment given WM's findings on cost • Based on & supported by assumptions & inputs from Wood Mackenzie's 2 °C scenario	• Not meant to be a bottom-up evaluation of CCS economics nor a quantification of CCS deployment • Not meant to be a comprehensive evaluation of all external factors which could influence CCS deployment • Not meant to conclude on whether CCS is plausible or how much would be deployed • Is not directly comparable to 1.5 °C scenarios such as IEA's NZE nor meant to be a critique of the plausibility of various scenarios

Key assumptions regarding indicative CCS costs that being used by Wood Mackenzie in their analysis:

Capture:

- Reflects cost of capture excluding transport and storage
- Input data based on consistent technology assumption – i.e., no mixing of SCPC/Oxy fuel/IGCC, etc.
- Future costs derived using published estimates for “next of a kind” or historic learning curves

Transport:

- Costs assumed to be constant given mature tech.
- Onshore/offshore costs applied based on potential storage reservoir location
- Pipeline sharing assumed, normalised to 250 km length

Storage:

- Costs assumed to be constant given mature technology.
- Onshore/offshore costs applied based on potential storage reservoir location
- Assumes saline aquifers given greater availability

Disclaimer