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Supply Chain + Energy + Artificial Intelligence

Carbon Capture and Storage

Investment Analysis and Strategic Outlook

Technology Assessment, Market Dynamics, and Policy Landscape 2025-2035

Comprehensive analysis for investors, financial institutions, and policymakers

October 2025

Presentation Overview

Seven critical dimensions of CCS technology and market opportunity

Global CCS Landscape

Current deployment status across Europe and North America with project pipeline analysis

- 50 operational facilities
- 628 projects in pipeline
- North America leads with 314 projects

Historical & Future Trajectory

Evolution from 2015-2025 and projections through 2035

- 4x capacity growth by 2030
- 430 Mtpa target
- $80B investment required

Economic Analysis

Carbon abatement cost curves and competitive positioning versus alternatives

- $50-150 per tonne CCS
- Renewables: $40-80/tonne
- Policy support critical

Challenges & Enablers

Technical barriers, policy frameworks, and public acceptance dynamics

- 10-20% energy penalty
- Public familiarity key
- Regulatory support essential

Global CCS Deployment Status 2024-2025

Current operational capacity and project pipeline

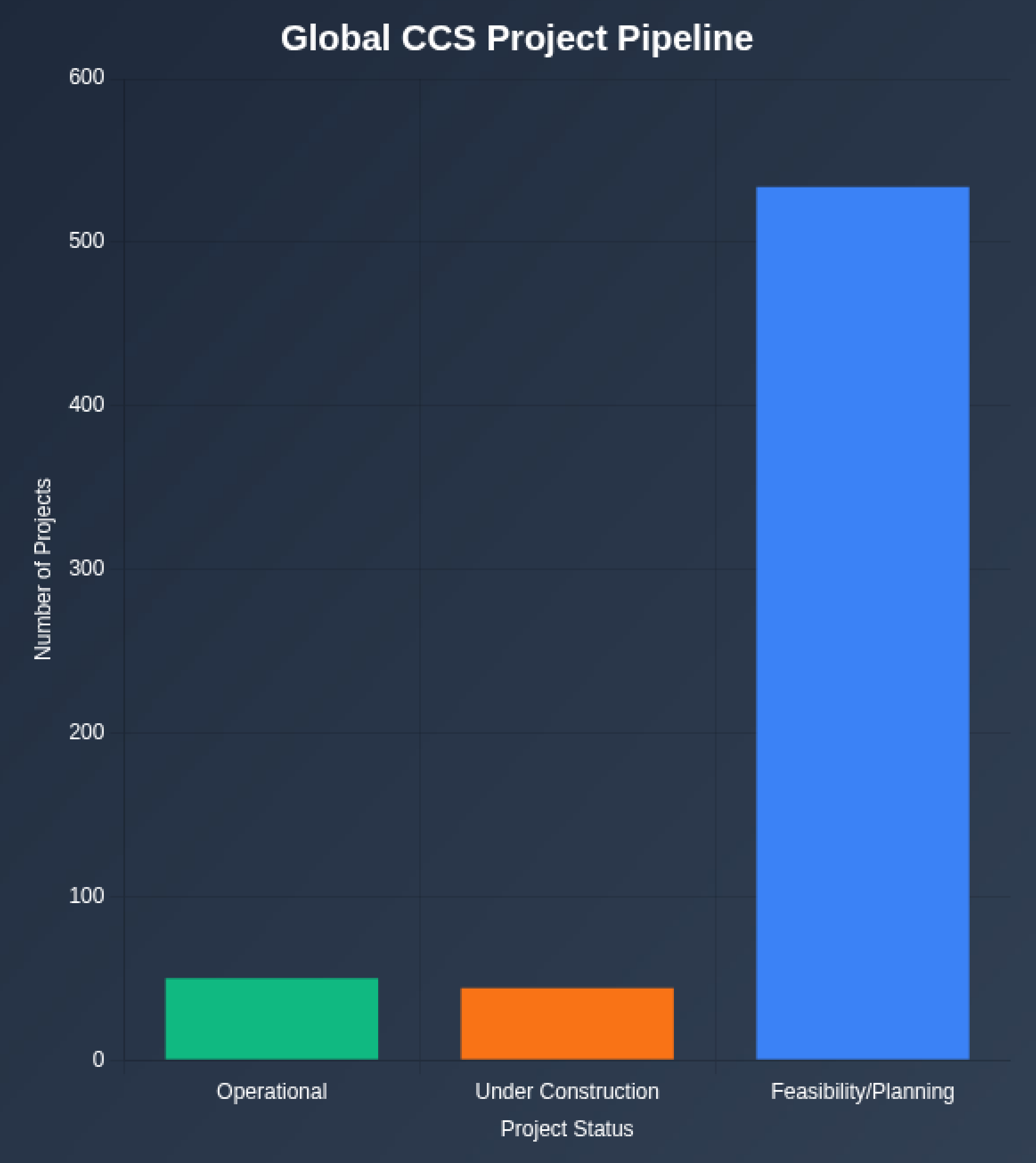
50
Operational CCS Facilities

628
Total Projects in Pipeline
+60% YoY

50 Mtpa
Current Annual Capture Capacity
0.1% of global emissions

44
Facilities Under Construction
Additional 50-60 Mtpa

Global CCS capacity represents only a fraction of required deployment, but pipeline growth indicates accelerating momentum



Source: Global CCS Research 2024 | Data as of mid-2024

Regional CCS Leadership: North America vs Europe

Comparative Deployment and Market Share

North America

314

Total Projects

45% of global projects

Key Facilities

ExxonMobil Shute Creek: 7 Mtpa

Alberta Carbon Trunk Line: 1.6 Mtpa

Leading Sectors

Natural gas processing, ethanol, hydrogen

Europe

73

Total Projects

37% of global capture projects

Key Facilities

Northern Lights: Targeting 5 Mtpa

Sleipner: 1 Mtpa (since 1996)

Leading Focus

Hub development & offshore storage

North America accounts for 80% of upcoming capacity additions through 2030

CCS Application by Industrial Sector

Current deployment and revenue distribution

Key Application Sectors

Oil & Gas Industry
90% of global capacity

Enhanced Oil Recovery, Natural gas processing

Power Generation
69% of revenue (2024)

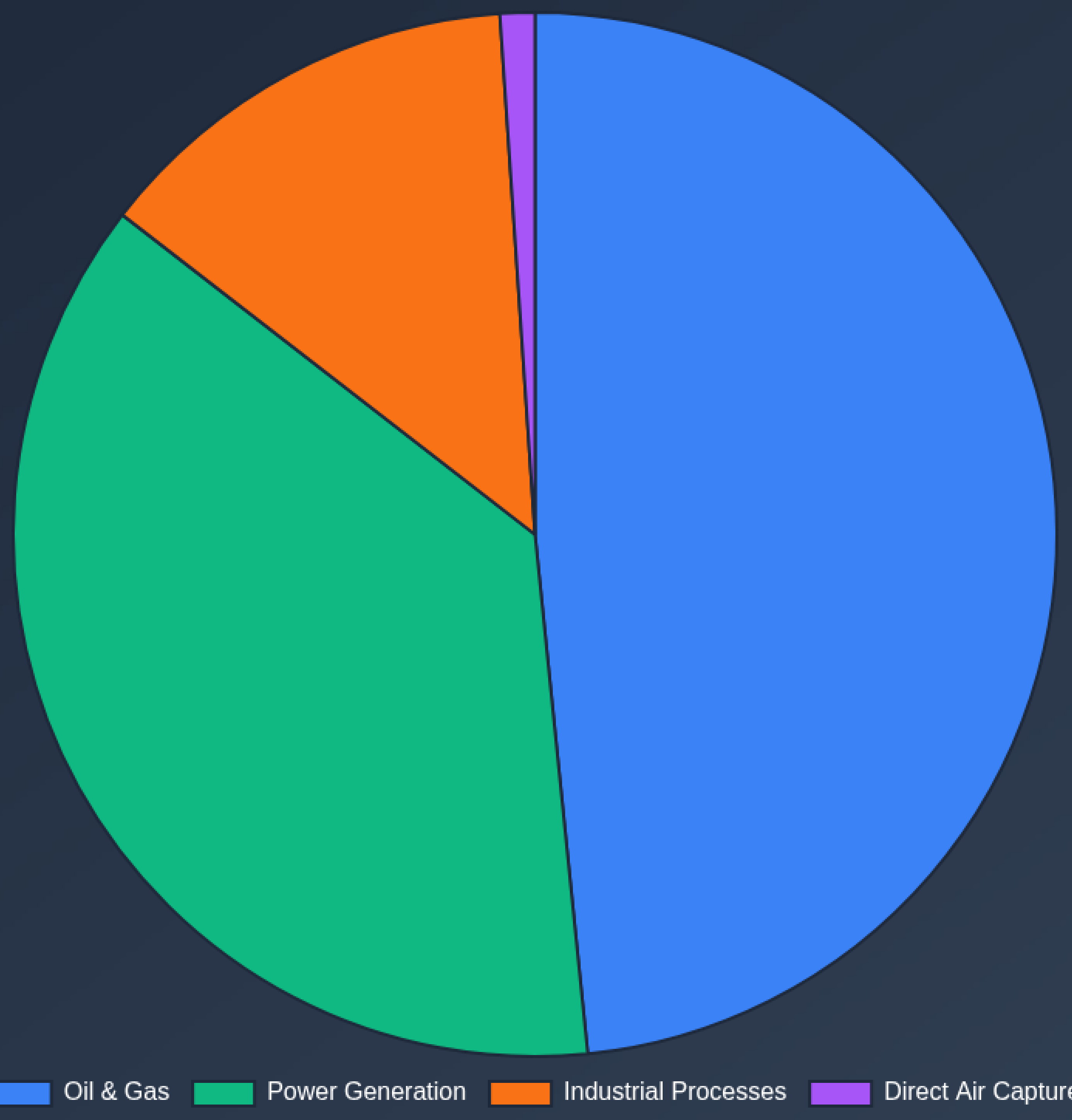
Coal retrofits, Gas-fired plants

Industrial Processes
Growing segment

Cement, Steel, Chemicals, Hydrogen

Direct Air Capture
20+ projects in development

Emerging tech, high cost & potential



Note: Power generation value represents revenue share; others represent capacity share.

Oil & Gas applications dominate current deployment; industrial and DAC represent growth frontiers.

Historical Context: CCS Development 2015-2020

A foundational period for policy and early projects

2015 Baseline

Global Projects
<200

Operational Capacity
10-15 Mtpa

Primary Barrier
High costs, limited incentives

Milestone
Paris Agreement adopted Dec 2015

Major Milestones 2015-2020

2015
Paris Agreement & Climate Alignment
Stricter US emission regulations (420 tonnes/GWh).

2018
Bipartisan Budget Act
45Q tax credit expanded to $10-50/ton.

2020
Limited Commercial Deployment
41 global projects, 15 in US (0.4% of national emissions).

Key Learning
High-purity CO_2 sources proved most viable; >70% of projects failed.

Success Story
Shell Quest stored 7M+ tonnes with >99% retention.

Challenge
Gorgon project achieved only 30% capture rates.

2015-2020: A foundational period establishing critical policy frameworks.

Acceleration Phase: 2021-2025

Policy breakthroughs drive exponential project growth

2021-2022
Policy Breakthroughs

US Inflation Reduction Act (2022)
$85/ton storage credit, $180/ton DAC, extended to 2033

Canada ITC Announced
C$2.6B investment tax credit, 37.5-60% capex coverage

EU Innovation Fund
Expansion for CCS demonstration projects

2023-2024
Project Expansion

204 new projects
Announced in 2023 alone

44% increase
In global planned project capacity

Northern Lights Phase 1
Operational in Norway, targeting 5 Mtpa Phase 2 by 2028

Multiple US hydrogen hubs
CCS-integrated hydrogen production projects initiated

2025
Current Trajectory

77 operational
CCS facilities globally

47 under construction
Significant capacity coming online

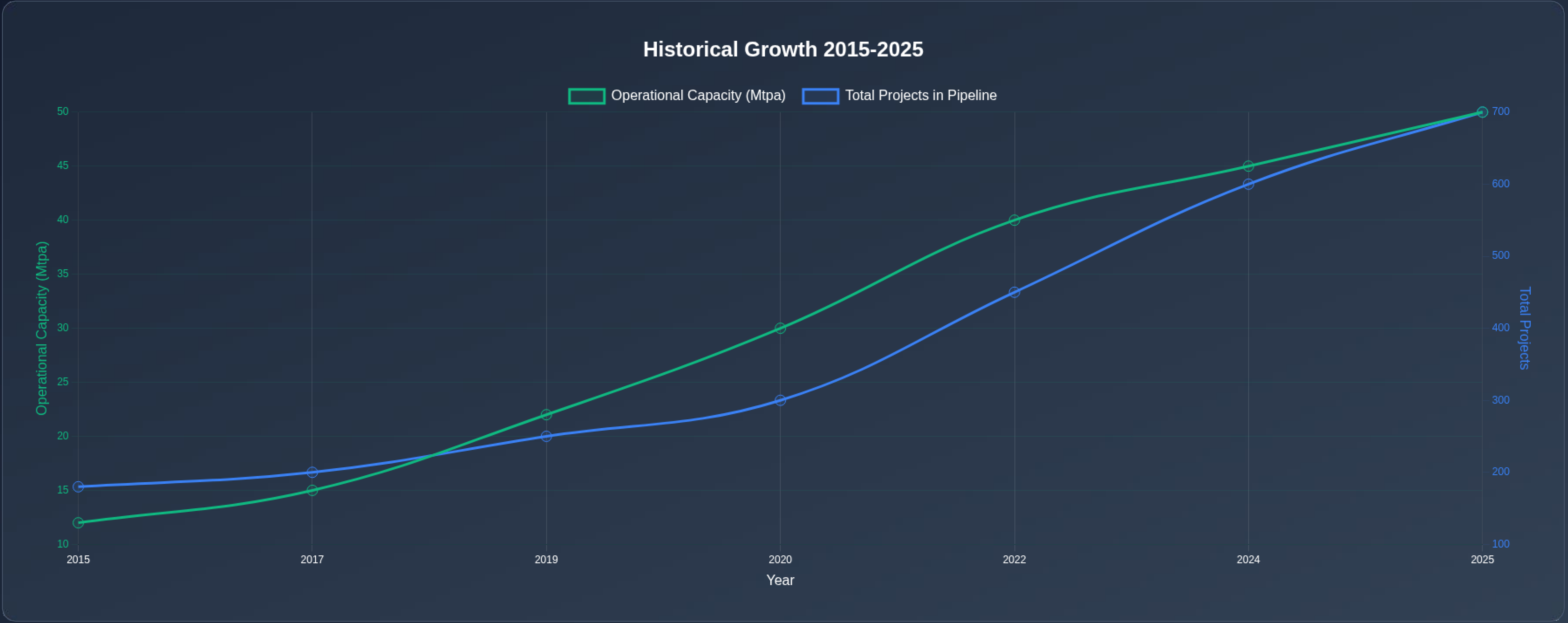
$8.2B
US federal funding committed

Emerging CCS hubs
UK, China, US Gulf Coast development

2021-2025: Transformational period with policy-driven acceleration and 3x project pipeline growth

CCS Deployment Growth Trajectory 2015-2025

Operational capacity and project pipeline evolution



Note: 2022 marks inflection point driven by IRA and enhanced policy support | Capacity growth steady; project pipeline shows exponential acceleration

2030 CCS Capacity Projections

Multiple forecast scenarios and regional distribution

Conservative

279 Mtpa

Source: BloombergNEF

6x increase from current, assumes moderate success rates

Historical precedent suggests caution

Base Case

430 Mtpa

Source: DNV / WEF

4x expansion, 0.5% of global emissions captured

Most cited industry consensus

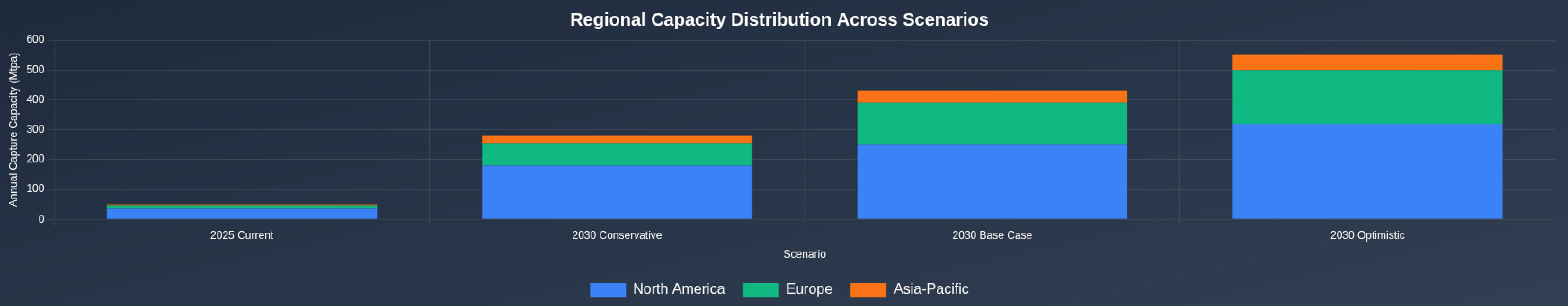
Optimistic

550+ Mtpa

Source: Rystad Energy

10x increase, assumes strong policy continuation and high success rates

Requires acceleration beyond current trajectory



Base case (430 Mtpa) represents 4x growth but still captures only 0.5% of global emissions | North America projected to account for 58% of 2030 capacity

2035 Long-Range Projections

Market growth and sectoral deployment pathways

2035 Market Outlook

1,300 Mtpa

On trajectory to mid-century targets

Market Size	CAGR	Investment
$21-51B	14-16%	$200B+

Key Drivers

- Cost reductions via scale & innovation
- Enhanced policy support & hub development

Reality Check: IEA estimates 4-6 Gt/year needed by 2050 for net-zero.

Sectoral Applications

Hydrogen Production
95 Mtpa

Power Generation
90 Mtpa

Industrial Processes
50+ Mtpa

Direct Air Capture
Scaling from low base

Combined capacity approaching 250 Mtpa by 2030, a foundation for 2035 expansion.

Projections assume policy continuation and 40% cost reductions. Hydrogen and industrial uses are primary growth vectors.

Investment Risks & Feasibility Constraints

Critical factors that could limit CCS deployment

Historical Precedent Risk

- High historical project failure rate (70-98%).
- Only 10% of IPCC pathways align with 2030 targets.
- Deployment analogues (wind, nuclear) suggest slower growth.
- Supply chain dependencies create bottlenecks.

Severity: High

Policy & Regulatory Risk

- Policy uncertainty due to political changes.
- Heavy dependence on subsidies & carbon prices.
- Permitting delays and inconsistent standards.
- Support may drop as renewables become cheaper.

Severity: Medium-High

Technical & Economic Risk

- High energy penalties (10-20% efficiency loss).
- CCS costs ($50-150/t) vs. cheaper renewables.
- Infrastructure gaps in CO_2 pipeline networks.
- Scale requirements create a chicken-and-egg problem.

Severity: Medium

Social Acceptance & Competition

- Public opposition limits site availability.
- Low public familiarity remains a key challenge.
- Strong competition from cheaper renewables.
- Perceived as extending fossil fuel life, reducing support.

Severity: Medium

Gap Analysis: Optimistic 550 Mtpa by 2030 is ~1% of global emissions; IEA's net-zero path requires 1.6 Gt.

Carbon Abatement Cost Curve Framework

Methodology for comparing emission reduction technologies

Understanding the MACC

The MACC ranks technologies by cost per tonne of CO_2 avoided to guide climate investments.

Key Concepts

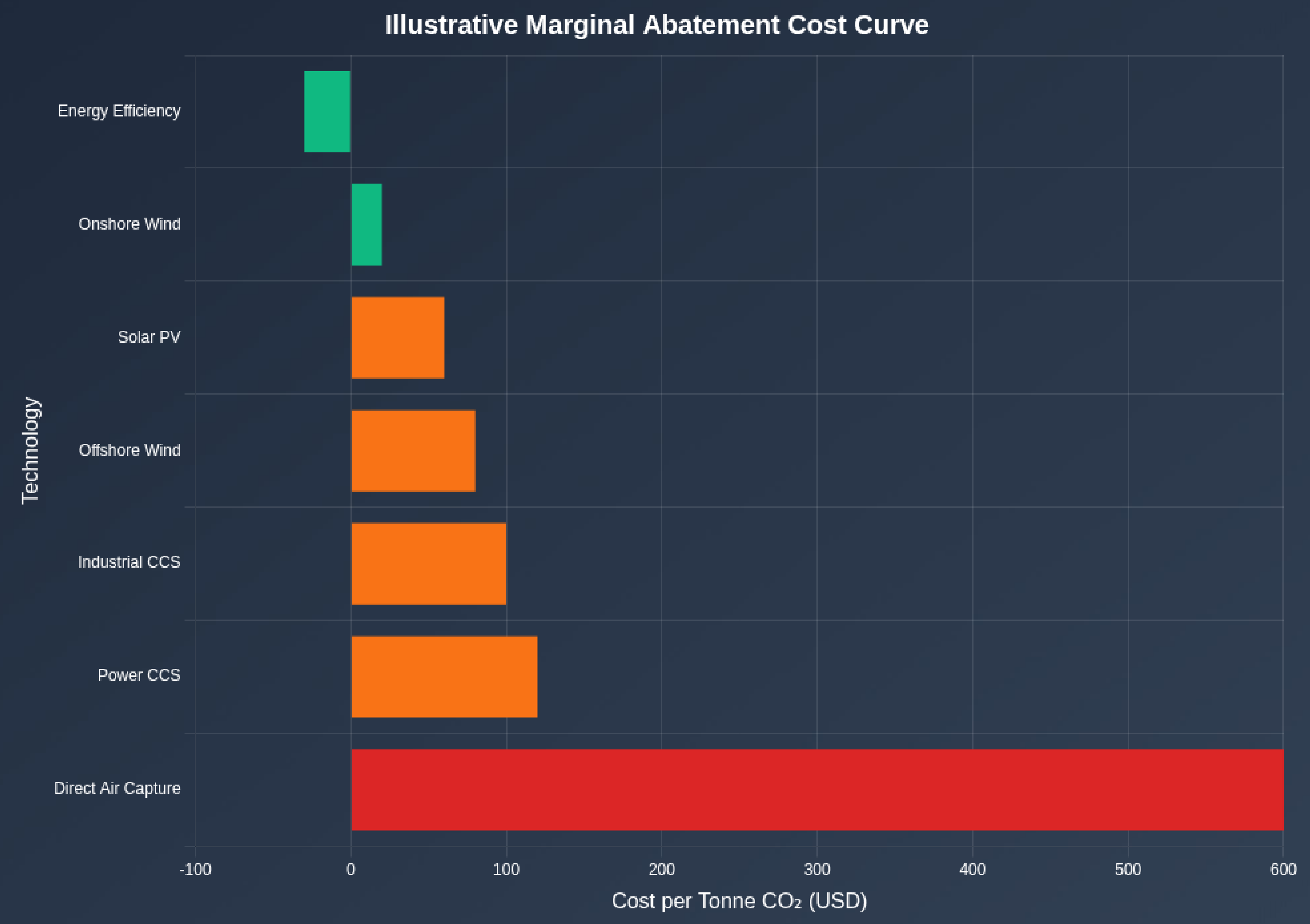
MAC: Incremental cost to reduce one additional unit of CO_2.

Measurement: Dollars per tonne of CO_2 equivalent.

Interpretation: Negative values save money; positive values are a net cost.

Limitations: Static snapshot; costs vary by geography, scale, and policy.

Application: Helps identify cost-effective climate strategies to allocate capital.



Framework enables systematic comparison across technologies | Lower MAC indicates more cost-effective emission reductions

$ CCS Cost Profile Analysis 2024-2025

Application-specific costs and component breakdown

Industrial CCS

$50-150 per tonne

- Natural gas applications: Lower end
- Coal applications: Higher end
- Cement/steel: $150+ per tonne

Mid-range for hard-to-abate sectors

Power Generation with CCS

$60-150 per tonne

- Natural gas combined cycle: $60-100/ton
- Coal-fired plants: $100-150/ton
- 17-33% increase in electricity costs

Less competitive than renewables

Direct Air Capture

$300-1,000+ per tonne

- Current average: ~$490/ton
- Voluntary market: $100-2,000/ton range
- Scalability: $385-530/ton at gigaton scale

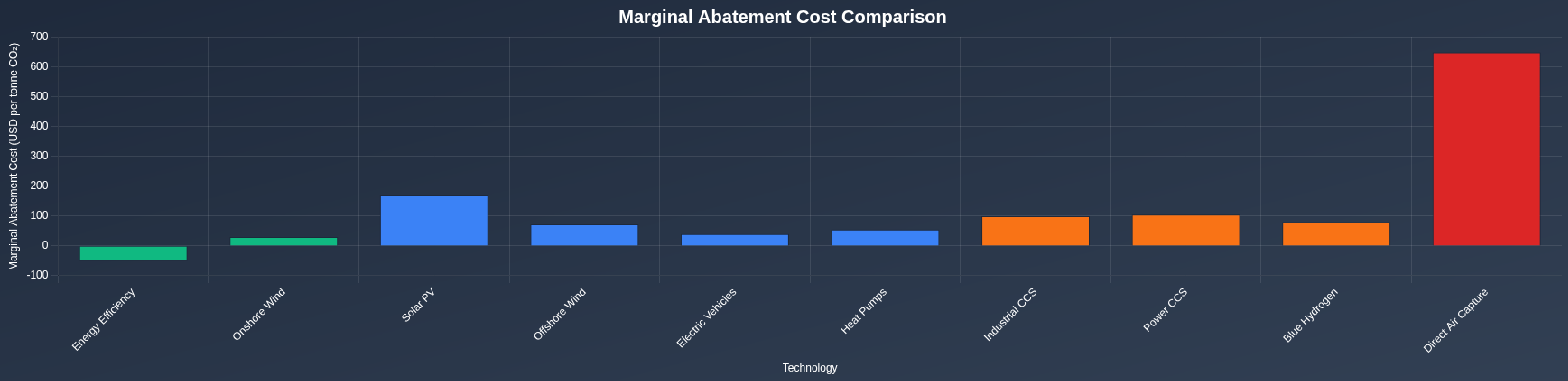
Premium cost; negative emissions value

CCS Cost Component Breakdown

Capture represents 70-80% of total costs | Transportation costs vary widely ($4-45/ton) based on distance and scale

Comparative Abatement Costs: CCS vs. Alternatives

Cost-effectiveness analysis across emission reduction technologies



Energy Efficiency & Wind
Cost-Saving to Low Cost
Highest priority investments

Industrial CCS
$50-150/ton
Competitive for hard-to-abate sectors

Direct Air Capture
$300-1,000+/ton
Premium cost for negative emissions

Analysis: 90% of economically viable decarbonization achievable below $80/ton | Renewables and efficiency offer lower-cost pathways for majority of emissions

Optimal Climate Investment Strategy

Prioritizing Abatement Costs & CCS Niches

Investment Priority Hierarchy

1. **Energy Efficiency** 15-20%
   Negative to $0/ton
   Immediate ROI, reduces energy demand at source.

2. **Renewable Energy** 50-60%
   $40-80/ton
   Low cost, high volume abatement, mature tech.

3. **Electrification** 15-20%
   $20-80/ton
   Amplifies renewable benefits via infrastructure.

4. **Industrial CCS** 10-15%
   $50-150/ton
   For hard-to-abate industrial sectors.

5. **Direct Air Capture** 5%
   $300-1,000+/ton
   Handles residual & legacy CO_2 emissions.

Where CCS is Most Competitive

Cement Production
$150-200/ton
Unavoidable process emissions, few alternatives.

Ammonia/Chemicals
$50-120/ton
High-purity CO_2 streams, often profitable.

Blue Hydrogen
$60-100/ton
Nears cost parity with green H_2 by 2030.

Steel Manufacturing
$100-180/ton
Competes with H_2 reduction for process emissions.

Key Insight
CCS is vital for <10% of industrial emissions, but not cost-competitive for power generation.

Economic analysis: Low-CCS pathway saves ~$1T/year vs. high-CCS. CCS is critical for the final 10% of hard-to-abate emissions.

European Climate & CCS Policy

EU Regulatory Framework and Support Mechanisms

European Green Deal Framework

Primary Target
Climate neutrality by 2050

Interim Goal
55% emission reduction by 2030

Legal Basis
European Climate Law (2021) & Fit for 55 package

CCS Target (Net-Zero Industry Act)
50 Mt CO_2 annual storage by 2030

Key Elements
EU ETS reform, Carbon Border Adjustment (CBAM), Innovation Fund, and Modernisation Fund.

Strategic Approach
Focus on CCS clusters, North Sea storage, and cross-border infrastructure.

Key CCS Support Mechanisms

Innovation Fund
Grant funding from EU ETS revenues for hard-to-abate sectors. Increased allocations in 2023-2024.

EU ETS Carbon Price
Market mechanism (~€60-90/ton in 2024) on a rising trajectory, incentivizing emission reductions.

UK Track 1 Clusters
Business models & contracts with £22B committed to capture 20-30 Mt CO_2 by 2030 via key clusters.

Norway Support
Direct funding, subsidies, and carbon tax (since 1991). Key project: Northern Lights flagship.

Assessment
Climate Action Tracker rating: 'Insufficient', recommends prioritizing renewables over CCS dependence.

EU approach: Top-down targets, innovation funding, and cross-border coordination | 73 CCS projects in Europe

$ North American Climate Legislation & CCS Incentives

US Inflation Reduction Act and Canadian Investment Tax Credit

United States

Inflation Reduction Act (2022)

Largest climate investment in US history with major CCS provisions.

Section 45Q Enhancements

Credit Amounts

- $180/ton (DAC Storage)
- $85/ton (Geological Storage)
- $60/ton (Utilization/EOR)

Key Features

- Direct pay option
- Starts by Jan 1, 2033
- Lower capture thresholds

Projected Impact

13-fold increase in CCS deployment by 2035.

Also includes: $8.2B for CCS hubs & state-level policies (CA, TX, LA).

Canada

CCUS Investment Tax Credit

Refundable tax credit for eligible CCUS costs (2022-2040).

Credit Rates (2022-2030)

- **60%** for Direct Air Capture
- **50%** for Other Capture Projects
- **37.5%** for Transport, Storage, Use

Key Requirements

- Eligible uses: geological storage, concrete mineralization
- 20-year operational life & knowledge sharing
- EOR projects have limited eligibility

Economic Impact

PBO estimates a $5.7 billion cost from 2022-2028.

North America's market-based incentives represent the most generous direct financial support for CCS globally.

⚖️ Policy Comparison: EU vs North America

A look at support structures, effectiveness, and implementation gaps

Region	Mechanism	Value/Support	Duration	Key Features
European Union	Innovation Fund	Variable grants from ETS	Project-specific	Top-down targets, strict regulations
United States	45Q Tax Credit	$60-180/ton	12 years per project	Market-based, tech-neutral
Canada	CCUS Tax Credit	37.5-60% of capex	Through 2040	Refundable credits, accountability

Comparative Effectiveness Assessment

United States
Effectiveness: High

Strengths
- Generous direct financial support
- Flexible, tech-neutral approach

Challenges
- Policy uncertainty from politics
- State-level coordination

European Union
Effectiveness: Medium

Strengths
- Comprehensive regulatory framework
- Cross-border cooperation model

Challenges
- Slower deployment vs. N. America
- Higher project costs

Canada
Effectiveness: Medium-High

Strengths
- Strong accountability
- Complements carbon pricing

Challenges
- EOR subsidy controversy
- Smaller market size vs. US

Policy Gap: All regions require carbon pricing of $50-150/ton for viability; EU ETS is approaching this threshold.

Public Sentiment Analysis: European Perspective

Key findings from the Danish national survey on CCS

Danish National Survey 2022/2024

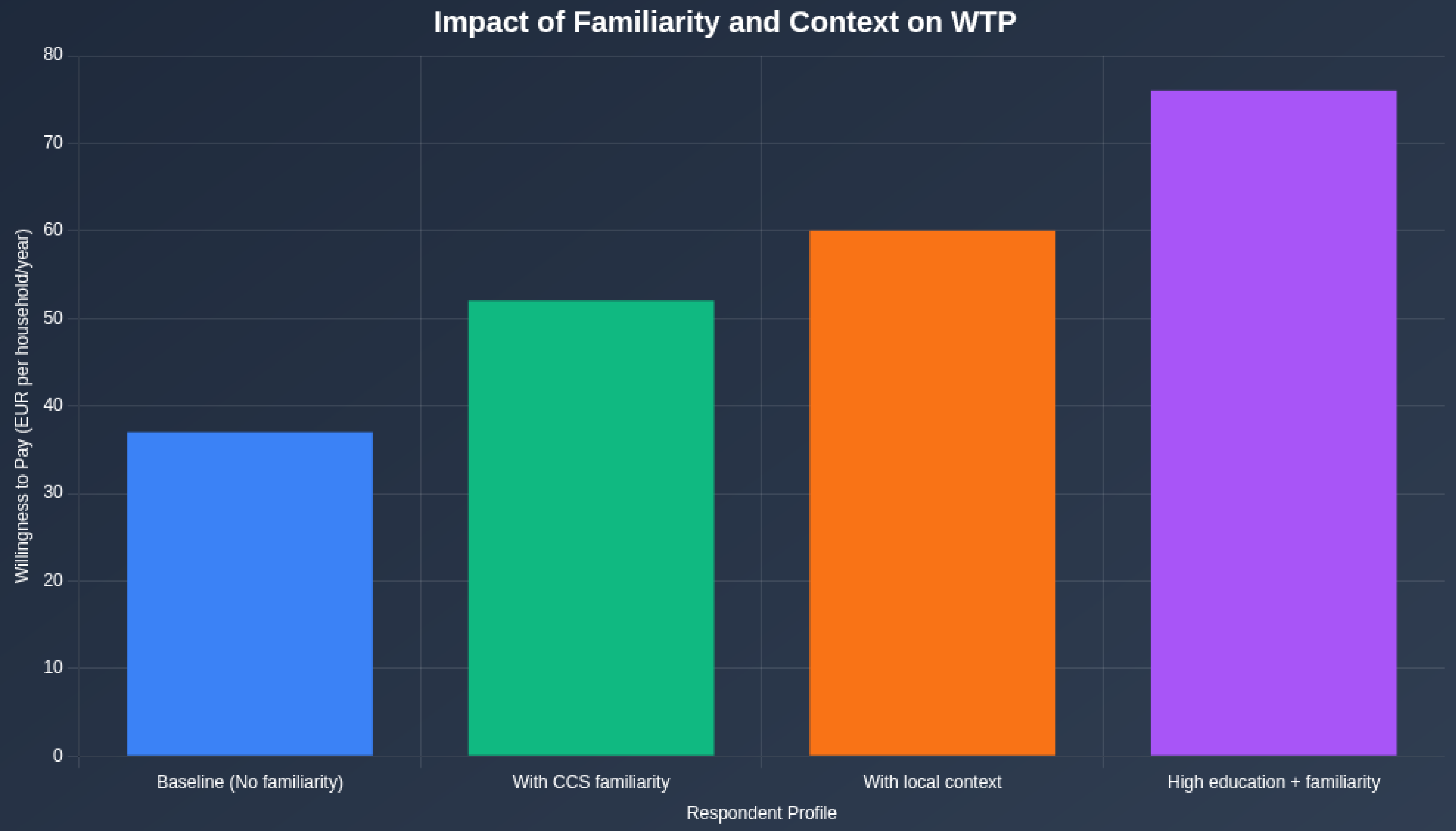
3,390 respondents | Comprehensive EU study

Willingness to Pay (WTP)
20-37 EUR per household/year
per ton CO_2 mitigated

Familiarity Premium
11-16 EUR higher WTP
Prior CCS knowledge boosts support

Information Effects
+8 EUR WTP with local context
Danish-specific info enhances support

Socio-Demographic Patterns
Support increases with age, education, and urban location.



With CCS familiarity
+41% vs baseline

High education + familiarity
+105% vs baseline

Key Implication: Education and awareness campaigns can significantly boost public acceptance of CCS projects.

Public Sentiment: North American Context

Analysis based on related climate surveys and social media sentiment

Data Limitation: No recent, comprehensive CCS-specific polling exists for the US or Canada. Analysis is based on indirect indicators.

United States

Mixed: Region & Interest-Dependent

Positive Indicators

- Bipartisan support for ecosystem-based carbon solutions.
- Support in industrial regions, citing economic benefits.

Negative Indicators

- Skepticism about extending fossil fuel viability.
- Concerns over cost-effectiveness vs. renewables.

Key Dividing Line
Support is higher when framed economically and for hard-to-abate sectors like cement or steel.

Canada

Supportive but Skeptical of Implementation

Positive Indicators

- Strong support for climate solutions with job creation.
- Recognition of CCS for hard-to-abate industries.

Negative Indicators

- Criticism of subsidies for oil & gas industry.
- Concerns about costs vs. renewable alternatives.

Key Concern
Public fears that CCS investment is "greenwashing" or a subsidy for continued oil production.

Support varies by application; industrial uses are more accepted than power generation.

Community Acceptance: Factors & Recommendations

Critical enablers for CCS project success

Awareness & Knowledge

Challenge
Low public familiarity and misconceptions amplify perceived risks.

Opportunity
Balanced education from trusted sources increases acceptance.

Recommendation
Invest in targeted education using trusted local messengers.

Risks & Benefits

Primary Concerns
- CO_2 leakage & contamination
- Induced seismicity

Undervalued Benefits
- Job creation & economic development
- Climate mitigation

Recommendation
Transparent risk assessment and highlight tangible local benefits.

Trust in Stakeholders

Trust Builders
- Government credibility & independent validation
- Transparent communication

Trust Barriers
- Industry skepticism & perceived greenwashing

Recommendation
Multi-stakeholder governance with independent oversight.

Engagement & Participation

Success Factor
Early, substantive engagement before project announcement.

Effective Approaches
- Community advisory boards & benefit-sharing
- Meaningful participation in decisions

Recommendation
Begin dialogue pre-announcement; establish community benefit funds.

NIMBY Mitigation

Challenge
Global benefits vs. local costs; proximity increases opposition.

Solutions
- Offshore storage is more acceptable
- Compensation and benefit-sharing

Recommendation
Prioritize offshore when feasible with robust compensation frameworks.

Framing & Communication

Effective Framing
- 'Waste reuse' over 'storage'
- Complementary role to renewables

Ineffective Framing
- Techno-fix narrative; enabling fossil fuels

Recommendation
Emphasize industrial necessity and integration with renewables.

Evidence from Sleipner (Norway) & Quest (Canada): offshore sites, transparency, economic benefits, and early engagement are key.

Energy Penalties & Efficiency Impacts

Analyzing the parasitic load of capture technologies

Capture Technology Penalties

Post-Combustion Capture

10-15% reduction

- High energy for solvent regeneration
- Solvent degradation & corrosion

Pre-Combustion Capture

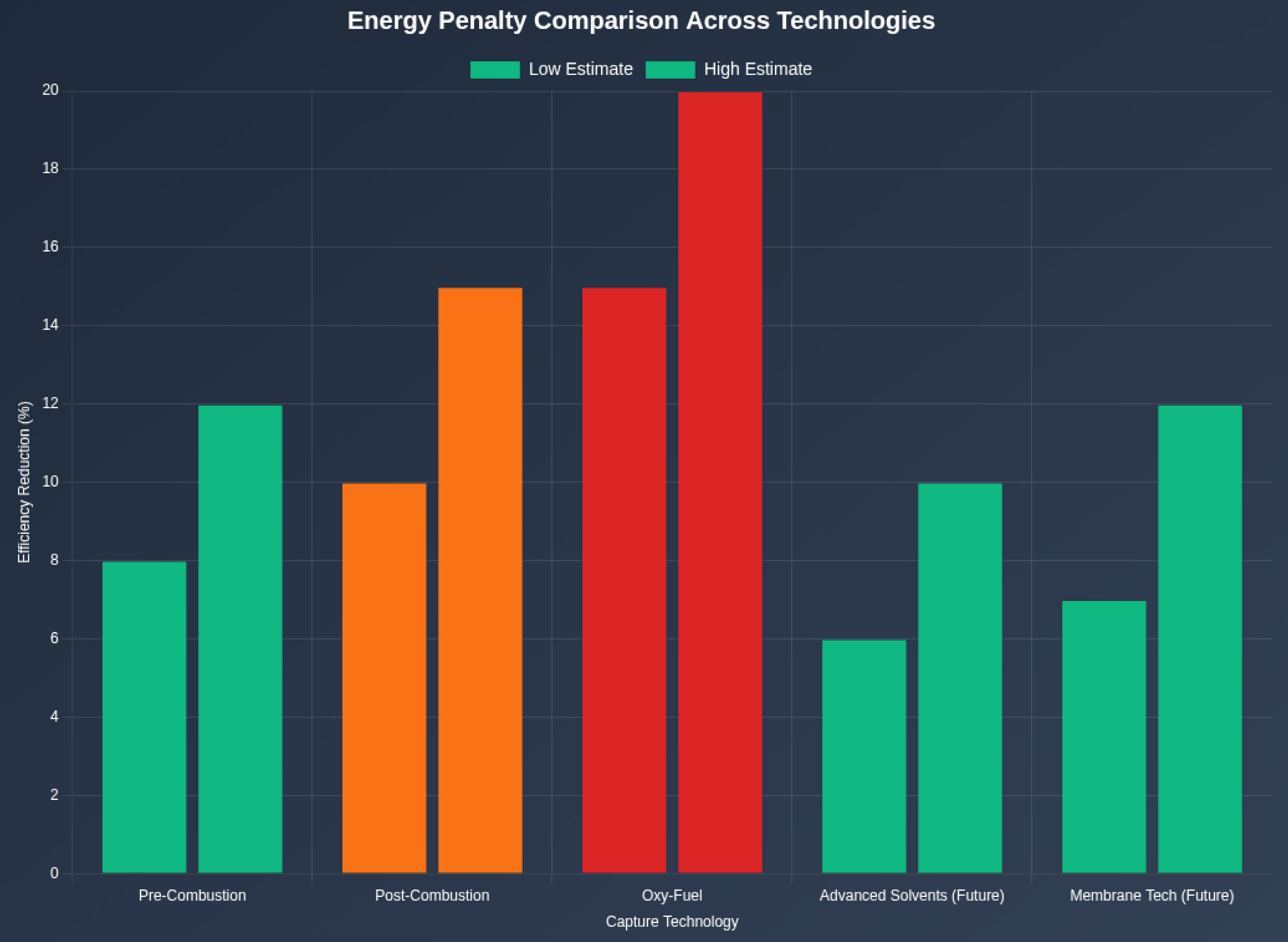
8-12% reduction

- Higher capital costs
- Limited to new facilities

Oxy-Fuel Combustion

15-20% reduction

- Energy-intensive oxygen production
- High temperature materials required



Economic viability hinges on balancing capture rates (90-95%) with the steep rise in energy penalty above that threshold.

Transportation & Proximity Challenges

Navigating Source-Sink Mismatches and Infrastructure Needs

CO_2 Transportation Economics

Primary Method: Pipeline (8,000+ km in US, mainly for EOR)

Short <100km, Large >5Mtpa
$4-10/ton
Economical

Mid 100-300km, Mid 1-5Mtpa
$10-25/ton
Viable with support

Long >300km, Small <1Mtpa
$25-45/ton
Marginal

The Proximity Problem

CO_2 sources are often far from suitable geological storage sites.

Regional Mismatches

- **Europe**: North Sea storage is distant from industrial centers.
- **US Midwest**: Emissions sources are far from storage, with pipeline hurdles.
- **Canada**: Oil sands are distant from the best storage locations.

Impacts

- Transport can be 10-20% of total CCS cost.
- Complex cross-jurisdiction pipeline projects.
- Many high-emitting facilities lack nearby storage.

Optimization Strategies

Hub and Cluster Model
Concentrate sources near shared storage (e.g., UK East Coast Cluster).

Source-Sink Matching
Use GIS analysis to optimize pipeline routes and minimize system costs.

Storage Site Prioritization
Develop storage sites near emission sources, balancing quality and proximity.

Emerging Solution
Cross-border projects (e.g., Northern Lights) create shared networks.

Infrastructure Gap: Point-to-point systems are costly; hub networks face coordination challenges.

Geological Storage: Challenges & Risk Management

Site selection, containment risks, and monitoring requirements

Site Selection

Saline Aquifers

Largest global potential

Pros: Widely distributed. Cons: Less characterized, pressure management is critical.

Depleted Oil/Gas Fields

Moderate capacity

Pros: Well-known geology, existing infrastructure. Cons: Limited availability, well integrity risks.

Key Site Requirements

- Depth >800m for supercritical CO_2
- High porosity (>10%) and permeability
- Secure, low-permeability caprock seal
- No major faults for structural integrity

Containment Risks

Leakage Pathways

- Caprock breaches or induced fractures
- Poorly sealed abandoned wells
- Fault reactivation from pressure changes

Retention Rates & Consequences

Well-managed sites can achieve >99% retention. Leaks risk groundwater contamination and negate climate benefits.

Induced Seismicity

Generally low magnitude, but pressure changes can reactivate dormant faults. Requires careful site-specific analysis.

Long-Term Challenge

Containment must be ensured for millennia, requiring robust, long-term monitoring strategies.

Monitoring (MMV)

Monitoring Phases

Pre-Injection: Establish baseline geology & groundwater quality.

During Injection: Track CO_2 plume and monitor pressure/seismicity.

Post-Injection: Long-term plume stability and surface monitoring.

Key Technologies

- 4D seismic imaging (time-lapse)
- Downhole pressure and temperature sensors
- Satellite-based surface deformation monitoring

MMV Challenges

- Quantifying stored CO_2 with high accuracy
- High cost (can be 10-20% of project total)
- Potentially indefinite monitoring duration

Storage is feasible with rigorous site selection and monitoring, but MMV represents a significant long-term cost and technical challenge.

Investment Outlook & Strategic Conclusions

Capital allocation recommendations for CCS in a net-zero pathway

Market Momentum

- 4x capacity growth projected by 2030.
- Strong policy support (US IRA, EU Fund).
- 600+ projects in pipeline, led by North America.

Near-term growth trajectory is strong, backed by policy.

Economic Reality

- CCS costs ($50-150/t) exceed renewables.
- Significant energy penalty (10-20%) persists.
- Most abatement is cheaper without CCS.

Economically viable only for hard-to-abate industrial sectors.

Critical Barriers

- High historical project failure rate.
- Massive CO_2 transport infrastructure gap.
- Public acceptance and scaling challenges remain.

High execution risks require technical and social solutions.

Capital Allocation Recommendations

Invest selectively in industrial CCS, while maintaining a portfolio balanced towards renewables and efficiency.

P1: Industrial CCS (10-15%)
Target cement, steel, chemicals. Rationale: Few alternatives, strong policy.

P2: Blue Hydrogen w/CCS (5-10%)
Target hydrogen hubs. Rationale: Complements green H_2, regional advantages.

P3: CCS Infrastructure (5%)
Target CO_2 pipelines, storage. Rationale: Enables scale, long-term value.

Emerging: Direct Air Capture (2-5%)
Target DAC tech. Rationale: Essential for net-zero, high policy support.

Portfolio Context

- 50-60% Renewables (lowest cost)
- 15-20% Energy Efficiency (low cost)
- 10-20% Industrial Decarbonization (incl. CCS)

Key Success Factors

- Policy continuity and robust project selection
- Focus on North America for best risk/reward
- Strong public and community engagement

Risk Mitigation
Diversify technologies; prioritize projects with offtake agreements.