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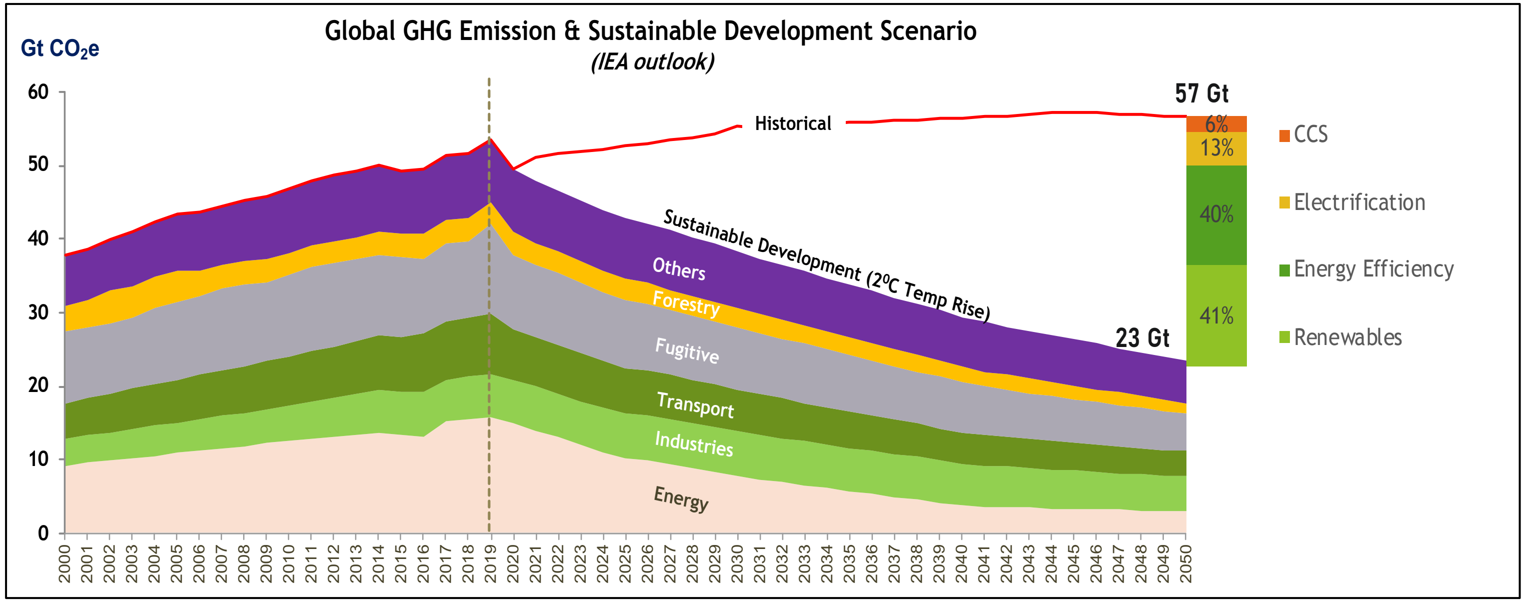
# Introduction of Carbon Capture and Storage (CCS)

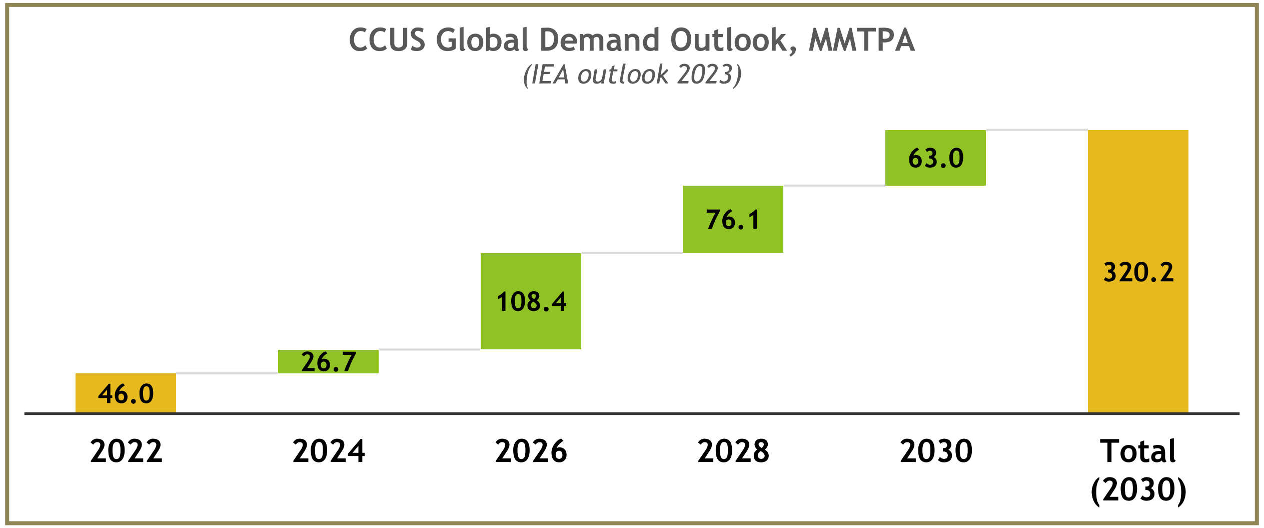
# CCS Overview

| | |
|---|---|
| CCS Growth Outlook | The current onstream capacity of CCS (45 MMTPA) is projected to grow to 320 MMTPA by 2030 to meet decarbonization and energy transition (blue H2) demand. |
| CCS Value Chain | The CCS value chain is mainly comprised of CO2 capture, purification/dehydration, transport and storage. The quality of CO2 source and storage plays a key role in shaping the CCS economics. |
| $CO_2$ Capture Technologies | Selection of the best-fit capture technology to improve $CO_2$ purity of the emission source to achieve an optimal CCS solution. In general, the CO2 purity between 95vol% to 99 vol% is desired depending on the reservoir/sink geology. |
| $CO_2$ Purification & Dehydration | Treatment of high-purity $CO_2$ stream to reduce the stream oxygen and sulphur impurities and water content to avoid pipeline corrosion and mitigate associated operational risks. Setting a sweet spot specification of these impurities is key to achieving an optimal CO2 transportation solution. |
| $CO_2$ Compression | Selection of the most suited compression machine (beam, integral gear etc.) is governed by the impurities spread of the $CO_2$ stream and the final discharge stream specification. An optimal machine selection would minimize associated electrical, civil and infrastructure requirements also. |
| $CO_2$ Transportation | The unique thermodynamic properties of dense-phase CO2 make it a preferred choice of transport. The dense phase transportation allows handling the CO2 in a small bore pipeline at no added friction loss. |
| $CO_2$ Storage | The nature of storage geology greatly influences the cost of upstream development and the surface facilities as well. The injection wells' MAOP influences $CO_2$ compression & transport cost. Whereas, the subsurface geology (permeability, porosity, depth, formation footprint) governs the upstream development cost. |

# Global Outlook



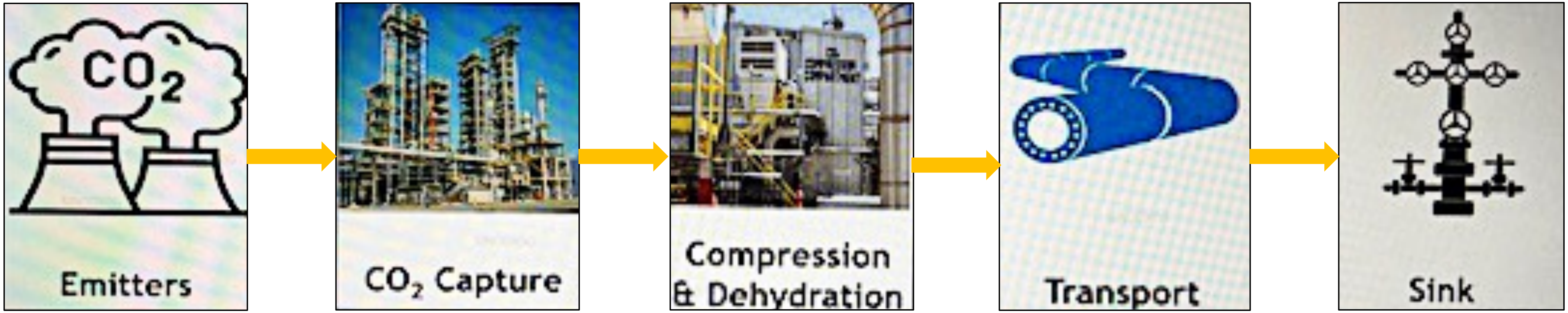



- 6% share of low carbon energy (blue $H_2$) in the global abatement portfolio to meet sustainable development scenarios.
- This reflects a dominant global growth outlook of CCS to facilitate energy transition.
- The second sketch projects an accelerated growth outlook for CCS

# CCS Value Chain






$CO_2$ Emission Source

Enhance $CO_2$ source purity (≥95 vol%)

Removal of oxygen, sulfur and water impurities

Conduit to deliver $CO_2$ molecules from source to sink

Store $CO_2$ molecules safely and permanently

The value chain definition assists in defining the following:

- CCS development's cost benchmarking with global developments
- Develop an effective proposal to obtain government incentive
- Help to form a viable JV having clarity on scope boundaries and responsibilities

# $CO_2$ Capture Dynamics



- A wide range of emitters spread on $CO_2$ purity.
- The cost of capturing $CO_2$ decreases as the emission source's $CO_2$ purity increases.
- Emission sources with <4 vol% $CO_2$ purity & <0.3 MMPTA capacity incur very high capture costs and shall be avoided in the development.
- High cost of capture for emitters having $H_2S$ impurities > 500 ppm due to availability of limited capture technologies and poor capture performance.
- Efforts are underway to reduce capture costs <$40/ton

# $CO_2$ Capture Technology Spread

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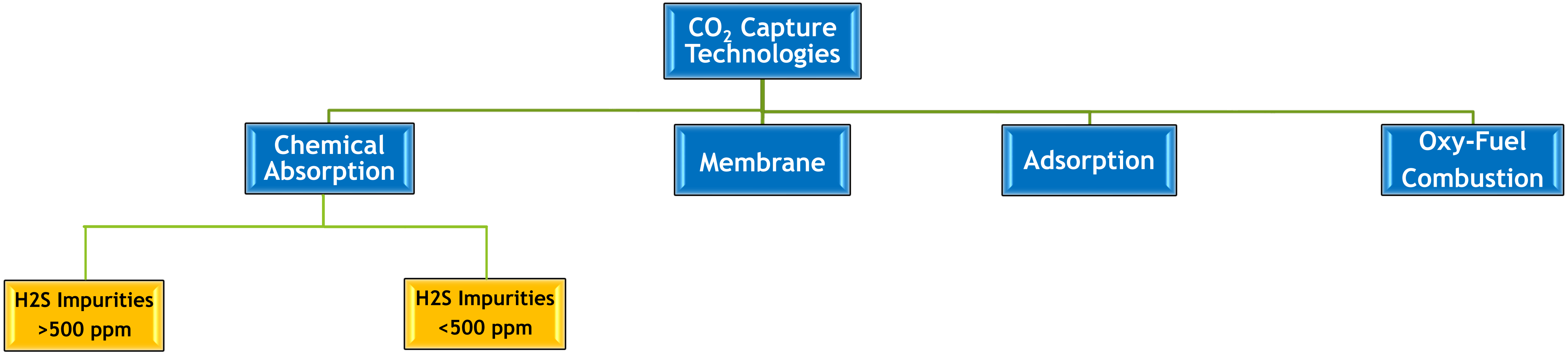


| CO2 Recovery 70%-90% | TRL Level |
|---|---|
| MDEA | 9 |
| BASF / ExxonMobil Flexsorb™ SC Plus | 9 |
| BASF OASE® sulfexx™ | 8 |

| CO2 Recovery >90% | TRL Level |
|---|---|
| Fluor Econamine FG PlusSM | 9 |
| MHI KM CDR Process™ | 9 |
| Shell CANSOLV | 9 |
| Aker Carbon Capture | 7-8 |
| Carbon Clean CDRMax™ | 6-7 |
| Axens DMX™ | 4-5 |
| BASF OASE® Blue | 7-8 |

| CO2 Recovery 65%-90% | TRL Level |
|---|---|
| Membrane Technology & Research PloarCap™ | 6-7 |

*(Polaris™ polymeric membrane)*

| CO2 Recovery 90% | TRL Level |
|---|---|
| Svante | 6-7 |

*(Metal Organic Framework (MODs)*

| CO2 Recovery 100% | TRL Level |
|---|---|
| Inherent $CO_2$ capture | 5.6 |

*(Allam Cycle)*

# $CO_2$ Treatment - Driver and Goals



**Driver**

**Cost Optimization**

Treating oxygen, sulfur and water impurities of the $CO_2$ stream to a sweet spot lowers the development cost by:

- Requiring less stringent pipeline material specification
- Improving plant availability and reducing the risk of unplanned shutdowns.
- Simplifying CCS configuration
- Allowing for dense phase $CO_2$ transport

**Enhance Integrity**

Limiting the presence of oxygen, SOx, NOx, H/C impurities to a safe level in a $CO_2$-rich environment improves the integrity of the system by:

- Reducing the risk of water and hydrocarbon dropouts in $CO_2$-rich gas phase environment to prevent corrosion
- Eliminate the risk of strong acid formation in a $CO_2$ rich environment due to the presence of SOx and NOx in the presence of $O_2$.

**Ensure Safety**

Treated $CO_2$ stream eliminates the risk of corrosion in gas phase transport, allowing the routing of a gas phase pipeline through populated areas to reduce the risk of fatalities in the event of an uncontrolled bulk release of $CO_2$.

- $CO_2$ is 1.5 times heavier than air
- Exposure to a 3vol% concentration of $CO_2$ for one hour can cause headaches, increased respiratory and heart rate, dizziness, muscle twitching and confusion.
- Just one minute of exposure to a 15vol% concentration of $CO_2$ can pose an immediate threat to life.

# Cryogenic or Compression to Reach $CO_2$ Supercritical Region

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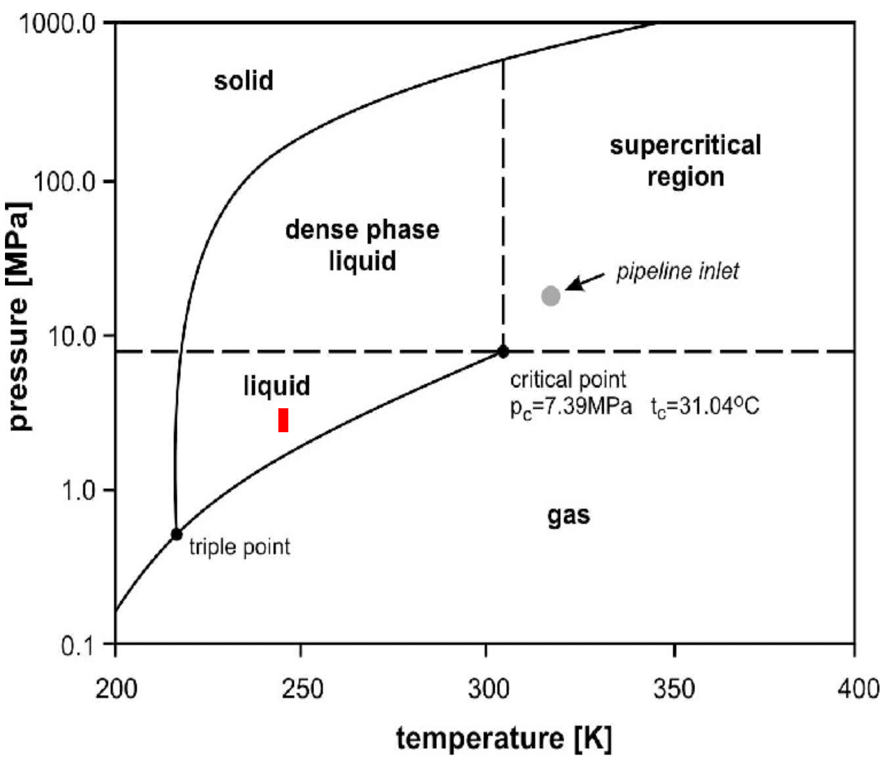
Chart-1: $CO_2$ Phase Envelop




- An ideal operating range for the $CO_2$ cryogenic process is shown in red on chart-1 (Pressure: 3.8 -5 Mpa, and temp $223^0$K/-50°C)
- It's important to note that the quality specifications for liquid $CO_2$ can increase costs..
- The cryogenic option offers lower operating expenses (OPEX) compared to the compression option because of its lower power consumption. However, the cryogenic option requires higher initial capital expenditure (CAPEX) and involves more operational complexities, making it less attractive than compression.
    - The cryogenic option necessitates upfront removal of heavy hydrocarbons and water to prevent fouling in the cold box at -5°C.
    - Additionally, there's a risk of potential loss of $CO_2$ due to the venting of non-condensable gases in the cryogenic process.

# $CO_2$ Dehydration - TSA or TEG

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- 580-650 psi pressure range offers minimum saturation water in the $CO_2$ stream, i.e. a sweet operating spot for the dehydration unit delivering an optimal compression and dehydration solution.
- TSA (temperature swing adsorber) is preferred over the legacy TEG option due to its following technical superiority.
    - Achieves a stringent water specification required to avoid corrosion caused by acid impurities in the $CO_2$ stream.
    - Avoid the presence of TEG carryover in the treated stream to $CO_2$ pipeline prom to severe corrosion
- A corrosion study conducted using premier software such as OLI suggests that even a small presence of TEG in a dry CO2-rich environment could cause severe corrosion in the presence of parts per million levels of acid impurities.

| Parameters | TEG | TSA |
|---|---|---|
| Sweet Operating Point | Approx. 580 psi | Approx. 580 psi |
| Operating Temp Limit | $\geq 100F$ (foaming below this temp) | $\geq 75F$ (Hydrate formation issue) |
| Achievable Water Spec | $\geq 150\ ppm$ | $\geq 40\ ppm$ |
| Water Spec to avoid hydrate formation | 50 | 50 |
| TEG carryover to avoid corrosion | <10 ppb | NA |
| CAPEX/OPEX | Dense phase | All |
| Preferred Service | Dense phase | All |

# Best Fit Compressor Type for $CO_2$ Service



| Parameters | Beam Type | Integral Gear (IG) | Notes |
| --- | --- | --- | --- |
| CAPEX | - | Lower | IG offers a compact footprint by capitalizing on a water-cooled interstage option. |
| Acceptable H2S impurity in CO2 stream | No limit | 16 ppm (max) | IG requires expensive tandem/double dry gas seals for CO2 service with more than 16 ppm H2 impurities, posing added risk of frequent seal failure. |
| Interstage Cooling | Air-cooled or water cooled | Water cooled recommended | IG offers reduced footprint and lower power consumption with water-cooled option |
| Driver Type | No reservation | No reservation | Driver selection (VFD/VSG/Fixed speed) is a function of motor size (MW) and service type (turndown ratio and frequency) |

- **In general, IG compressors are more economical than beam compressors**
- **IG is not recommended on the technical ground for $CO_2$ streams having H2S impurity >16 ppm**

# Preferred Phase for $CO_2$ Transport



- The unique thermodynamic properties of dense phase (supercritical) CO2 make it a preferred choice of transport.
    - The dense phase demonstrates a viscosity similar to that of a gas, but with a density closer to that of a liquid, allowing for the use of a small bore pipeline.
    - The dense phase has excellent solvent properties, significantly reducing the risk of corrosion in the pipeline.
- Dense phase operation over 1,400 psig is desired to avoid inflection of the density curve (irregular pressure drop profile).
- The presence of non-condensable gases such as hydrogen, methane, and nitrogen in $CO_2$ reduces the density of the dense phase, leading to an increase in frictional pressure drop.

# $CO_2$ Sink's Geology

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- The geology of sinks greatly influences the development cost. The following supports a low-cost CCS development.
  - Lower WHIP offers overall lower surface development cost.
  - High permeability/porosity offers less number of injection wells
  - Shallow sinks offer low upstream development costs.
  - Circular or square formation of reservoirs reduces infrastructure costs associated with wellhead (power, flowlines etc.)
- Sinks close to emitters reduce $CO_2$ compression and transport costs.