Industrial Decarbonization: Hard to Abate Sectors

Charging Ahead Webinar

March 18, 2025

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Agenda and Housekeeping

Agenda

- Housekeeping and Introductions
- Review of the US and State CO2 Targets
- Identification of Industrial Fuel Consumption and CO2 Emissions
- Examination of Key End Uses and Industrial Electrification Pathways
- Outlook for Key Abatement Options
- Takeaways and Recommendations
- Next Charging Ahead Webinar

Housekeeping

This webinar is being recorded and distributed to all registrants along with this presentation

Add your questions to the chat. My colleague, Sara Gonzales, is monitoring the chat for the Q & A session

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CO2 Emissions Targets

Paris Agreement

US Emissions

State Targets

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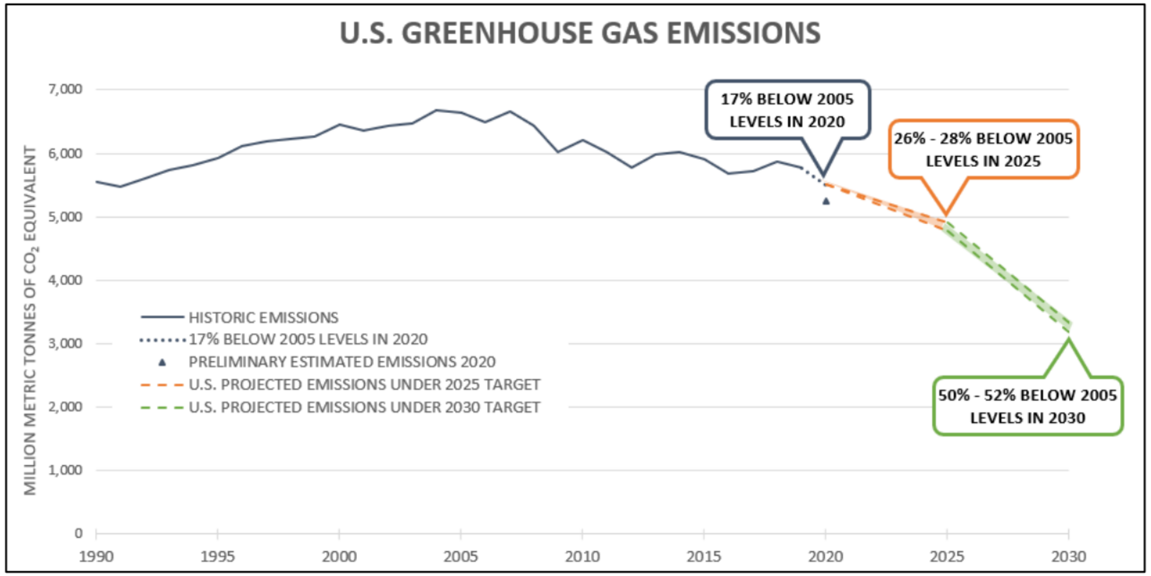
Paris Agreement and the US

US Historic and Projected Emissions Under 2030 Target



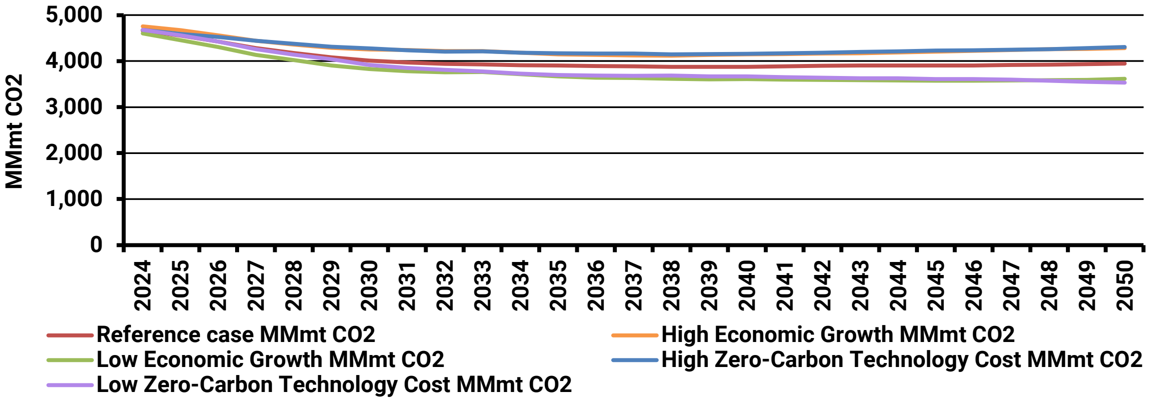
Source: United Nations Framework Convention on Climate Change (2022)

- The Paris Agreement targets limiting global warming below 2°C, with an additional goal to keep global temperatures below 1.5°C, from pre-industrial levels
- The current US targets include a 50-52% reduction in 2005-level (baseline) emissions by 2030, and a net-zero goal for 2050
  - Energeia notes that the United Nations Framework Convention on Climate Change (UNFCCC) has modeled US targets to be insufficient to achieve those temperature goals
- Every 5 years, each country must submit a climate action plan, known as a Nationally Determined Contribution (NDC), with the latest NDC submitted in Dec 2024 and the next NDC to be submitted in 2030
- While countries are not legally obligated to achieve their targets under the Paris Agreement, the current NDC submitted by the US remains active but NDCs can be revised at any time, and
- Under the new administration, the US has begun the process of withdrawing from the Paris Agreement, expected to take effect 1 year from submission on January 20th, 2025
- Some US States, which are detailed later, have committed to more ambitious emissions reduction targets

Source: The Paris Agreement, United Nations (2015)

United States Emissions Projections

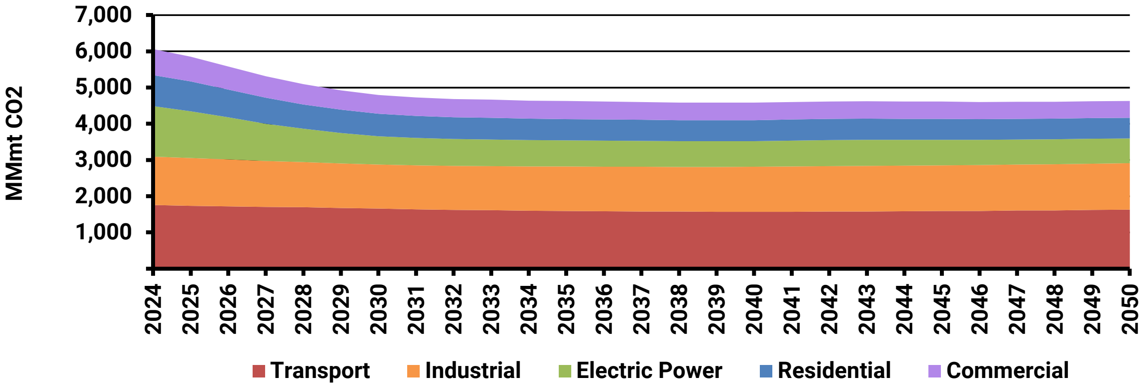
US Baseline Emissions Projections by Scenario



Source: Energeia Research, US EIA (2023)

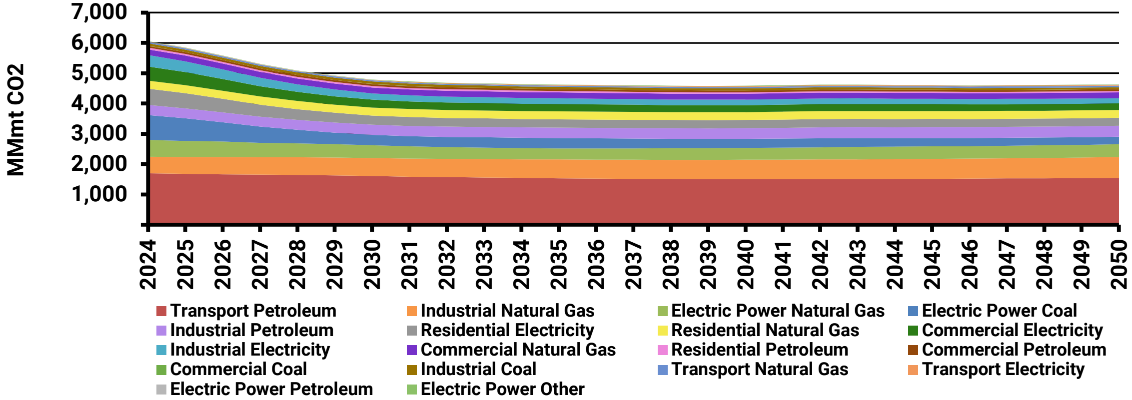
- Baseline US emissions projections show a steady increase or minimal change, even with high development and adoption of new technology
- Majority of US emissions from transport, coal, and residential and commercial end uses
- Industry and transport emissions account for around two-thirds of total baseline emissions

Reference Case Emissions Projections by Sector



Source: Energeia Research, US EIA (2023)

Reference Case Transport Projections by Sector and Fuel



Source: Energeia Research, US EIA (2023)

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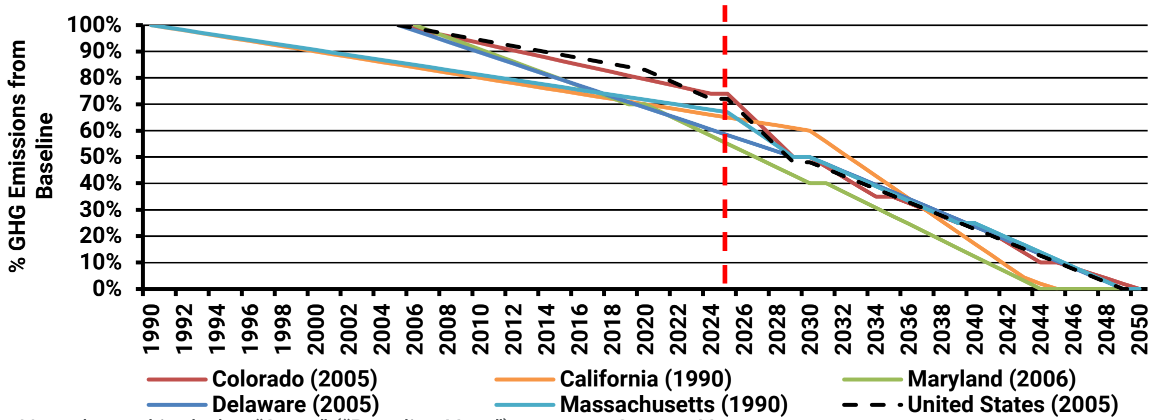
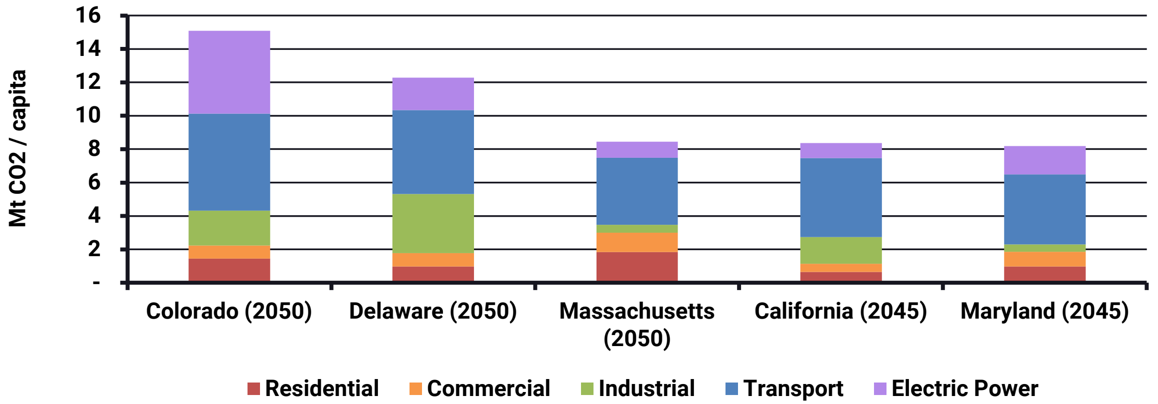
United States CO2 Targets by Key State

Leading State and Federal CO2 Targets



Note: legend includes "State" ("Baseline Year")
Source: Energeia Research, US EIA (2023)

Leading States Emissions per Capita by Sector



Note: labeling includes "State" ("Target Year")
Source: Energeia Research, US EIA (2022)

- The United States had adopted a trajectory to reduce emissions by 50-52% of 2005 baseline levels by 2030 under its NDC to the Paris Agreement, but is expected to alter or scrap the targets per the withdrawal from the Paris Agreement
- State CO2 targets vary substantially in terms of baseline year, target sectors, and trajectory, with California, Colorado, Massachusetts, and Maryland undertaking some of the most comprehensive climate action plans, driven by state policy
  - States with most comprehensive CO2 roadmaps have been included, but may not represent the states with the most stringent targets
- The role of industrial emissions varies by state, based on the economic mix, with DE seeing the largest and MD or MA the smallest, percentages of emissions from the industry sector
- *A key question is how much will it cost the industrial sector to transition, and if a CO2 price is used, what level will it need to be to achieve emissions targets*

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Industrial Energy Usage and Emissions

Energy Usage by Sector

Fuel Usage by Sector

Emissions by Sector

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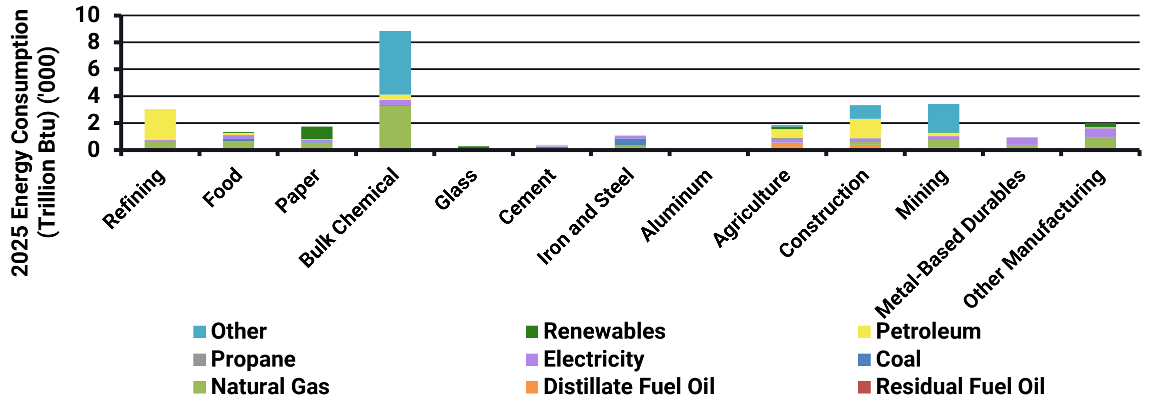
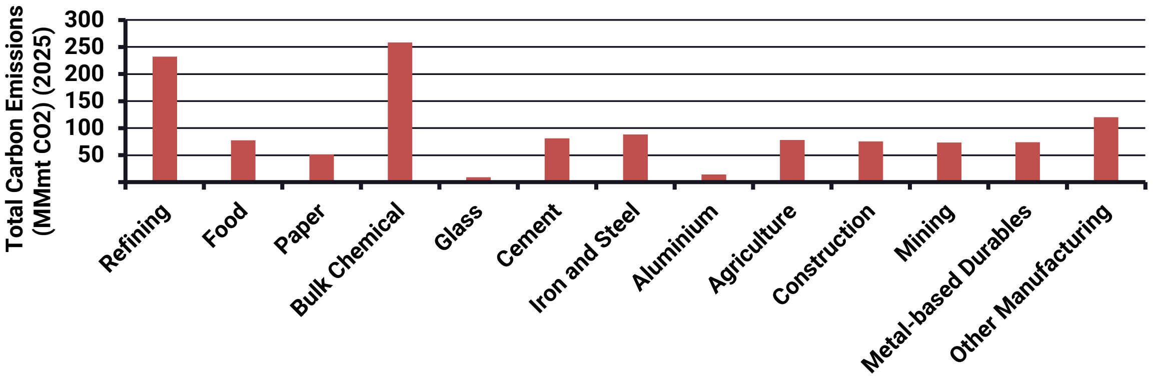
Industrial Energy Consumption and Emissions

Industrial Energy Usage by Segment and Fuel Type in 2025



Source: EIA (2023)

Industrial CO2 Emissions by Segment in 2025



Source: EIA (2023)

- Industrial energy usage is shown left by industrial segment and fuel type along with corresponding emissions
- Bulk chemicals, mining, refining, and construction have the highest total energy use

- Refining and bulk chemical generate more than double the level of CO_2 than most other sectors
- We have focused on a subset of these, where more than electrification is likely to be required for a range of reasons

CO2 Abatement Challenges and Pathways

Challenges by Sector

Potential Solutions by Sector

Costs to Abate by Sector

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What Makes Industry Sectors Hard to Abate?

Summary of Hard to Abate Industry Sectors

Sector	Main Hard-to-Abate Process	How It Produces Emissions
Iron and Steel Production	The conventional reduction of iron ore pellets uses the blast furnace or direct reduced iron (DRI) method to produce liquid iron. Both use high temperatures (1,650°C and 900°C) and carbon monoxide as the reducing agents	Fossils fuels are burned to achieve extreme temperature, creating CO2, and are required to produce the carbon monoxide reducing agent, which can escape
Cement Production	The calcination of limestone in cement kilns utilizes extreme heat (1,450°C) to produce clinker - a key ingredient in cement	Fossils fuels are burned to achieve extreme temperature, creating CO2, and additional CO2 naturally escapes from within the limestone in which it was once trapped
Aluminum Production	Alumina is refined from bauxite in a process involving high-temperature calcination (1,000°C+) which is then used in a molten (950°C) reduction-oxidation reaction with a carbon anode to produce pure aluminum	Fossils fuels are conventionally burned to refine alumina and are also burned to produce the molten bath chemistry to produce aluminum, where CO2 is a product of the oxidization of the carbon anode
Chemical and Petrochemical	Production of olefins, produced through high-temp (750-900°C) steam cracking of hydrocarbons, and aromatics, produced through catalytic reforming using high-temp (500°C+) dehydrogenation	Fossils fuels are conventionally used to produce the extreme heat required, generating emissions and are often utilized in the production process (e.g. natural gas for steam methane reforming in ammonia production)
Mining	Energy-intensive processes including extraction (e.g. boring, drilling, blasting), pulverization (e.g. surface griding, volume grinding) and on-site material transport (haulage) are conducted using heavy machinery	Heavy machinery typically powered by emissions generating fossil fuel engines, explosives produce carbon monoxide, and broken rocks can release trapped gasses (e.g. methane)
Heavy Duty Transport	The engine combustion process to convert the chemical energy of fuel into thermal energy which is transformed into mechanical energy	When diesel fuel is injected into the combustion chamber, it mixes with the hot, compressed air and ignites at high temperature and releases carbon dioxide (CO2), nitrogen oxides (NOx), and particulates into the atmosphere
Shipping	The engine combustion process to convert the chemical energy of fuel into thermal energy which is transformed into mechanical energy	Low sulphur fuel oil (LSFO) and Heavy fuel oil (HFO) is injected into the engine's combustion chamber where it mixes with hot compressed air and ignites and release CO2, NOx, SOx, particulate matter, and other pollutants
Aviation	The expanding high heated gases from the combustion process push the turbine blades, converting the chemical energy of the fuel into mechanical energy	Jet A or Jet A-1 fuel is injected into the combustion chamber of the engine. The injected fuel mixes with the extreme hot, compressed air and ignites and produce CO2, Nox and SO2

Source: Energeia research

- Each of the hard to abate processes generally involve one of the following:
  - Very high temps, which have to date been relatively high cost for electricity to achieve
  - CO2 as a feedstock
  - Petrochemicals as a feedstock
  - CO2 as a byproduct
  - Relatively light-weight fuel (aviation)
  - Relatively dense fuel (shipping)

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Key Solutions for Hard to Abate Processes

Summary of Solutions for Hard to Abate Industry Sectors

Abatement Solution	Description
Energy Efficiency	Emissions are reduced by increasing efficiency of current process
Electrification	Electricity used for heating or motor
Alternative Processes	Alternative processes avoids emissions
Green Hydrogen	Used as synthetic feedstock into chemical production
Biofuels	Used as synthetic feedstock as well as high density or light fuels
CCUS	Uses or buries emissions
Offsets	Offsets emissions, e.g. Land Use, Land-Use Change and Forestry (LULUCF)

Source: Energeia, Note CCUS = Carbon Capture, Utilization and Storage

Potential Solutions by Section

Sector	Decarbonization Options						
	Electrification	Energy Efficiency	CCUS	Alternative Processes	Hydrogen	Offsets	Green Fuels
1. Iron and Steel Production	✓	✓	✓	✓	✓	✓	✓
2. Cement Production	✓	✓	✓	✓	✓	✓	✓
3. Aluminum Production	✓	✓	✓	✓	✓	✓	✓
4. Chemical and Petrochemical	✓	✓	✓		✓	✓	✓
5. Mining	✓	✓	✓		✓	✓	✓
6. Heavy-Duty Road Transport	✓	✓			✓	✓	✓
7. Shipping	✓	✓			✓	✓	✓
8. Aviation	✓	✓			✓	✓	✓

Source: Energeia analysis

- Different hard-to-abate sectors benefit from different solutions for emissions abatement
- Mixed solutions may be required for different processes within the same industry
  - Energy efficiency and alternative processes may not abate all emissions

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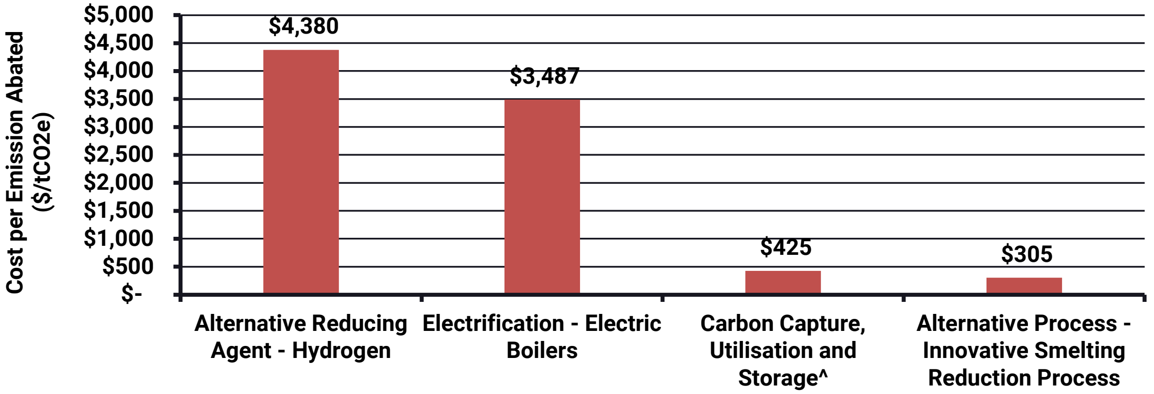
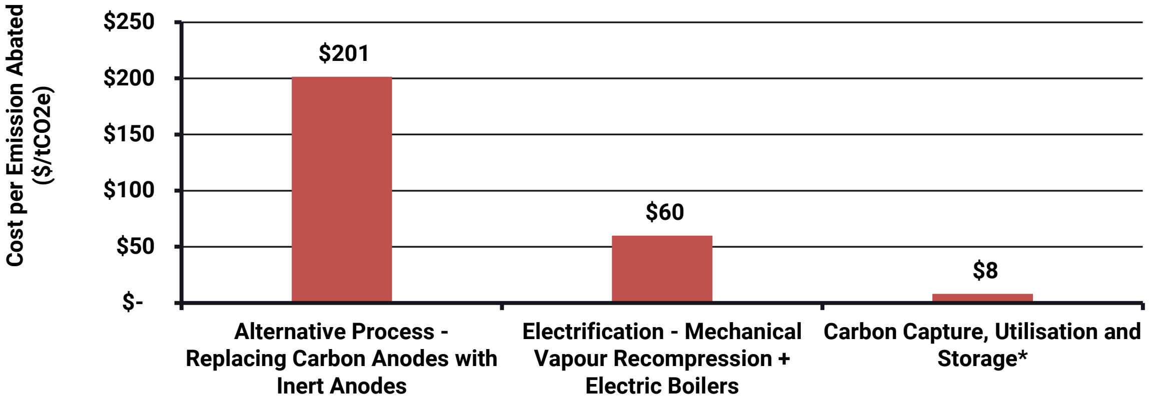
Cost to Abate by Solution and Sector (1 of 3)

Iron and Steel Production Costs by Key Abatement Solution



Source: Zuberi et al. (2022), IEA (2021 & 2020), ARENA (2021), Note * indicates a solution that can address all stages of production, ^ indicates a simplified levelized cost

Aluminum Production Costs by Key Abatement Solution

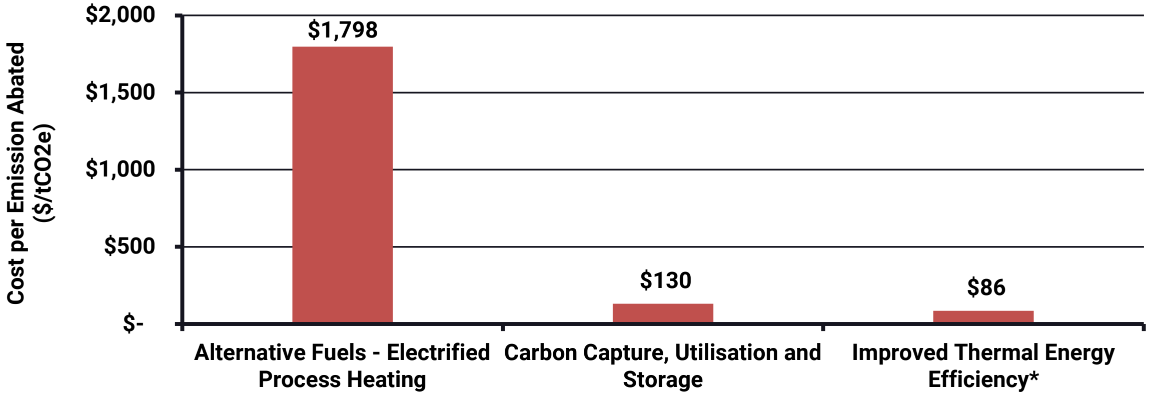


Source: Zuberi et al. (2022), Mission Possible (2022), ARENA (2022), Note * indicates a solution that can address all stages of production

- Energeia's analysis shows a wide range of costs among potential decarbonization pathways for hard to abate industry sectors
- Importantly, many of the identified key solutions here, will not be able to reduce 100% of sector emissions, requiring a portfolio approach, and/or offsets
- Key Iron and Steel abatement options can be extremely expensive at over $3,000/CO2e, with carbon capture, utilization and storage (CCUS) or offsets potentially being more cost-effective solution
- For Aluminum, there are a number of options at much lower cost, but as is the case for Iron and Steel, CCUS is the only solution (other than offsets) capable of achieving 100% abatement net of lower cost alternative process solutions
    - Note that the CCUS costs are vastly different between Steel and Iron vs. Cement, mainly due to the difference in capture and utilization costs

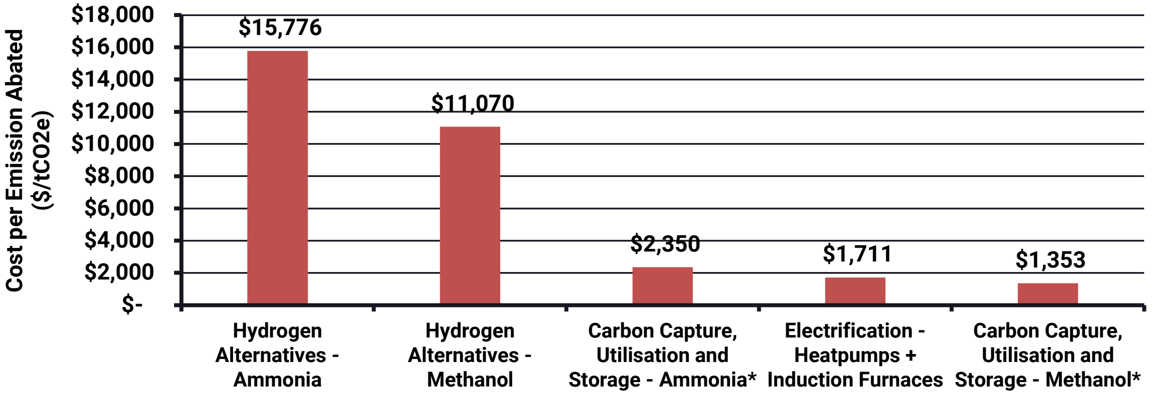
Cost to Abate by Solution and Sector (2 of 3)

Cement Production Costs by Abatement Solution



Source: Zuberi et al. (2022), Mission Possible (2022), ARENA (2022)
Note * indicates a solution that can address all stages of production

Petrochemical and Chemical Production Costs by Abatement Solution



Source: IEA (2021 & 2023)
Note * indicates a solution that can address all stages of production

- For cement, electrification of the heating process, CCUS and improving thermal efficiency are the key pathways, of which only CCUS can achieve the remaining abatement net of the lower cost, improved energy efficiency (EE)
- In the chemical sector, the pathway seems to be some electrification, but mostly CCUS as the most cost-effective solution that can deliver 100% abatement

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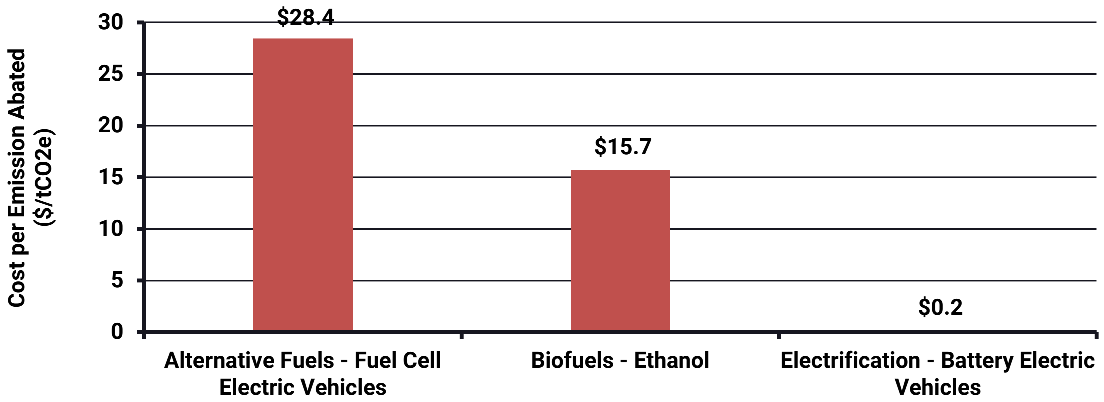
Cost to Abate by Solution and Sector (3 of 3)

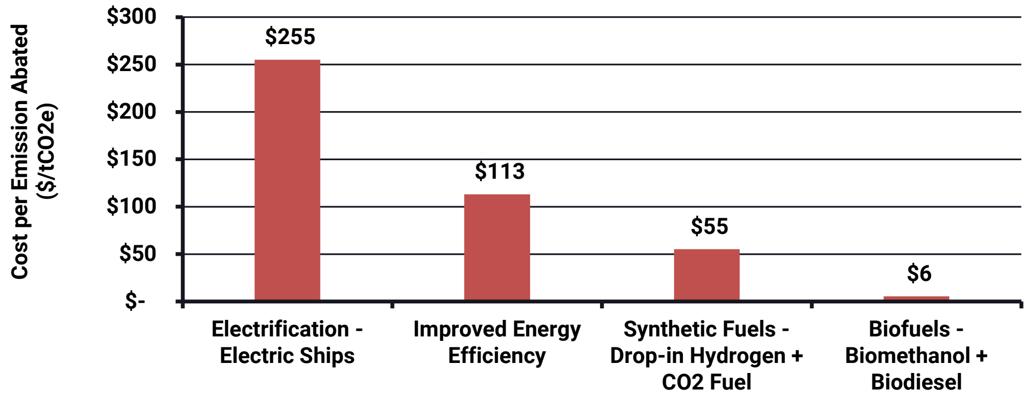
Heavy Duty Transport



Source: European Commission (2022), European Parliament (2023), freethink (2024), Energeia Research

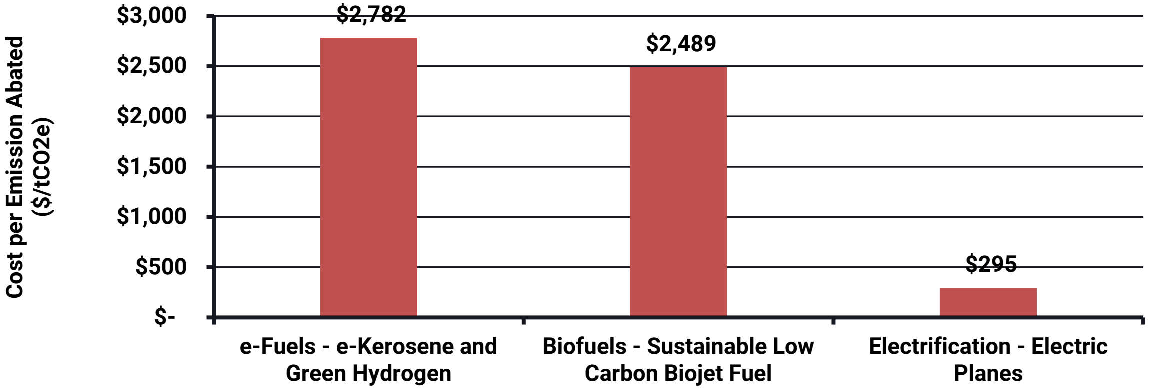
- Transport remains one of the largest emitting sectors that many countries are looking to decarbonize moving forward
  - Electrification least cost for short-distance road applications but becomes constrained by energy density for heavy duty transport
  - Biofuels provide a cost-effective solution for reducing emissions in existing fleets across all sectors despite its lower energy density
  - Alternative fuels (ie. hydrogen) offer potential but face infrastructure and scalability issues due to the immaturity of the technology
- Heavy duty and shipping appear capable of decarbonization without CCUS or offsets, aviation remains high cost

Shipping



Source: ARENA (2024), Concawe (2022), Rony et al. (2023), NatureEnergy (2024), Energeia Research

Aviation



Source: ARENA (2024)

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Outlook for CO2 Prices and Abatement Solution Costs

Carbon

Biofuels

Green Hydrogen

CCS

LULU

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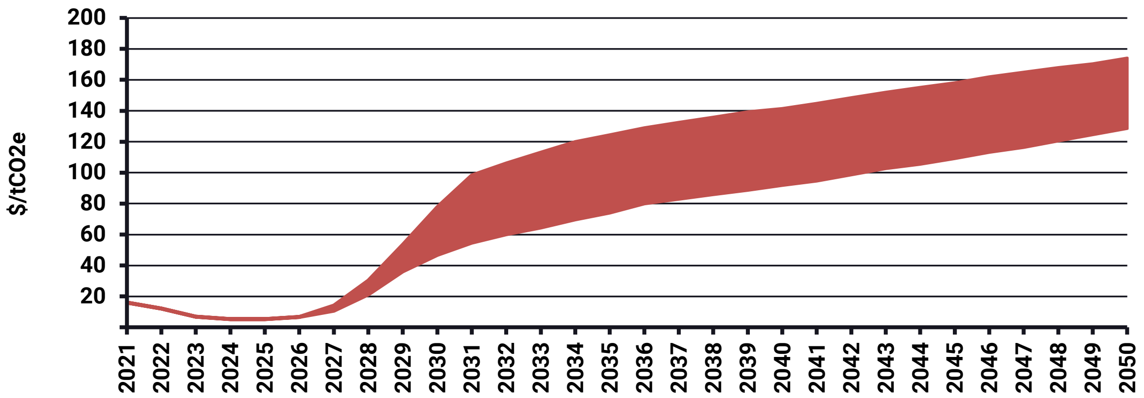
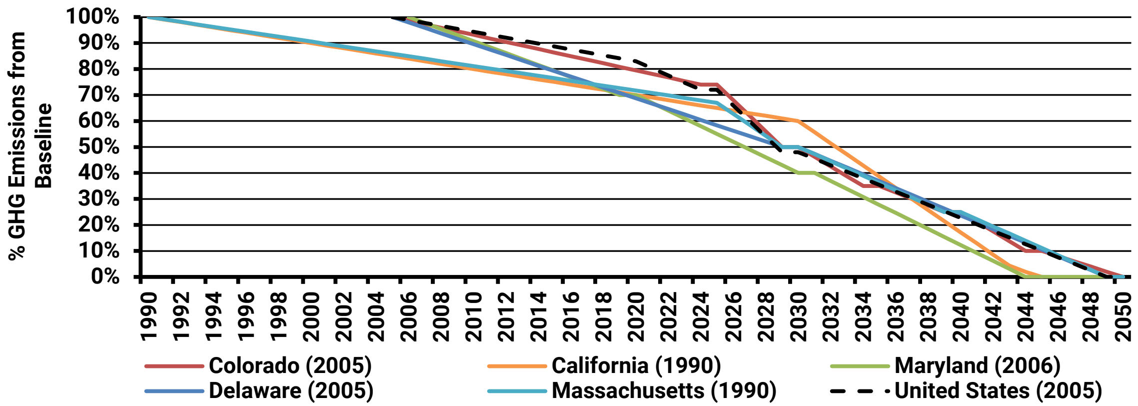
Cost of Carbon Abatement

Carbon Price



Source: EY (2024)

Leading State and Federal CO2 Targets



Note: legend includes "State" ("Baseline Year") = Current Year
Source: Energeia Research, US EIA (2023)

- EY's Forecast for CO2 pricing consistent with the Paris Accord shown at left
  - Energeia was not able to find any recent other CO2 forecast, which is interesting of itself
- The CO2 price will need to be high enough to drive sufficient decarbonization in each jurisdiction to hit its target
- It shows an expected ramp up in 2027, which is consistent with the change in trajectory shown in the graphic below left
- Energeia notes these are within the ranges shown for CCUS, which is given in a subsequent slide

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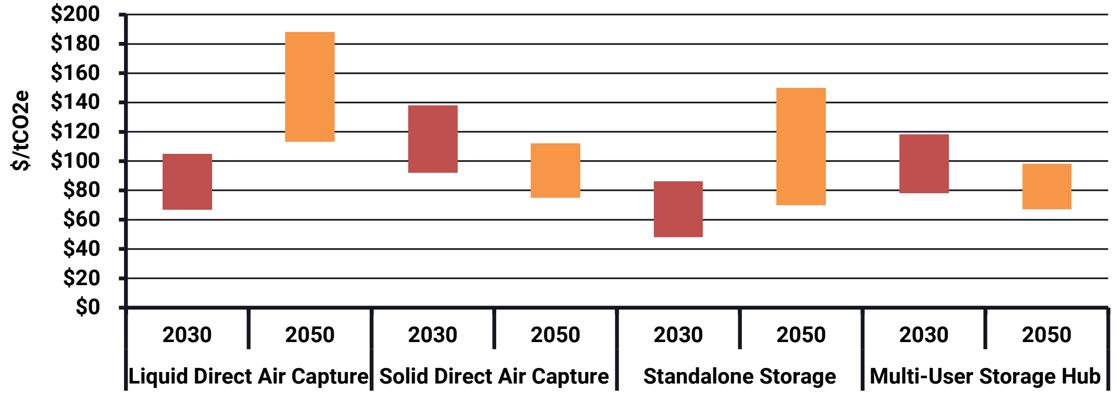
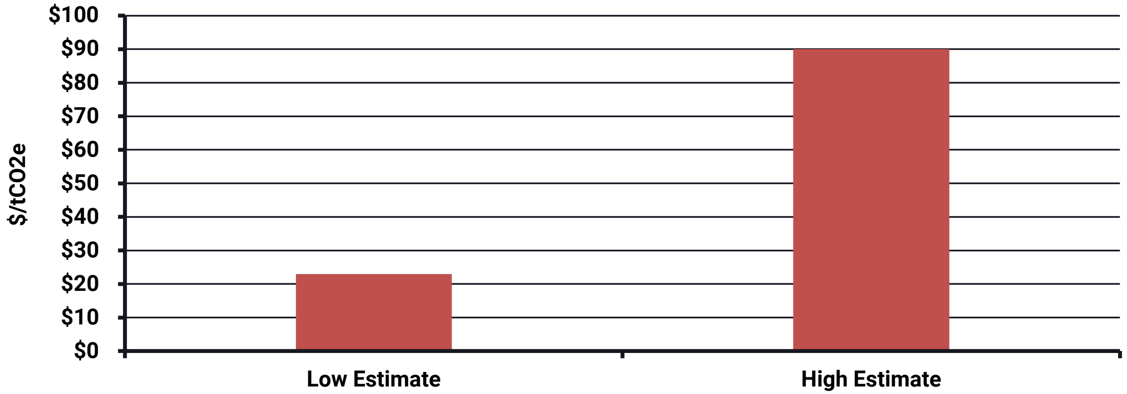
Cost of CCS and LULUCF Abatement

Carbon Capture and Storage (CCS)



Source: IEA (2022), Wood Mackenzie (2021)

Land Use, Land-Use Change and Forestry (LULUCF)



Source: MIT (2024)

- The charts show the cost of carbon capture and storage and afforestation and storage as solutions for abatement
  - These are generic CCS abatement costs, which will vary by sector due to differences in the cost of capture
  - Even high estimates of emissions abatement through afforestation are lower cost than carbon capture
- Carbon capture costs are consistent with forecast CO2 prices, suggesting they are likely to be the marginal abatement source

Takeaways
and Recommendations

Takeaways and Recommendations

- **Takeaways**
  - Industry and transport sectors (excluding light duty) represent 2/3 of baseline emissions in the US
  - Of these, a large proportion of them are not suited to electrification for a range of reasons
  - While specific solutions are being developed in each case, they can be very high cost
  - CCS/CCUS and offsets are general approaches that may be needed to achieve abatement targets
  - A key question is how accurate the CCS / CCUS cost estimates are
- **Recommendations**
  - Electric high temp heat technologies are a key solution that will be essential to the transition
  - R&D focus will be key to bringing its cost down
  - While biofuels are relatively low cost, there are not enough of them to meet all needs
  - Green hydrogen will be needed to provide feedstock, and the focus should be on this application
  - Much is riding on CCS / CCUS and LULUCF, and additional effort should be focused on them to bring cost down and ensure capacity

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Charging Ahead

Q & A

Next Charging Ahead Topic

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Energeia's Charging Ahead

- Q&A
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  - Unanswered questions will be answered via email
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  - Best Practice Virtual Power Plant Programs
  - Natural Gas Transition Pathways
  - Heavy/Medium Transportation Electrification
  - Best Practice Approaches to Climate and Weather Impacts
  - Electrification Workforce Analysis and Planning

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Bridging the Skills Gap:
Workforces for Electrification

May 20, 2025
9:30 AM – 10:00 (PDT)

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Watch for a follow-up email with recording and presentation links to share

Thank You!

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