Rhodium Group

Capturing New Business

The market opportunities associated with scale-up of Direct Air Capture (DAC) technology in the US

PREPARED FOR THE LINDEN TRUST FOR CONSERVATION | JUNE 23, 2020

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About this analysis

The Linden Trust for Conservation commissioned Rhodium Group to assess and quantify the business opportunities associated with the scale-up of Direct Air Capture technology in the US. The research was performed independently. The results presented in this report reflect the views of the authors, unswayed by those of the Linden Trust.

About Rhodium Group

Rhodium Group is an independent research provider combining economic data and policy insight to analyze global trends. Rhodium's Energy & Climate team analyzes the market impact of energy and climate policy and the economic risks of global climate change. This interdisciplinary group of policy experts, economic analysts, energy modelers, data engineers, and climate scientists supports decision-makers in the public, financial services, corporate, philanthropic and non-profit sectors. More information is available at www.rhg.com.

John Larsen is a Director at Rhodium Group and leads the firm's US power sector and energy systems research. John specializes in analysis of national and state clean energy policy and market trends. Previously, John worked for the US Department of Energy's Office of Energy Policy and Systems Analysis where he served as an electric power policy advisor.

Whitney Herndon is a Senior Analyst at Rhodium Group focusing on US energy markets and policy. She employs a range of energy and economic models to analyze the impact of policy proposals on the US electricity sector, energy market, and macroeconomy.

Galen Hiltbrand is a Research Analyst at Rhodium Group focusing on US energy policy and carbon management. She uses quantitative tools to assess the role that carbon capture and carbon removal technologies can play in decarbonizing the US energy system.

Goal and components of this analysis

Goal: Quantify the new market opportunities for producers of materials and services associated with the scale-up of Direct Air Capture deployment in the US.

Contents:

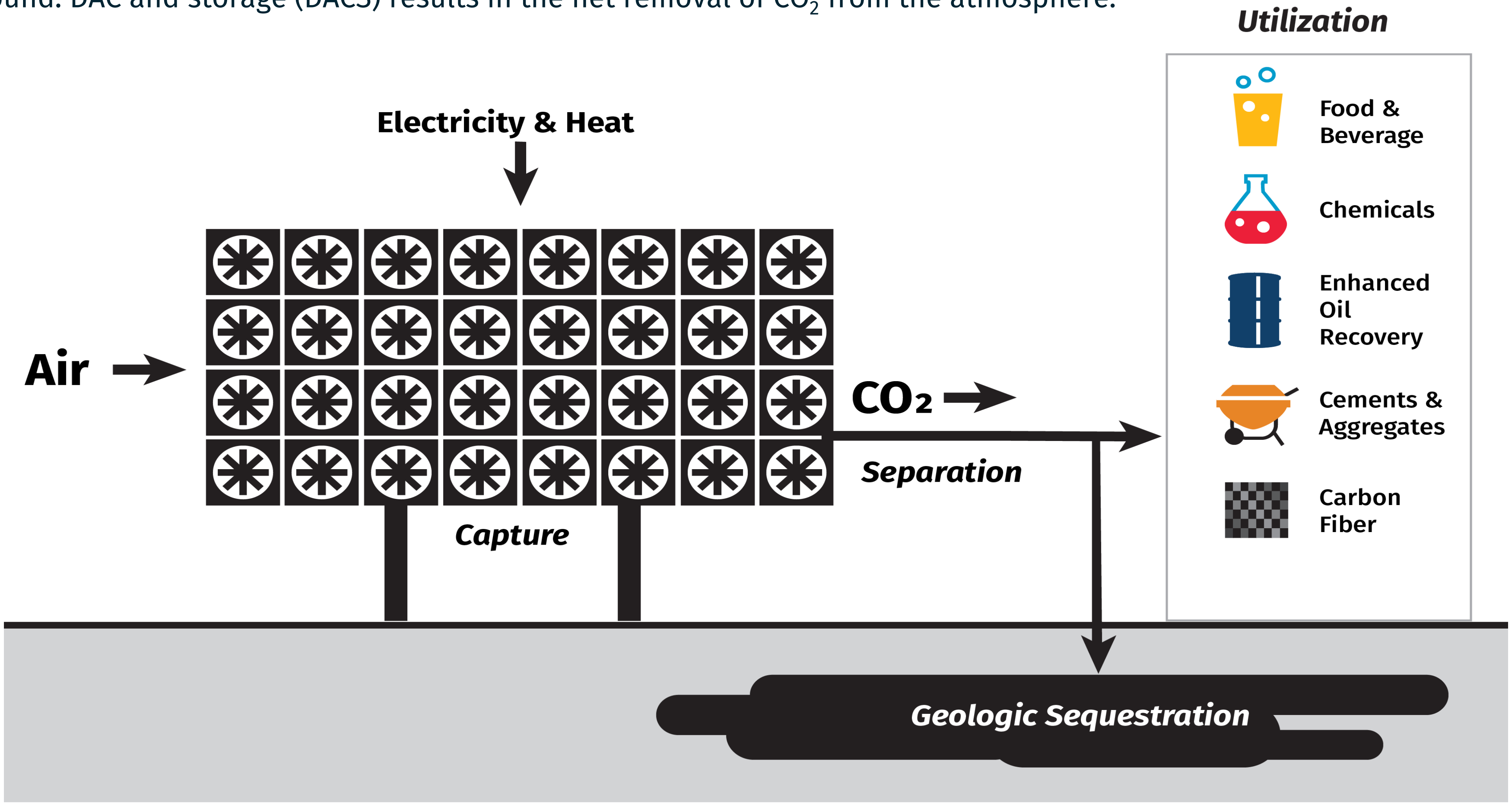
1. An introduction to Direct Air Capture technology
2. Methodology to estimate DAC business opportunities
3. Business opportunity estimates
    - Comparison of current demand for materials and services in relevant sectors to projected demand from direct air capture scale-up by midcentury
    - Identify leading companies in each sector
    - Relevant sectors assessed in this analysis:
        - Equipment
        - Cement
        - Steel
        - Chemicals
        - Electricity
        - Fuel
4. Key takeaways
5. Technical appendix

SECTION 1

An Introduction to Direct Air Capture

Direct Air Capture (DAC) technology

DAC uses electricity and heat to filter carbon dioxide (CO_2) from the ambient air for utilization or for permanent storage deep underground. DAC and storage (DACS) results in the net removal of CO_2 from the atmosphere.

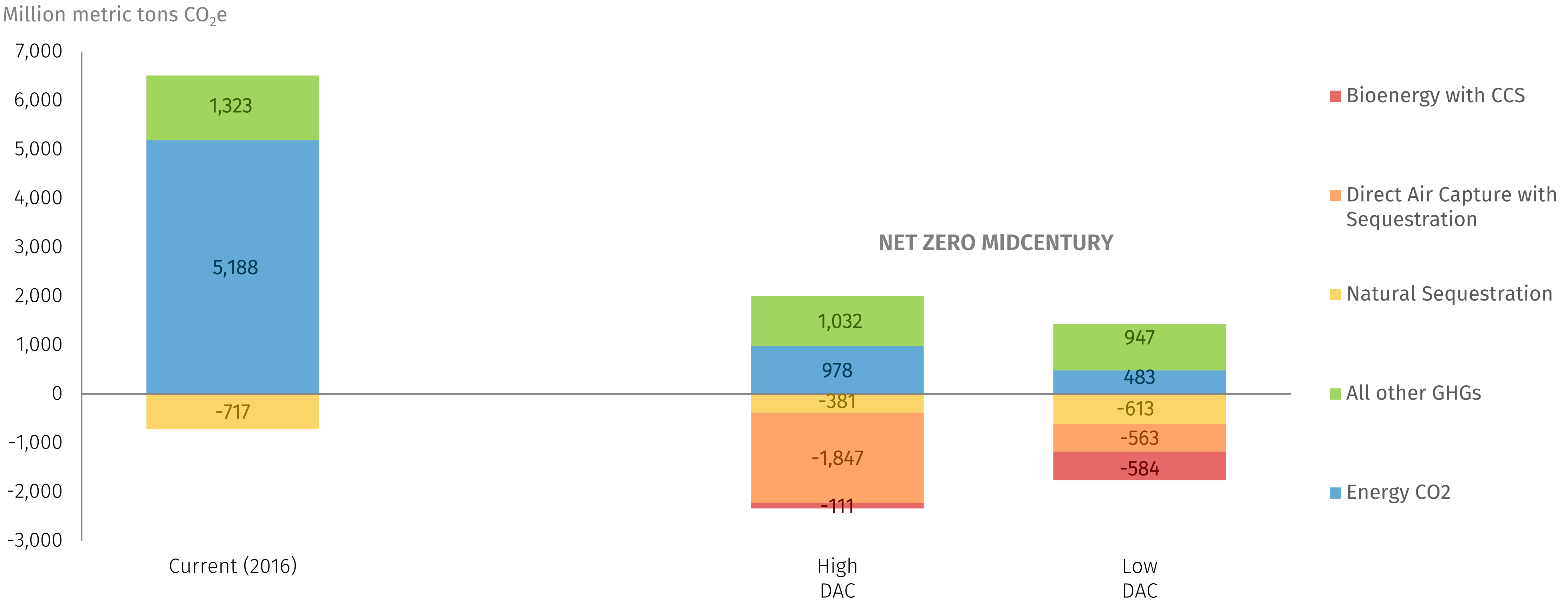


Source: Rhodium Group adapted from World Resources Institute

DAC is key to meeting climate targets

Previous Rhodium research found that DACS is an essential part of any US approach to reaching net-zero greenhouse gas (GHG) emissions by midcentury, a 6 billion metric ton reduction compared to current levels. Decarbonization efforts including electrification, energy efficiency, synthetic fuels, and other types of carbon removal are all required. Even with rapid scale-up of each strategy, 563 million tons of CO_2 will need to be removed from the atmosphere using DACS (Low DAC scenario) to meet a net-zero target. If other decarbonization options are slower to deploy, up to 1,847 million tons CO_2 removal using DACS will be needed (High DAC scenario).

US greenhouse gas emissions, current and 2050



Source: Rhodium Group and Evolved Energy Research analysis. Note: See Capturing Leadership for more information. 2050 results shown represent achieving net-zero GHG emissions by 2045 and negative emissions in 2050. DACS removal values are smaller than capacity values reported later in this presentation due to lower than 100% utilization.

DAC is a proven technology

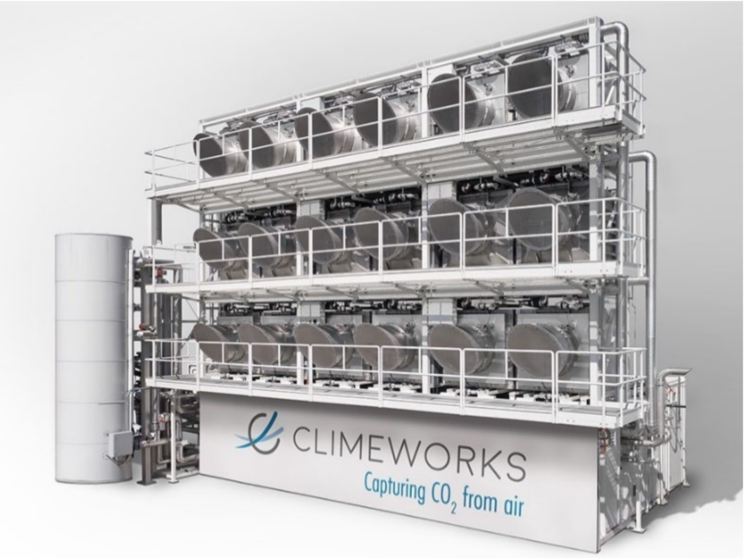
DAC has attracted hundreds of millions of dollars in private and public investment. There are three commercial companies with 11 pilot projects deployed across the world. One company, Carbon Engineering, plans to break ground on a megaton scale facility soon. Rhodium estimates that the first megaton scale DAC plant will have a levelized cost of $124-$325/metric ton of captured carbon with the range reflecting technology diversity and energy cost uncertainty. Costs are estimated to decline substantially with deployment.

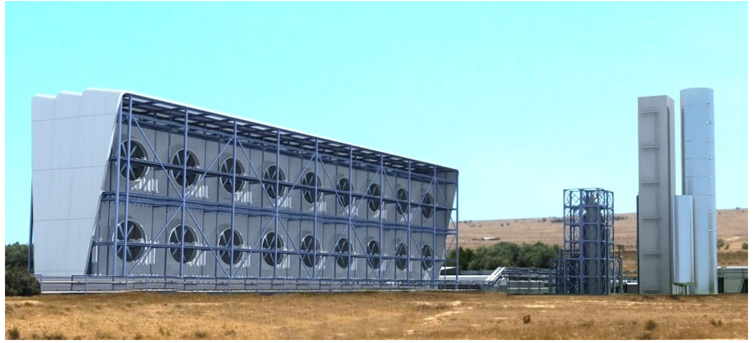
DAC companies with commercial technology

CLIMEWORKS

Carbon Engineering

Global Thermostat





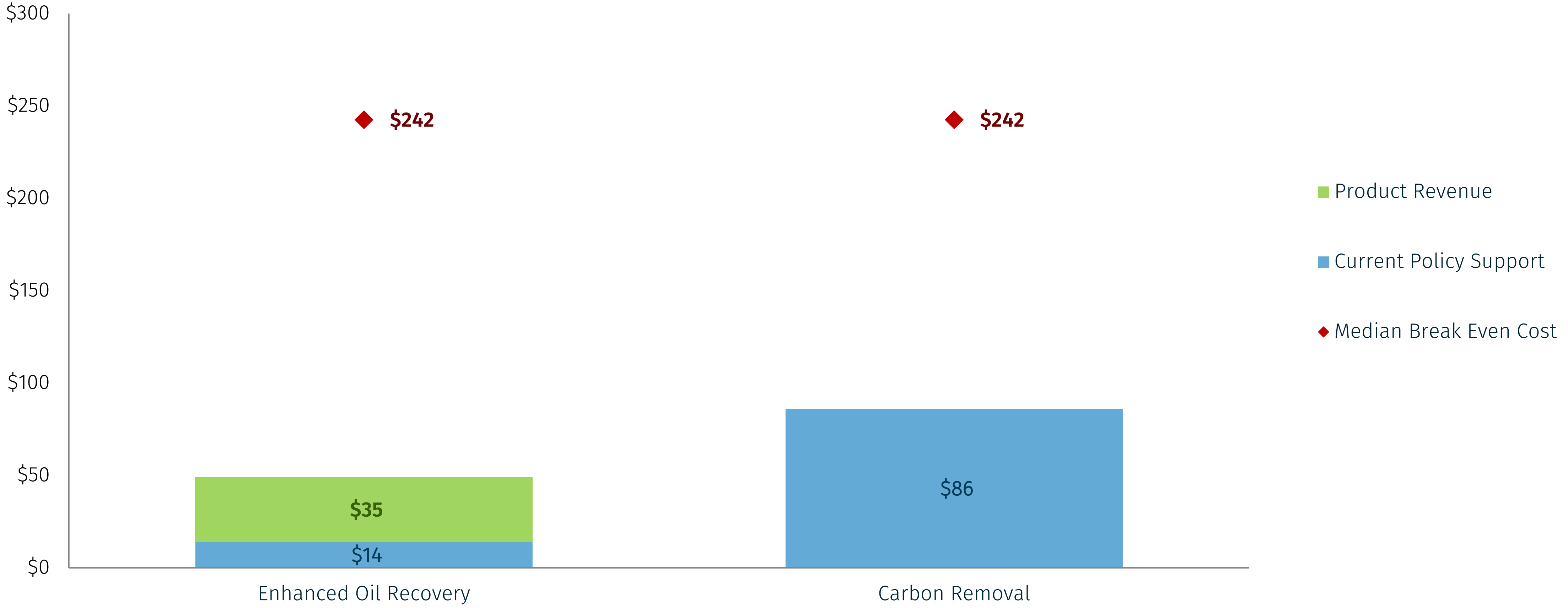
Source: Climeworks, Carbon Engineering

Federal action is needed for DAC scale-up

DAC has existing policy support from California's Low Carbon Fuel Standard (LCFS) and the federal 45Q tax credit. However, to overcome the current median costs of $242/ton, more federal policy support is needed for widespread DAC deployment. See Rhodium's Capturing Leadership for more on policy options for large-scale DAC deployment.

DAC costs exceed current revenue opportunities

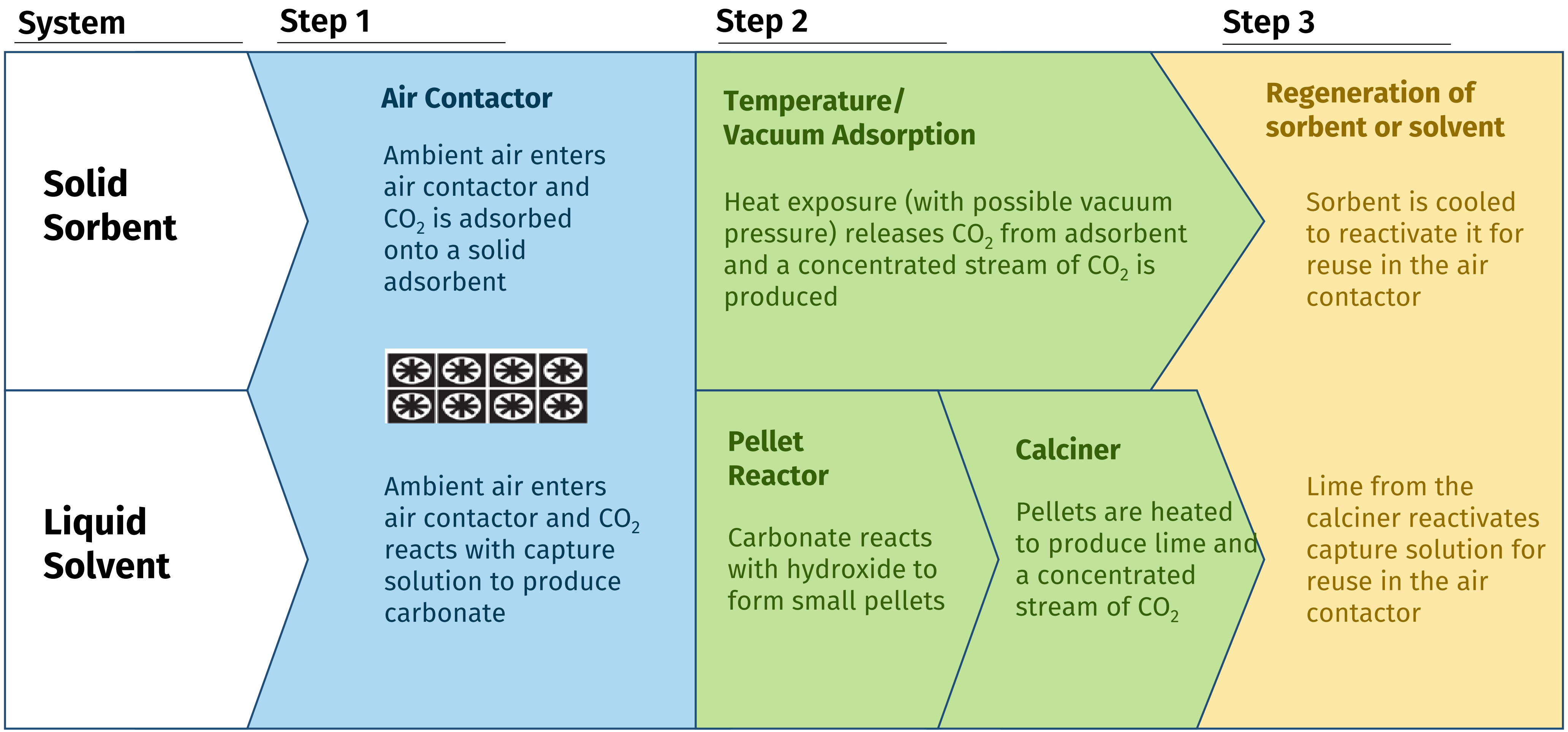
30-year levelized USD (2018 dollars) per metric ton CO_2



Source: Rhodium Group analysis. Note: all values reflect median DAC costs. See Capturing Leadership for more information.

Two main approaches to DAC

There are two main processes for commercial DAC technology. One uses a chemical solid sorbent to capture CO_2 and the other uses a liquid solvent. Each approach has different construction requirements and different costs and performance profiles. There is no clear front-runner technology. This analysis considers both approaches.



Source: Energy Futures Initiative. Process simplified.

DAC plants require a range of inputs

Like any industrial facility, DAC plants require steel, cement, energy and other inputs for construction and operation. The goal of this analysis is to quantify the business opportunities associated with DAC scale-up across a variety of key inputs identified below.

Construction/Capital

Equipment
- Non-standard Equipment
- Adsorbent Equipment
- Common Equipment

Materials
- Cement
- Steel

Chemicals
- Liquid Solvent - Potassium Hydroxide and Calcium Carbonate

Labor
- Not assessed in this analysis

Financing
- Not assessed in this analysis

Energy Requirements

Electricity

Heat
- Natural Gas
- Electric Heat

Operations and Maintenance

Chemicals
- Adsorbent
- Liquid Solvent - Potassium Hydroxide and Calcium Carbonate

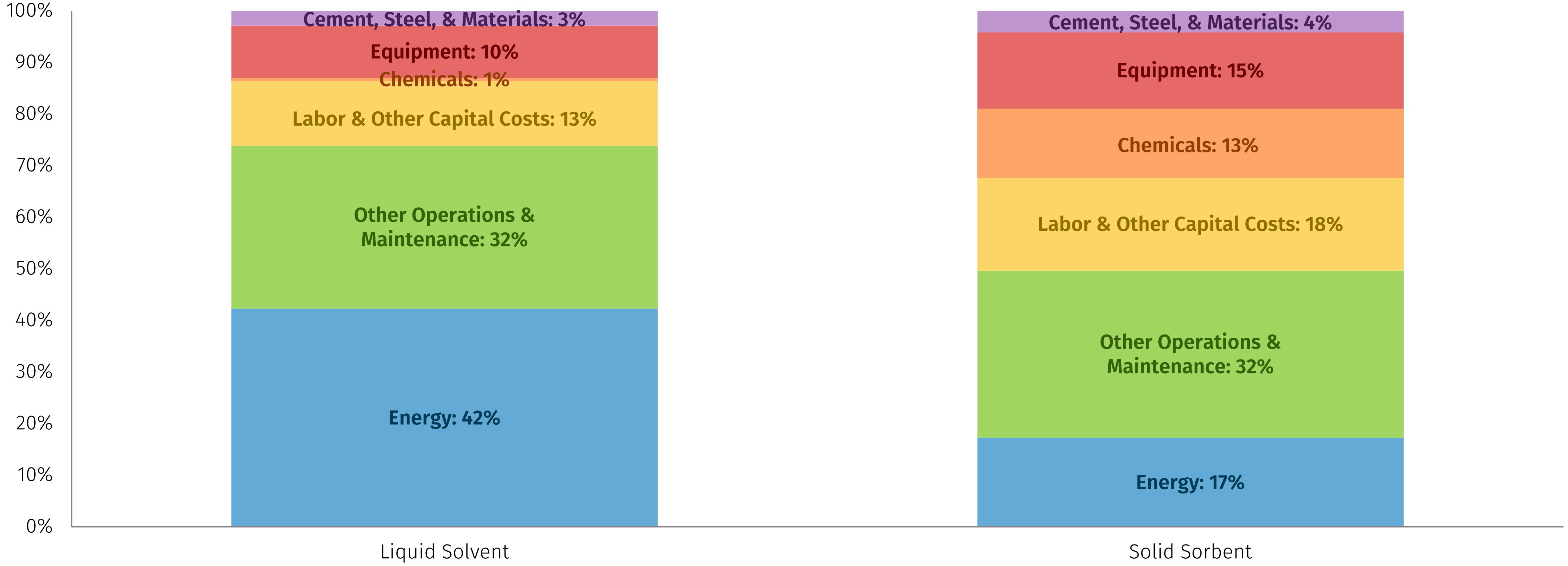
Labor
- Not assessed in this analysis

DAC technology cost comparison

Liquid solvent technology costs are concentrated in energy expenses and operations and maintenance (O&M). The solid sorbent technology is less energy dependent and costs are relatively more distributed with significantly higher chemical costs. Depending on the market share each technology secures during scale-up, specific business opportunities for supplier firms may differ. The capital investment associated with a typical DAC plant ranges from $665 million to $1.8 billion depending on the technology.

Percentage of total levelized cost of DAC

Excludes financing



Source: Rhodium Group analysis. Note: Typical DAC plant investment values do not include financing costs.

SECTION 2

Methodology to Estimate DAC Business Opportunities

Methodology and assumptions

In this analysis, we focus on the largest business opportunities associated with DAC scale-up. We rely on a range of data sources and previous Rhodium research to estimate the value of these opportunities.

Focus sectors

- Equipment
- Cement
- Steel
- Chemicals
- Electricity
- Fuel

DAC scale

A range of DAC deployment is quantified through 2050 associated with meeting a midcentury net-zero, economy-wide emissions target for the US*

Technology

- Both Solid Sorbent and Liquid Solvent technologies
- Projections assume the market is supplied by 50% Solid Sorbent and 50% Liquid Solvent
- Today's technology and cost are used

Construction and inputs

- Each plant is assumed to have the capacity of 1MMt/year
- Median operating and cost parameters
- Heat and electric requirements are assumed to be supplied by 100% electricity in Solid Sorbent plants and 100% natural gas in Liquid Solvent plants

Company selection

- Where available we list current suppliers to today's DAC technology
- Combining available data and analyst judgement we select the relevant major companies

Data sources

- Energy Information Administration
- Bureau of Economic Analysis
- National Academy of Sciences
- Keith et al. 2018
- American Institute of Steel Construction
- Portland Cement Association
- US Geological Survey
- ClearPath
- Natural Gas Supply Association
- Fortune 500

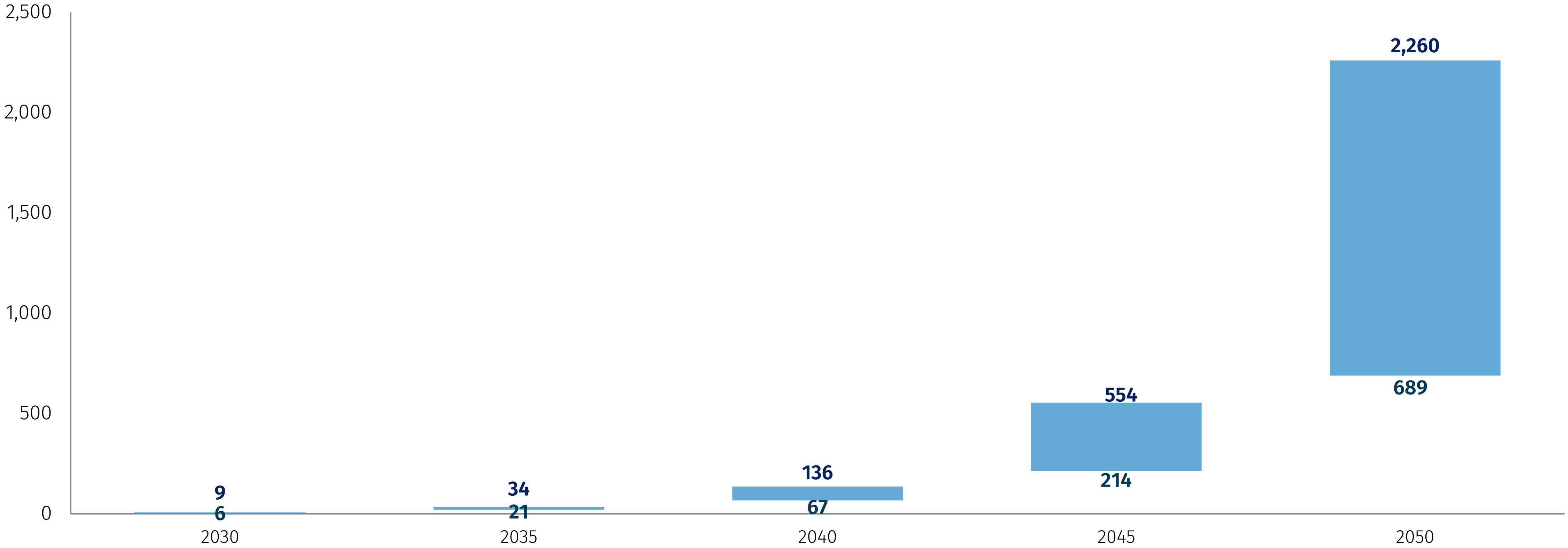
*See Capturing Leadership for more information.

Pathways to net-zero emissions by mid-century

Our previous research found that 689 to 2,260 million tons of capture capacity is necessary to achieve net-zero emissions by mid-century. We use this range for the level of DAC scale-up in this analysis. We assume a 50/50 split between liquid solvent and solid sorbent technologies. This rapid scale-up will only occur with ambitious federal policy action both in the near and long-term. Business opportunities may be larger, and more near-term if policy action is quicker and more robust than this analysis assumes.

Range of DAC deployment in the US

Million metric tons/year capture capacity



Source: Rhodium Group analysis. Note: See Capturing Leadership for more information. Note: Capacity values shown here are larger than the carbon removal values shown earlier in the presentation due to less than 100% utilization. The emissions associated with materials used to construct DAC capacity are not considered in this analysis but will need to be addressed if the US Is to achieve net-zero emissions by midcentury.

SECTION 3

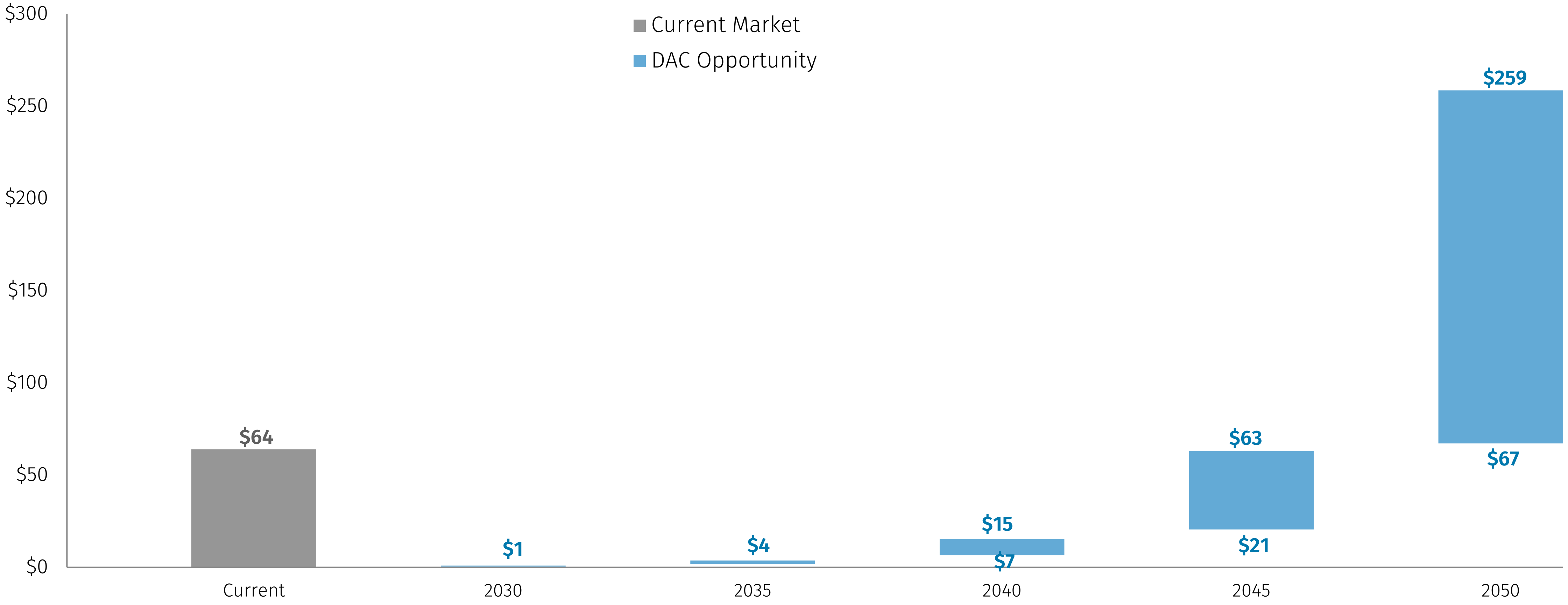
Business Opportunity Estimates

Business opportunity: Equipment

By mid-century, DAC equipment demand can exceed the existing US market for relevant equipment, which includes air contactor equipment, turbines, pumping equipment, industrial process furnaces, and other general purpose machinery.

Annual US equipment market

USD Billion (2018 dollars)



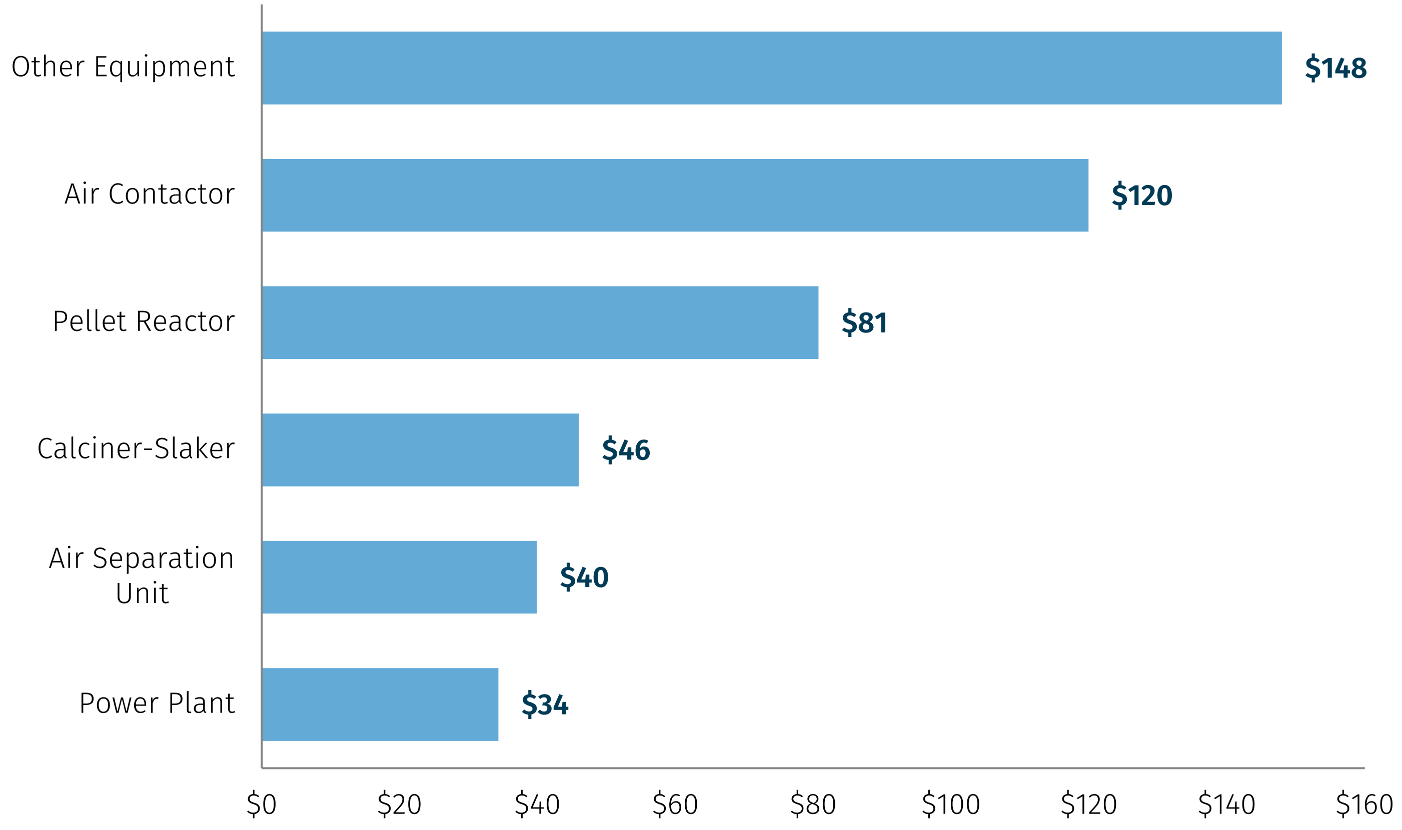
Source: BEA, Keith et al. 2018, Rhodium Group analysis.

Equipment costs breakdown: Liquid solvent

Equipment demand and leading manufacturers differ depending on DAC technology. For the liquid solvent technology, the most expensive piece of equipment is the air contactor. Other equipment includes CO_2 compressors, steam turbines, fines filters, and other general equipment.

Equipment costs per liquid solvent plant

USD Million (2018 dollars)



Source: Keith et al. 2018, NAS, Rhodium Group analysis.

Leading US Manufacturers:

Air Contactors
- SPX Cooling Technologies
- Brentwood Industries

Pellet Reactors
- Royal HaskoningDHV
- Procorp Enterprises

Calciner-Slakers
- Technip FMC

Air Separation Units
- Air Liquide

Power Plants
- General Electric

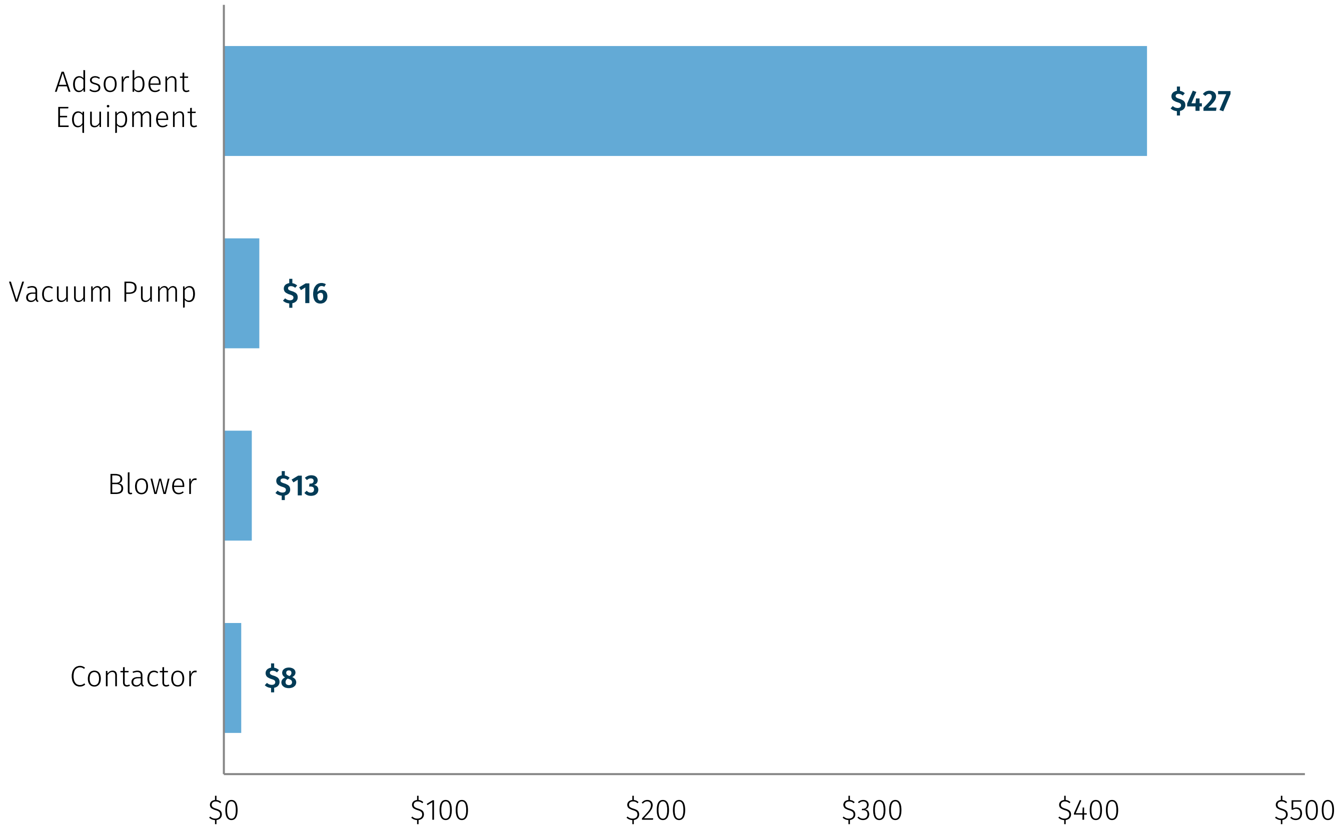
Source: Keith et al. 2018, Fortune 500, Rhodium Group analysis

Equipment costs breakdown: Solid sorbent

Equipment demand and leading manufacturers differ depending on DAC technology. The most expensive equipment for solid sorbent technology is the adsorbent.

Equipment costs per solid sorbent plant

USD Million (2018 dollars)



Source: Keith et al. 2018, Rhodium Group analysis.

Leading US Manufacturers:

Adsorbent Equipment
- Mosaic Materials
- Svante

Vacuum Pumps
- Sulzer
- SPX Flow

Blowers
- National Turbine Corporation
- Continental Blower

Contactors
- SPX Cooling Technologies
- Brentwood Industries

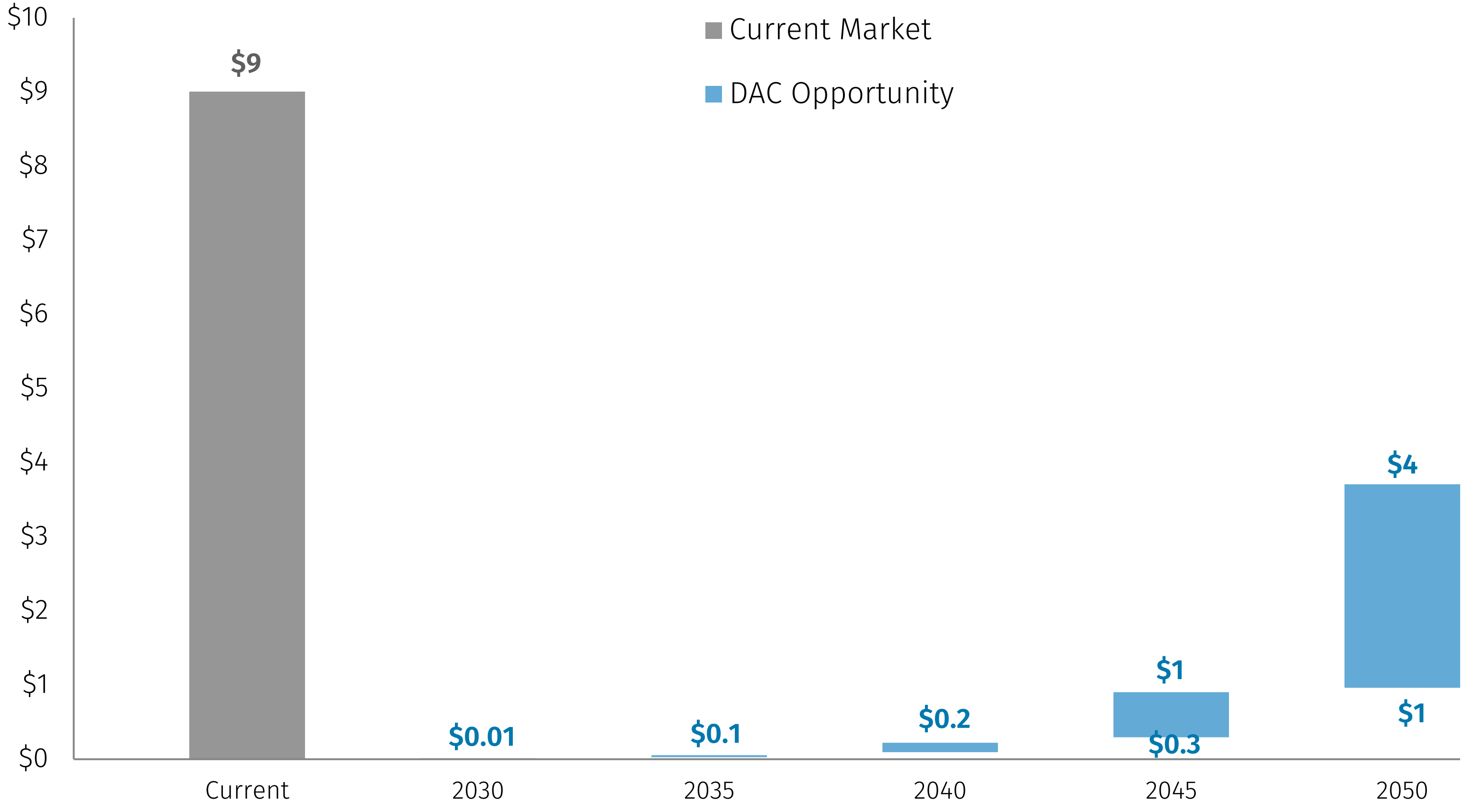
Source: Keith et al. 2018, NAS, Fortune 500, Rhodium Group analysis

Business opportunity: Cement

DAC demand for cement can be an important growth opportunity for manufacturers. Roughly equal to 10-40% of current demand in 2050. Estimates shown here do not include additional business opportunities that are likely to arise for cement associated with the build out of additional natural gas and renewable energy to power DAC plants.

Annual US cement demand

USD Billion (2018 dollars)



Source: BEA, AISC, Keith et al. 2018, Rhodium Group analysis

Top US Cement Producers:

- LafargeHolcim
- CEMEX
- Lehigh Hanson (HeidelbergCement)
- Buzzi Unicem
- CRH
- CalPortland Company
- Argos USA
- Ash Grove Cement
- Eagle Materials

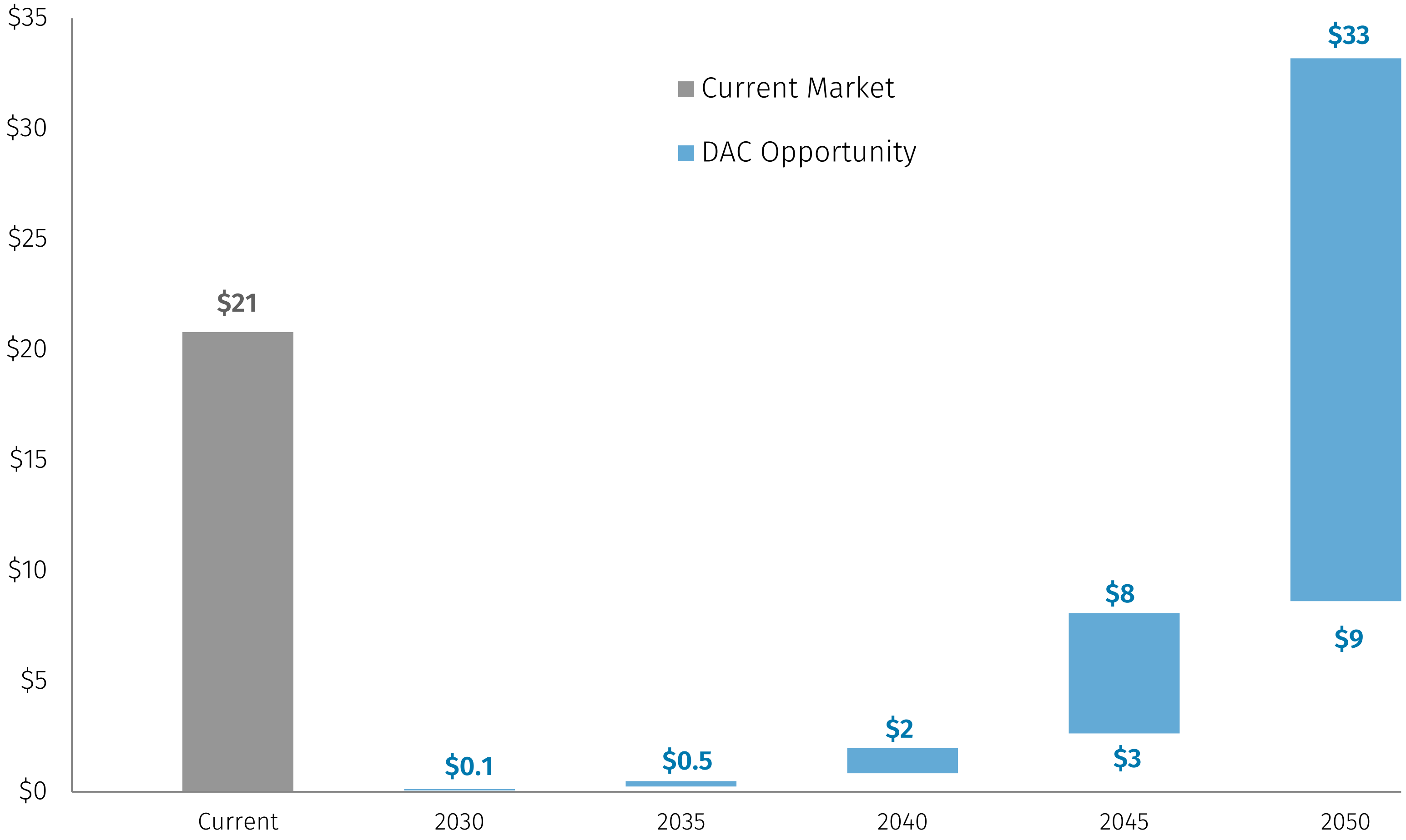
Source: PCA, USGS

Business opportunity: Steel

DAC can increase steel demand far beyond its current markets. These estimates do not include additional market opportunities for steel that could benefit from DAC scale up including natural gas production and renewable energy.

Annual US steel demand

USD Billion (2018 dollars)



Source: BEA, AISC, Keith et al. 2018, Rhodium Group analysis

Top US Steel Producers and Fabricators:

- Nucor
- US Steel
- Steel Dynamics
- Reliance Steel & Aluminum Co.
- AK Steel Holding
- Commercial Metals
- Bayou Steel
- Gerdau
- SSAB
- Arcelor-Mittal

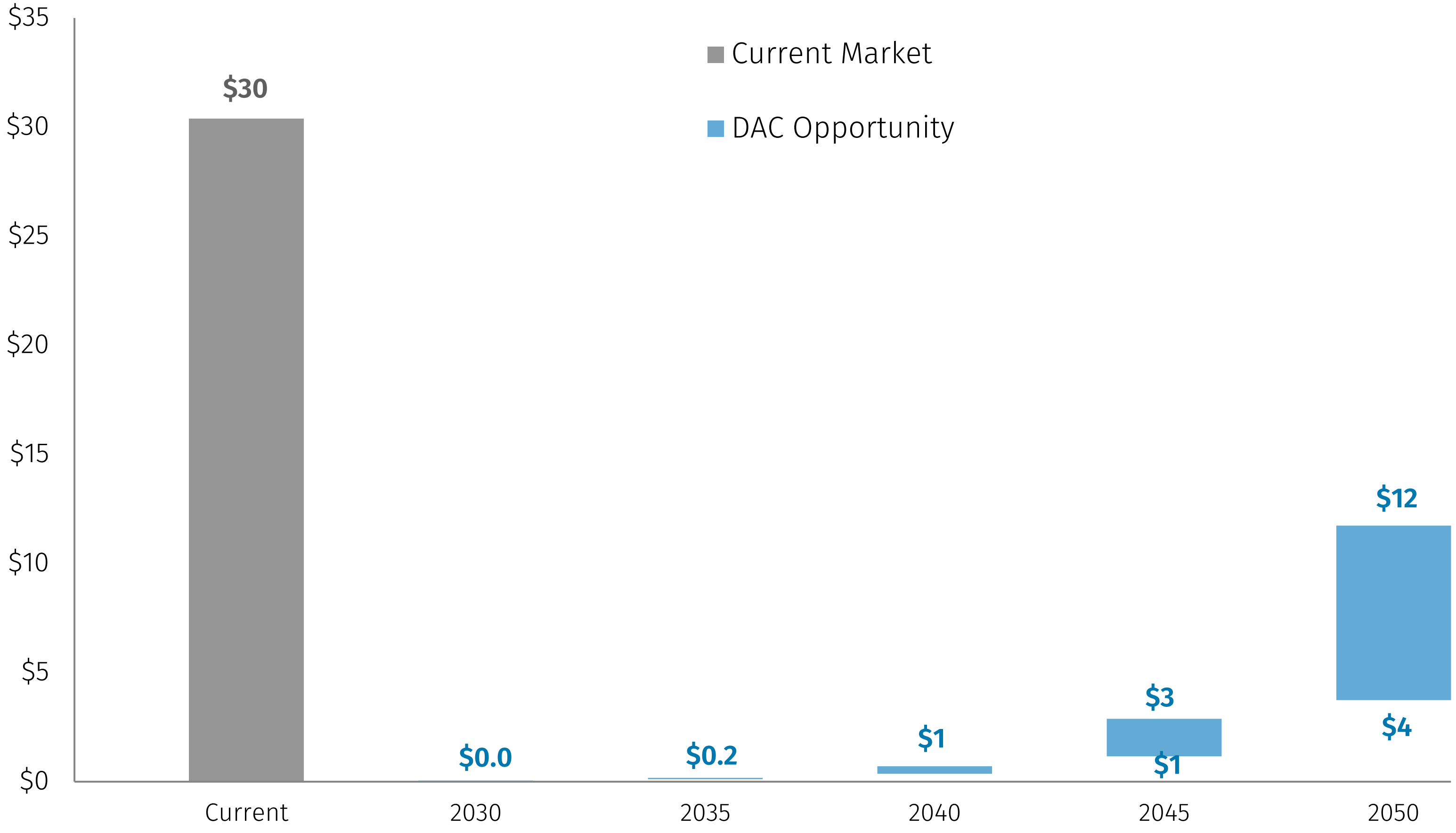
Source: Fortune 500, AISC

Business opportunity: Chemicals

DAC demand for chemicals could be up to one-third of the current basic inorganic chemical market. Liquid solvent relies on potassium hydroxide and calcium carbonate, while solid sorbent relies on specialized adsorbents.

Annual US inorganic chemical demand

USD Billion (2018 dollars)



Source: BEA, NAS, Rhodium Group analysis

Top US Solvent Manufacturers:

- DowDupont
- Huntsman
- Eastman Chemical
- LyondellBasell
- BASF
- Occidental Petroleum
- Olin Corporation
- The Chemours Company

Top US Sorbent Manufacturers:

- Mosaic Materials
- Svante

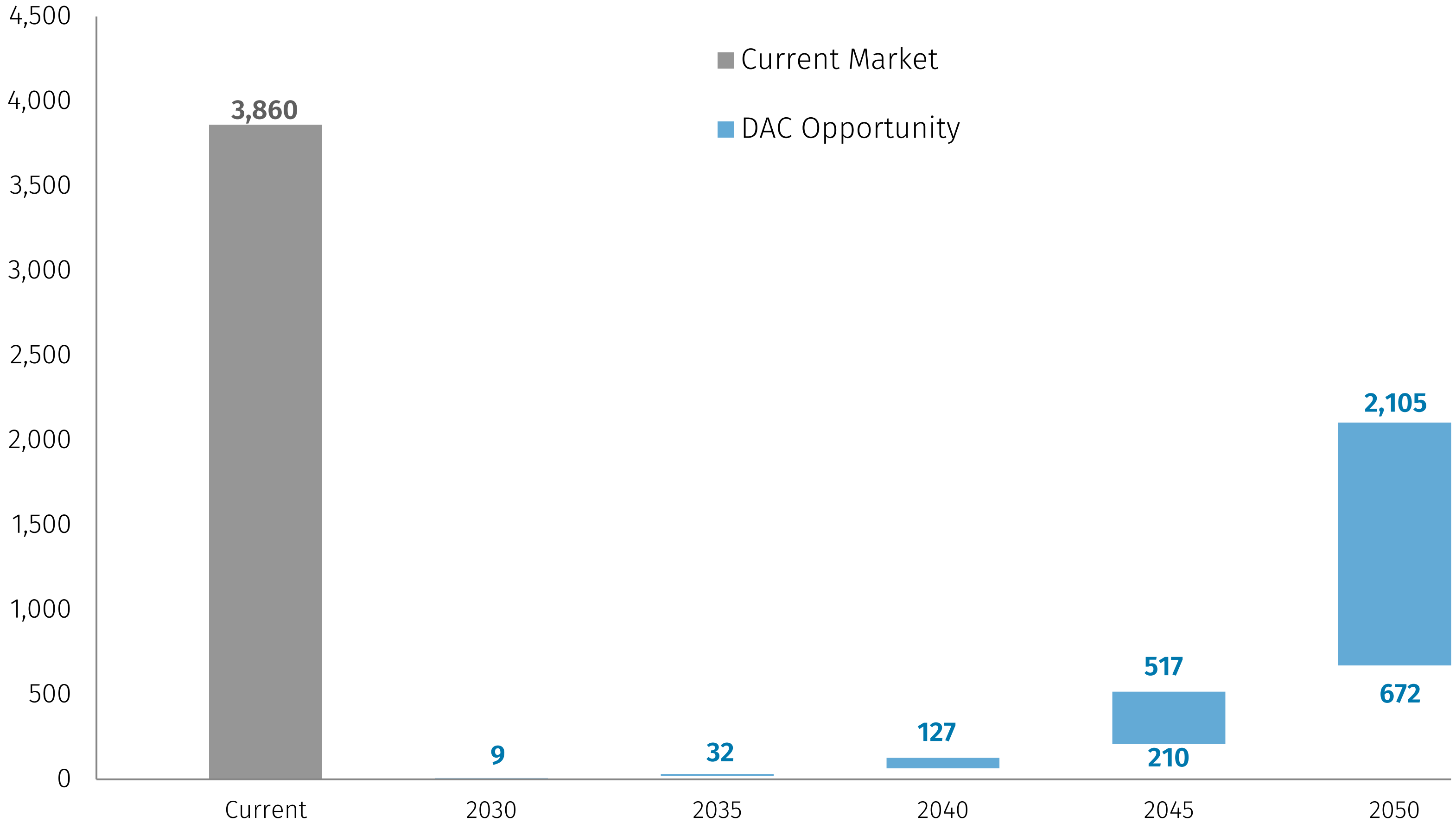
Source: Fortune 500, ClearPath, Rhodium Group analysis

Business opportunity: Electricity

If all Solid Sorbent DAC plants' energy requirements are met solely with zero-emitting electricity, demand could increase by more than half of total current electricity production.

Annual US economy-wide electricity demand

Terawatt-hours



Source: EIA, NAS, Rhodium Group analysis

Top US Electricity Generators:

- Southern Company
- Duke Energy
- Exelon
- Florida Power & Light
- Dominion
- PacifiCorp
- Arizona Public Service
- Luminant
- Entergy
- DTE Energy

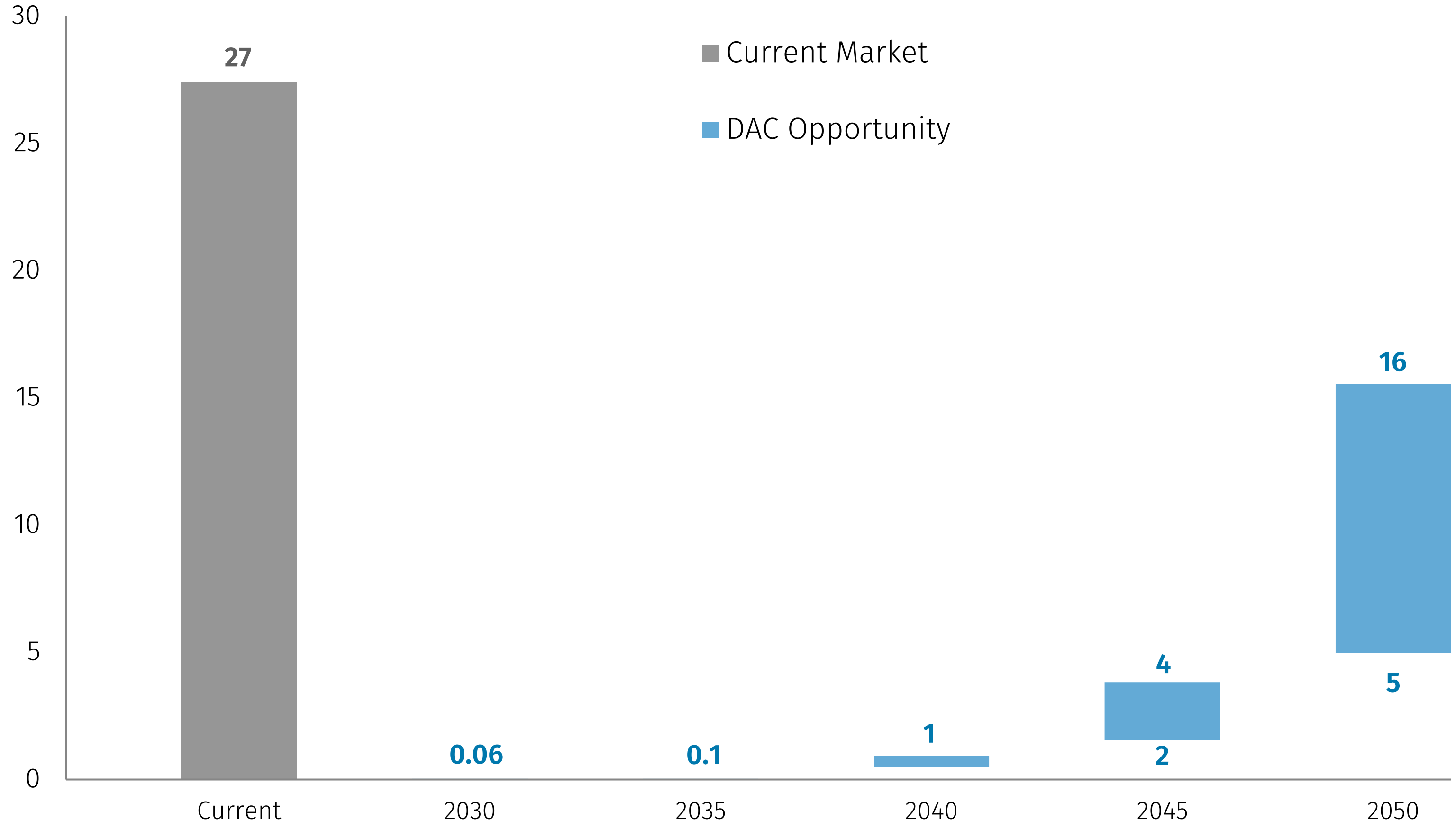
Source: EIA. Note: Only publicly traded companies considered.

Business opportunity: Natural gas

If all liquid solvent DAC plants' energy requirements are met entirely with natural gas coupled with capture of associated combustion CO_2 emissions, it could represent more than half of the current natural gas market.

Annual US economy-wide natural gas demand

Trillion cubic feet



Source: EIA, NAS, Rhodium Group analysis

Top US Natural Gas Producers:

- EQT
- Exxon Mobil
- BP
- Cabot Oil & Gas
- Antero Resources
- Chesapeake Energy
- Ascent Resources
- Southwestern Energy Co.
- Range Resources
- Occidental Petroleum

Top US Natural Gas Transmission Companies:

- Kinder Morgan
- Enbridge
- Transco
- Atmos Energy
- Boardwalk Pipeline Partners

Source: EIA, NGSA

SECTION 4

Key Takeaways

Significant business opportunities associated with DAC are there for the taking. We find that:

DAC is essential to address climate change and needs federal policy support

- DAC technology is commercially ready with hundreds of millions in investor backing and large-scale projects in the pipeline
- New federal policy is required to drive initial deployment of DAC because early-stage costs are higher than existing revenue opportunities*
- Long-term federal policy frameworks are needed for DAC to scale by midcentury

When DAC reaches full scale, manufacturers of key inputs will see a surge in demand

- Equipment and steel markets have the most to gain and could exceed total US demand today with DAC at full scale
- DAC represents a major new growth market for cement, chemicals, electricity, and natural gas
- While these opportunities are substantial they will not materialize for a 2-3 decades and are dependent on policy action

Market opportunities will accelerate with supportive DAC policies and established early supply chains

- Companies that want to secure first-mover advantage in a major new market will benefit from supportive federal DAC policy action
- Manufacturers that supply the first wave of DAC projects stand to lead in a major new growth market opportunity

*See Capturing Leadership for more information.

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SECTION 5

Technical Appendix

Methodology and assumptions

Technical Appendix (slide 11 and 14)

DAC Technology Cost Comparison (slide 11)

- Cost figures include all operating and capital costs, but exclude all financing costs
- Used a 30-year financing horizon to find the levelized costs of solid sorbent and liquid solvent technologies from total capital costs
- Found each components' cost percentage of the total levelized costs excluding financing
- Cost components:
  - Energy includes all heat and electricity requirements
  - Other operations and maintenance costs
  - Labor and other capital costs includes capital costs of construction and engineering, as well as all other capital costs
  - Equipment capital costs
  - Chemical capital and operations and maintenance costs
  - Cement, steel, and other material capital costs

Pathways to net-zero emissions by midcentury (slide 14)

- Straight-line emissions reduction pathway: 28% below 2005 levels in 2025, net zero emissions in 2045, 105% below 2005 levels in 2050
- High DAC:
  - Electrification = Moderate
  - 2050 Biomass Supply (Million Dry Tons) = 270
  - 2050 Natural Sequestration (MMt_CO_2) = 381
- Low DAC:
  - Electrification = Accelerated
  - 2050 Biomass Supply (Million Dry Tons) = 992
  - 2050 Natural Sequestration (MMT CO_2) = 613
- For more information see Capturing Leadership

DAC opportunity projections

Technical Appendix (slides 16, 19-23)

Calculation for DAC Opportunity

- The quantification of DAC opportunity for each individual market is bounded by our high and low DAC deployment scenarios based on pathways to net zero emissions by midcentury
- DAC opportunity is quantified in terms of the investment in the specified year based on the number of plants built in addition to the operating expense for all plants in operation
- Equipment demand projections assume the market is supplied by 50% Solid Sorbent and 50% Liquid Solvent
- While the emissions associated with inputs for DAC capacity such as steel and concrete have the potential to be large, they are not quantified in this analysis. Such emissions will need to be addressed as part of any comprehensive policy action to achieve net zero GHG emissions by midcentury

Equipment

Technical Appendix (slides 16 – 18)

Liquid Solvent Equipment Costs

- Took the sum of capital costs for equipment components (air contactor, pellet reactor, calciner-slaker, air separation unit, CO_2 compressor, steam turbine, power plant, fines filter, other equipment, buildings, transformer) found in Keith et al. 2018

Solid Sorbent Equipment Costs

- We based the portion of CAPEX used for Solid Sorbent equipment costs on the portion of CAPEX used for Liquid Solvent equipment costs found in Keith et al. 2018

- Used NASEM's mid-range CAPEX costs for Solid Sorbent technologies

Materials (cement & steel)

Technical Appendix (slides 19 – 20)

Liquid Solvent Material Costs

- Took the sum of material costs for system components (air contactor, pellet reactor, calciner-slaker, air separation unit, CO_2 compressor, steam turbine, power plant, fines filter, other equipment, buildings, transformer) not covered by equipment costs from Keith et al. 2018
- We assumed the composition of materials based on AISC's reported breakdown of material costs, which uses 34% of material costs for cement and 46% of material costs for steel

Solid Sorbent Material Costs

- Used NASEM's mid-range CAPEX costs for Solid Sorbent technologies
- We based the portion of CAPEX used for Solid Sorbent material costs on the portion of CAPEX used for Liquid Solvent material costs found in Keith et al. 2018
- We assumed the composition of materials based on AISC's reported breakdown of material costs, which uses 34% of material costs for cement and 46% of material costs for steel

Chemicals

Technical Appendix (slide 21)

Liquid Solvent Chemical Costs

- We needed to account for both the capital and operating costs of chemicals for the Liquid Solvent systems
- The costs of both KOH and $CaCO_3$ inputs were based upon NASEM's data
- To determine the OPEX costs, we used a utilization factor of 90% and a plant capture rate of 1MMt_CO_2/year

Solid Sorbent Chemical Costs

- The capital costs of Solid Sorbent chemicals are covered by the equipment costs in our analysis. Therefore, we only use the operating expenses for Solid Sorbent chemical costs. For this, we used NASEM's mid-range operating costs for adsorption OPEX

Energy (electricity & natural gas)

Technical Appendix (slide 22-23)

Liquid Solvent Energy Requirements

- Took the average of NASEM's estimated energy requirements (both thermal and electric) for Liquid Solvent systems
- Used a utilization factor of 90% and a plant capture rate of 1MMt_CO_2/year
- Natural Gas Input: 10.7 GJ/ton_CO_2

Solid Sorbent Energy Requirements

- Took the average of NASEM's mid-range for estimated energy requirements (both thermal and electric) for Solid Sorbent systems
- Used a utilization factor of 90% and a plant capture rate of 1MMt_CO_2/year
- Electricity Input: 1,371 kWh/ton_CO_2

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