Importance of Scale & Economics in Carbon Management

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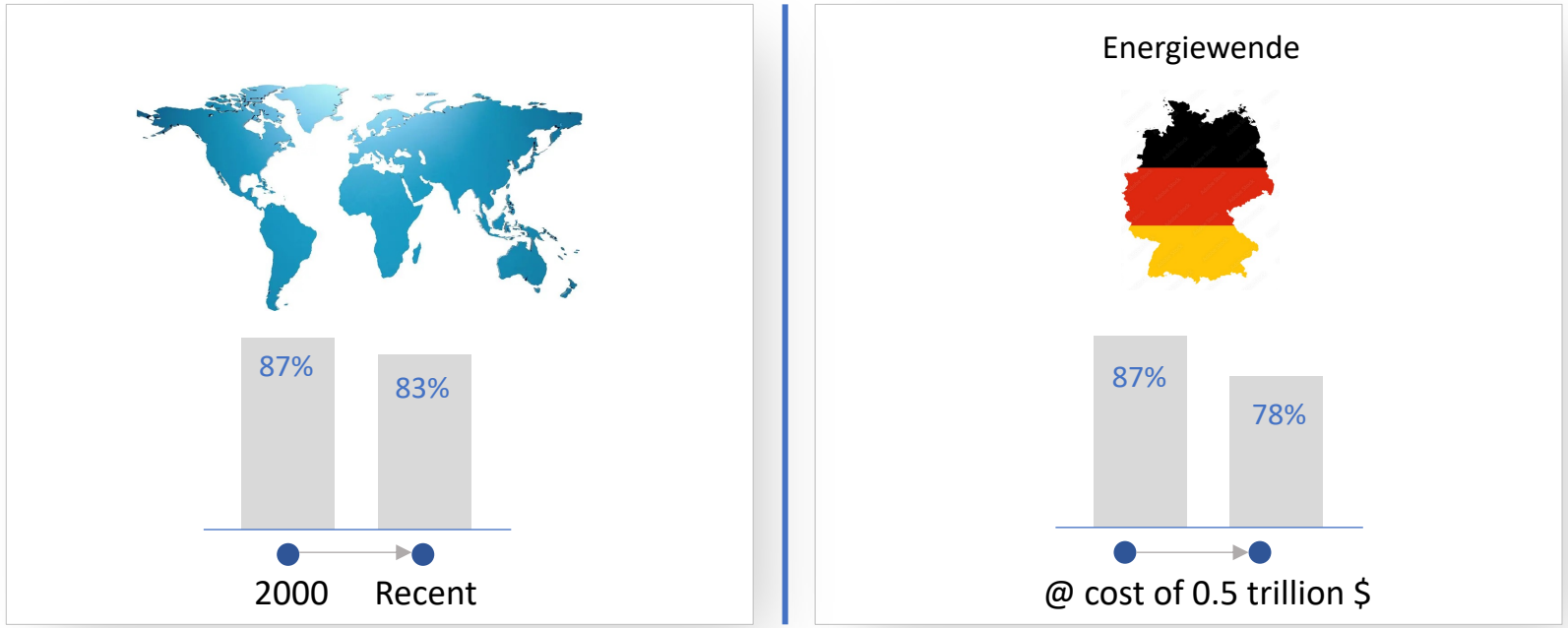
We still live in a fossil fuel world



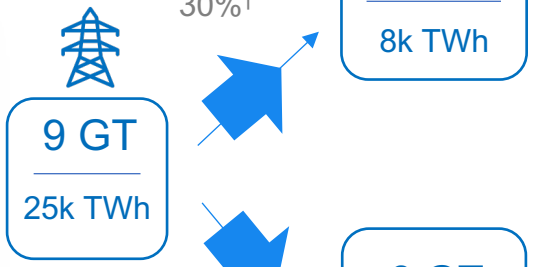
It's a transitioning of a large-scale complex system :: 600 EJ of energy

275 TT $ over 27 yrs at 10 TT$ / yr or over 10% of global GDP/yr for net zero.
A moon-shot is 1% of GDP one time at about 275 BB$

Such a large-scale complex system takes decades to transition

Renewables have a big role to play in the net-zero transition – but with limits

Renewables can at most solve 25 -35% of the emissions from power



30%†

3 GT
8k TWh

Beyond 30% dispatch is difficult due to increased volatility in the baseload mix

70%

6 GT
17k TWh

Coal, Oil, Gas with CCUS, Nuclear, H_2 based GT, Battery Storage, Pumped Hydro, Grid Integration

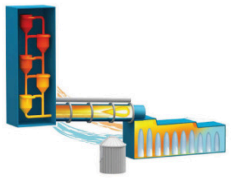
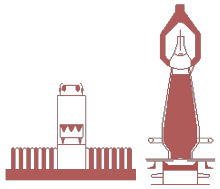
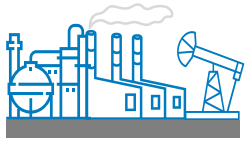
Renewable baseload requires energy storage (battery, pumped storage) at scale and economics + GT based peakers support

† Current production share of wind & solar is at 9%

* ~ 100 GW wind in EU requires 2 Twh of storage @ 500 $/Kwh ~ 1 TT$ of battery or 100-150 BB$ of pumped hydro if available

The modern world is based on four industrial pillars, all of which require fossil fuels

The 4 non-substitutable and critical sectors account for over 7 giga tons per year of emissions

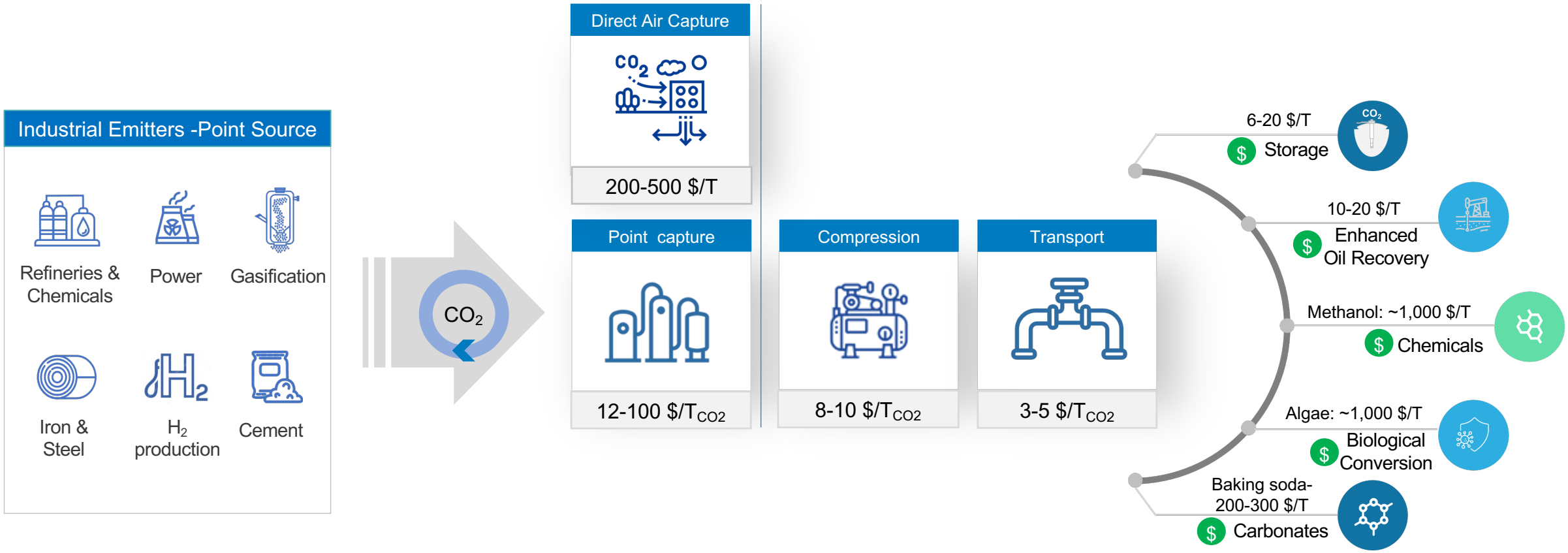
	Cement	Steel	Plastics	Ammonia	Other Industries
					
Annual Production	4,500 mtpa	1,900 mtpa	400 mtpa	180 mtpa	-
Equiv CO_2 Emissions	2.9 Gt	2.7 Gt	1.2 Gt	0.3 Gt	2.0 Gt

Use of fossil fuels is non-replaceable, both as a form of energy and in the process

Net zero industrial future requires abatement of CO_2 at giga ton (GT) scale

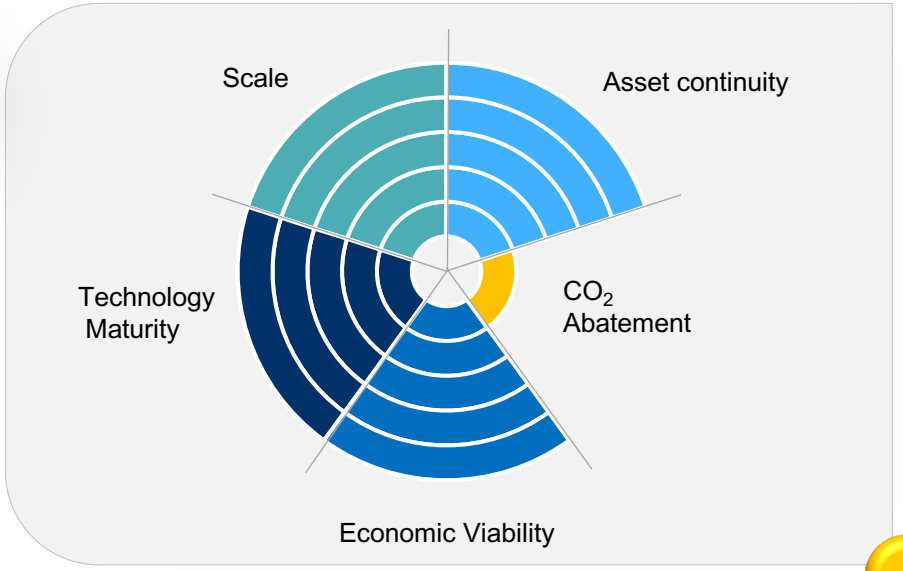
Source: IEA

Enabling the complete decarbonization value chain through GT scale capture, conversion, and storage

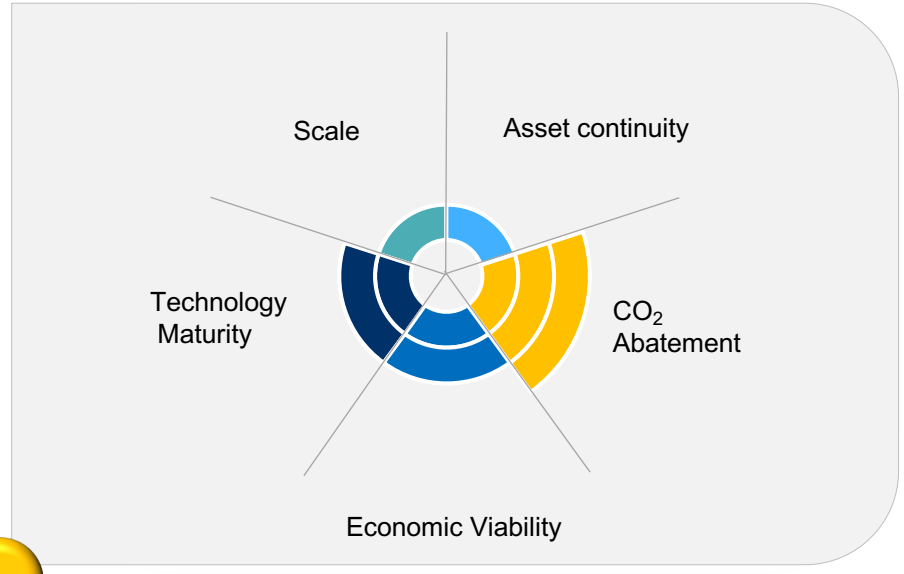


What are the potential levers for GT scale decarbonization?

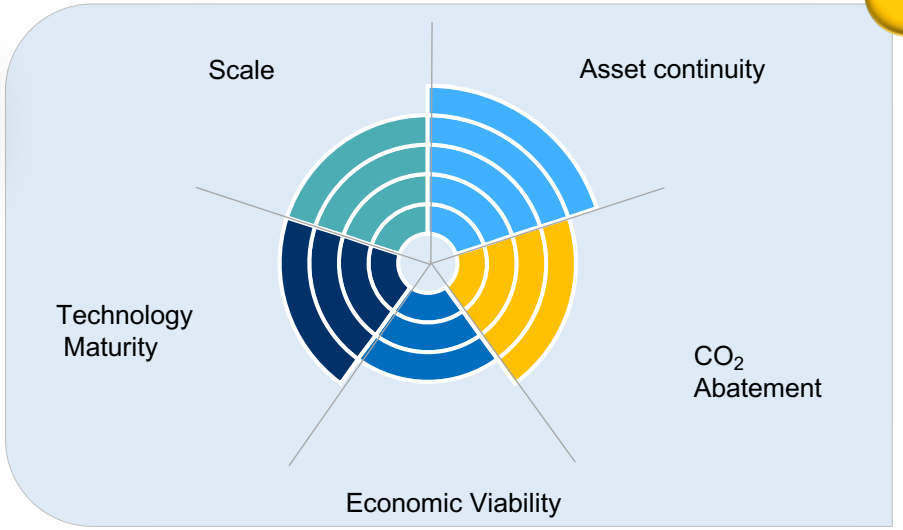
Process Improvement



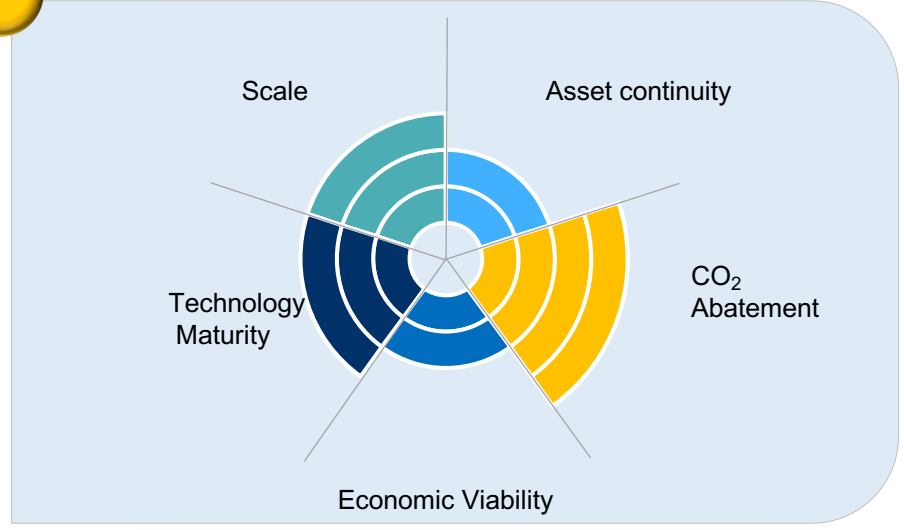
Process Innovation & Electrification



CCUS & Blue H_2

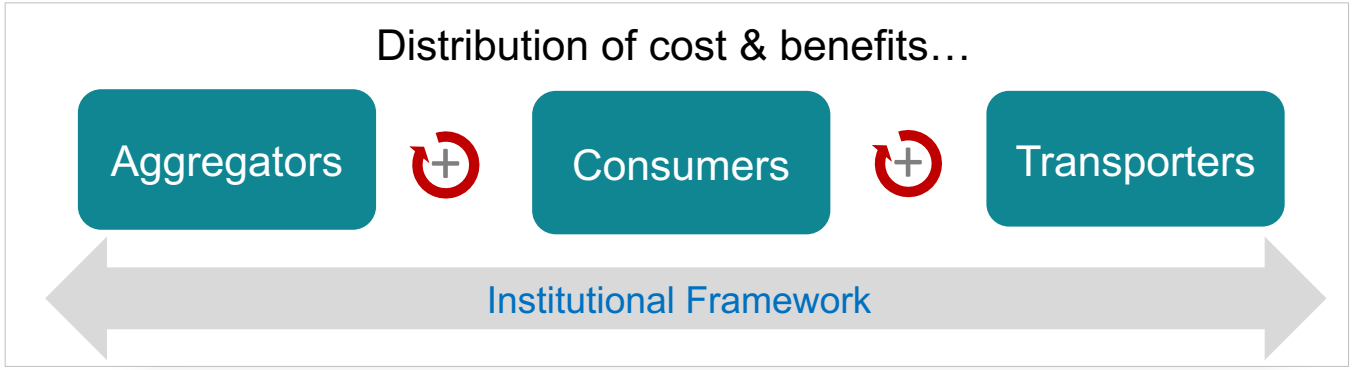


Green H_2



Market thickness and liquidity are essential to drive CCUS at GT scale

Create Market	Drive Scale	Drive Demand	Supply Availability
Market liquidity (Henry Hub Model)	Create common giga ton scale CO_2 transport infrastructure	45Q, waste & carbon to value, green premium	Business/aggregation models to connect emitters & consumers
Attract players through thickness of market	Underwrite risks for individual participants	Demand areas – sequestration, carbon to value, EOR	Incentivize investment in transportation infrastructure

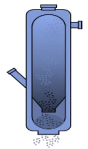


Enabling affordable GT scale CO_2 capture and management – '**GT scale CO_2 grid**'

Industrial emitters


Refineries


Power


Gasification / H_2 production


Iron & Steel

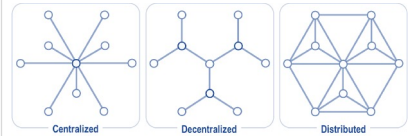

Chemicals / e-chemicals

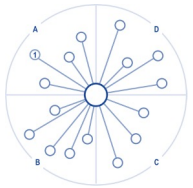
0.5 GTPA of CO_2

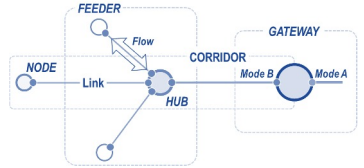
Ref : EIA, 2018

CO_2 Collection & Processing Hub

CO_2 Transportation







Storage

25 - 30 GT#

#Over 50 yrs.

- Gulf Coast
- Texas off-shore

EOR

10 - 50 MTPA

- Permian Basin (West TX)
- East Texas
- Central Texas

CO_2 Grid Operator's Boundary

Large scale CO_2 collection, aggregation, transport and disposition infrastructure that is economically attractive and operationally seamless for emitters

Operating principles of the GT scale CO_2 grid

1. Grid contains access points and hubs, federated pipeline, very large-scale sinks (sequestration)

2. Grid transfers to EOR disposition on a spot and contractual basis like other commodity markets

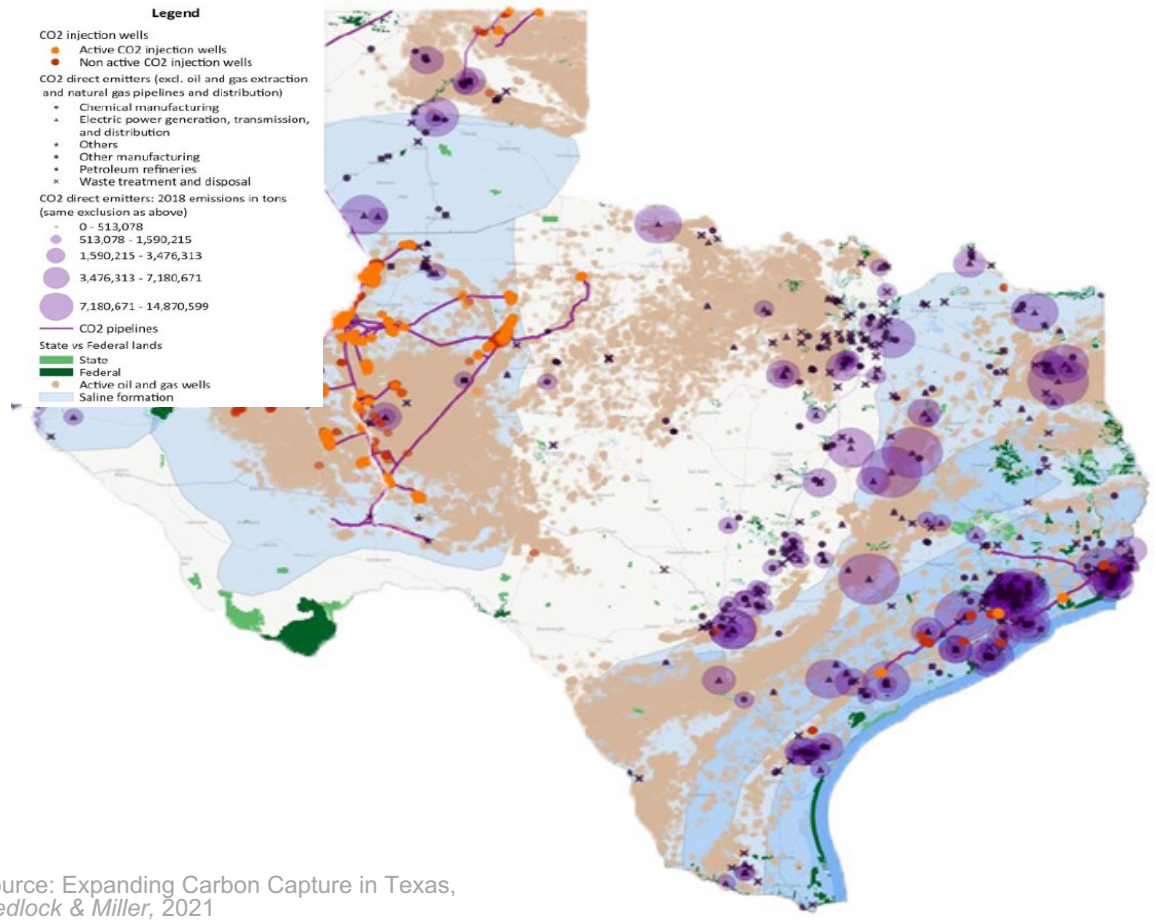
3. Grid carries out Monitoring Verification and Accounting (MVA) to enable emitter to collect credits

4. Grid offers ‘Take or Pay’ contracts for minimum volume of CO_2 to emitters

5. Grid prices in or transfers the operating risks of transport & sequestration away from emitters

Example: A GT scale CO_2 grid architecture in the Texas region

CO_2 Landscape in Texas



Source: Expanding Carbon Capture in Texas, *Medlock & Miller*, 2021

- Optimized Automated Switched Transport across Source-Sinks based on QoS
- Federated CO_2 Transport Grid Design
- Risk & Liability Hedge Model for Sequestration
- Investment, Financing & Policy Requirement
- Anchor GT Scale H_2 Projects

Resource challenges for large scale hydrogen production

Short to medium term

Refineries

Chemicals / e-chemicals

Power

Medium to long term

Transportation

Iron & Steel

100 mtpa

H_2

22% share of total energy demand

Electrolysis Renewable

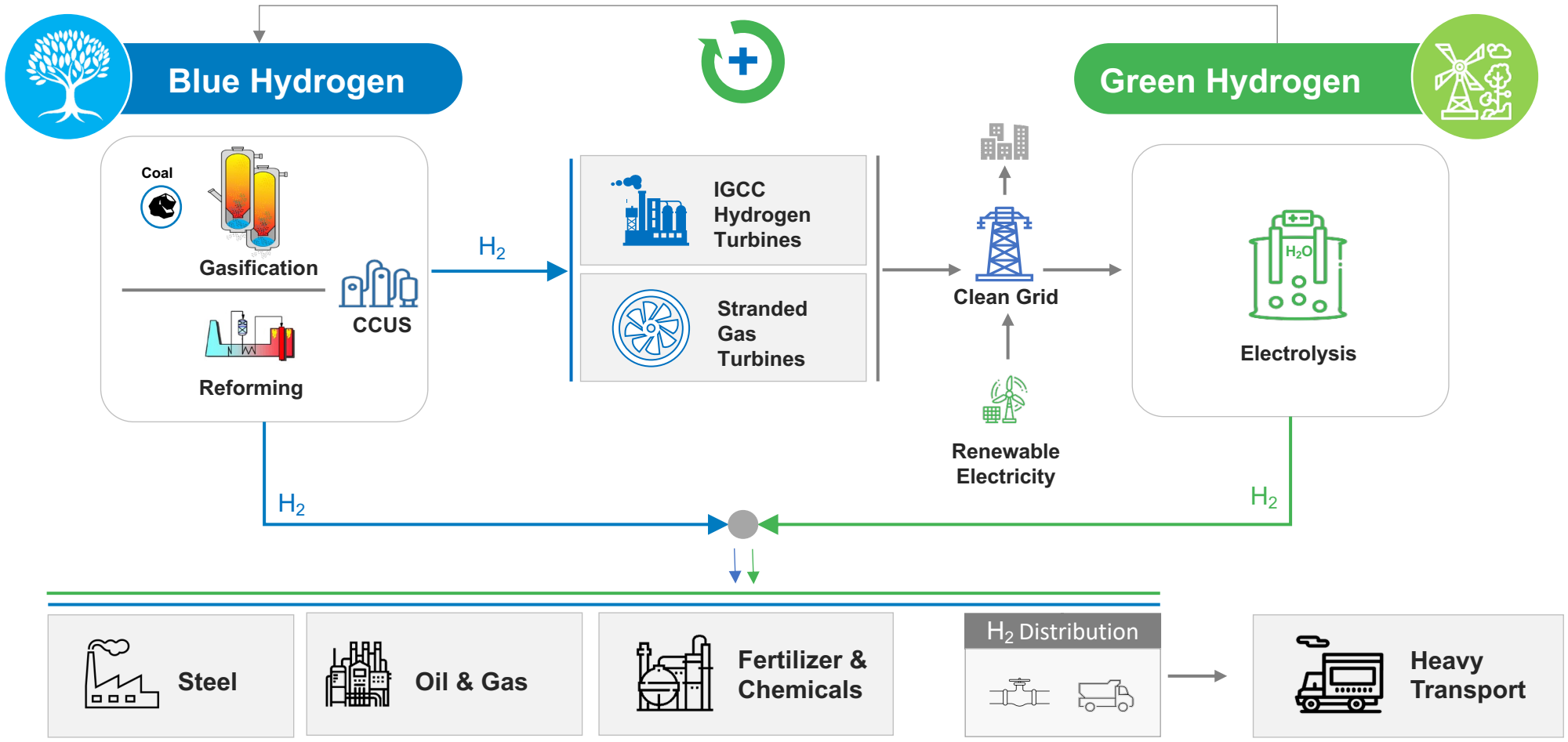
5.3 Trillion kWh	**1.25x** of USA's current consumption **2x** of current RE production
700,000 km^2	Equivalent to Texas landmass
600 Billion US$ + Investment for renewable capacity	
LCOH: 3-5 US$/ kg	

SMR and Hyper Scale Gasification with CCUS

10 tcf nat gas + 200 mtpa pet coke / biomass / plastics / MSW / coal
1 GT @ 25 US$/ton of CO_2 capture and disposition
200-250 Billion US$
LCOH: 1-1.5 US$/ kg

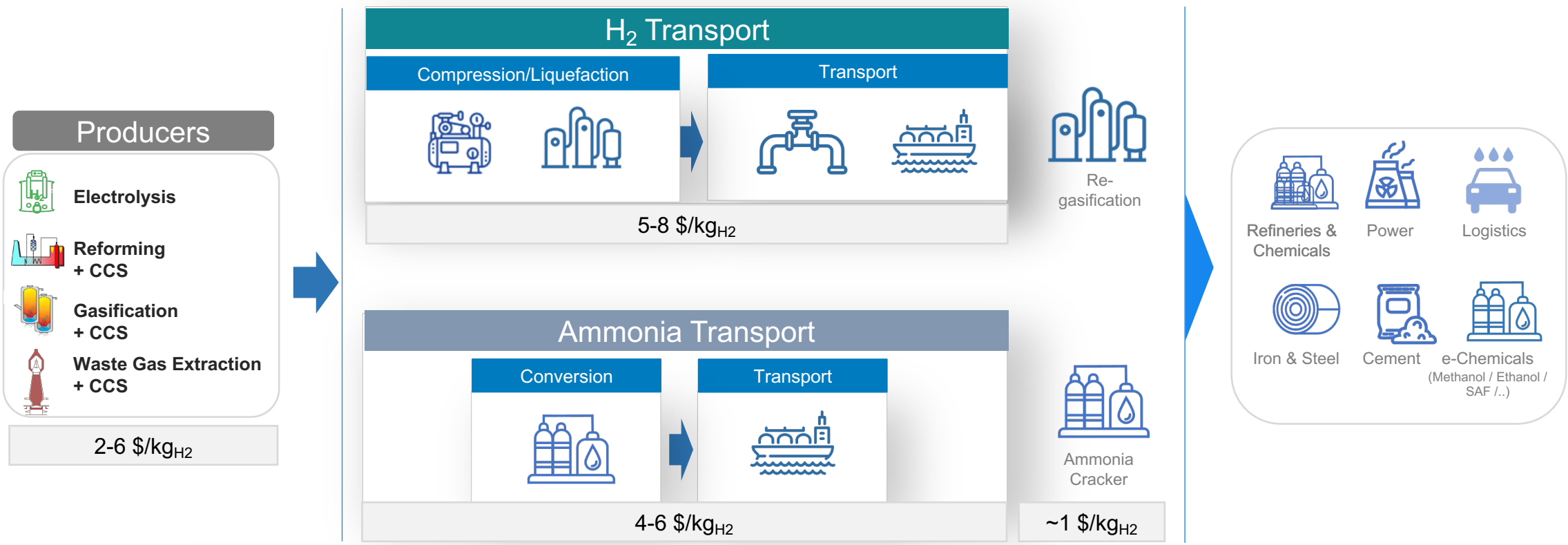
Source: 1. Roadmap to A US Hydrogen Economy, 2. The Future of Hydrogen 3. The water intensity of the transitional hydrogen economy, Michael E Webber 2007 Environ. Res. Lett. 2 034007 4. Dastur research

Hydrogen economy evolution



Energy Security, Economic Prosperity

Hydrogen value chain and trade?



How to organize - combination of green, blue, waste gas, in a hub at scale and economics?

What scale and combination makes sense?

What is the investment?

Our engagements in energy transition

DUKE ENERGY

FEED for 3.7 MMTPA carbon capture at 618 MW IGCC Power Plant

Production of clean base load power from coal

Air Liquide

FEED for 0.9 MMTPA carbon capture at merchant H_2 plant on US Gulf Coast

Use of cryogenic technologies for reducing Scope 2 emissions

CLIFFS
CLEVELAND-CLIFFS INC.

Pre-FEED for 2.8 MMTPA carbon capture at 5 MMTPA Burns Harbor steel plant

Production of 90 ktpa of blue hydrogen

ArcelorMittal

Techno-economic assessment of 2 mtpa carbon capture from DRI

H_2 based DRI making

ADNOC

5 MMTPA Coal & Petcoke Dual Feed Gasification

Multi product portfolio - Methanol, H_2, Ammonia & IGCC Power, CO_2 capture with EOR

IndianOil

0.7 MMTPA industrial scale carbon capture from Hydrogen Generation Unit

CO_2 disposition through CO_2 EOR and food grade utilization

Bharat Petroleum

1.24 MMTPA Petcoke Gasification

Multi product portfolio - Methanol, H_2, Acetic Acid, MEG and IGCC Power

G20

CCUS technology landscape & gap analysis

Policy review framework for international cooperation

NITI Aayog

Carbon capture policy framework

Hub and cluster business model

Financing framework

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