Industrial Decarbonization Pathways to Net-Zero

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Industriial Efficiency and Decarbonization Office

Hydrogen Program Annual Merit Review
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Industrial Efficiency & Decarbonization Office (IEDO):
https://www.energy.gov/eere/iedo/industrial-efficiency-decarbonization-office
U.S. Industrial CO₂ Emissions

Industrial sector is comprised of manufacturing | agriculture | mining | construction

ACCOUNTS FOR **30%** of energy-related CO₂ emissions

Energy-Related CO₂ emissions, 2020
(million metric tons)


Total Industry Emissions, 2018
(energy-related + non-energy; million metric tons CO₂eq)

EIA Monthly Energy Review, Manufacturing Energy Consumption Survey; EPA GHGRP Inventory
Decarbonizing Industry is an Opportunity for America’s Economy

U.S. manufacturing subsector...

CONTRIBUTES
$2.79 trillion to the U.S. Economy

GENERATES
12% of U.S. GDP

SUPPORTS
11.2 million jobs

U.S. Census Bureau Annual Survey of Manufactures & U.S. Bureau of Economic Analysis data for 2021
Decarbonizing Industry is an Opportunity for America’s Economy

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DOE Industrial Decarbonization Roadmap

- Pillars, and associated pathways to net-zero GHG emissions by 2050 for high-emitting industrial subsectors
- Rethink the opportunity for RDD&D and robust technology solutions
- Innovations for more sustainable manufacturing

Industrial Decarbonization Pillars

- Invest in all pillars
- Leverage cross-sector approaches
- Interdependencies require systems solutions
- Strategies are needed to minimize implementation hurdles, address scale-up, and accelerate adoption

Decarbonization pillars: inter-related, cross-cutting strategies to pursue in parallel

- Energy Efficiency
- Industrial Electrification
- Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES)
- Carbon Capture, Utilization, and Storage (CCUS)

Industrial Decarbonization Recommendations

Near-Zero GHG Emissions Scenario
(for five representative subsectors*)

- **Advancing Early-Stage RD&D**
- **Invest in Multiple Process Strategies**
- **Scale through Demonstrations**
- **Address Process Heating**
- **Decarbonize Electricity Sources**
- **Integrate Solutions**
- **Conduct Modeling and System Analyses**
- **Engage Communities, Develop a Thriving Workforce**

*Subsectors included in Roadmap analysis: Iron & Steel, Chemicals, Food & Beverage, Petroleum Refining, and Cement. (Near zero GHG scenario, excluding feedstocks.)

11% of All U.S. Energy-Related GHG Emissions are from Industrial Heat

**2020 Energy-Related CO₂ Emissions by U.S. Economic Sector**
- Buildings: 35%
- Transportation: 35%
- Industrial: Manufacturing: 25%
- Other: Mining, Agriculture, Construction: 5%

**2020 Estimated Industrial: Manufacturing Energy-Related CO₂ Emissions by Source**
- Industrial Heat: 46%
- Off-Site Emissions: 39%
- Non-process Use: 3%
- Other Process Use: 12%

Opportunity for improved energy productivity and reduced emissions

Sources: EIA Annual Energy Outlook (2021); IEDO 2018 Manufacturing Energy and Carbon Footprints (2022)
Develop cost competitive industrial heat decarbonization technologies with at least 85% lower greenhouse gas emissions by 2035

<table>
<thead>
<tr>
<th>Baseline</th>
<th>65 kg CO₂ equivalent per MMBtu</th>
<th>Current Average GHG Emissions Intensity of Industrial Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>2035 Target</td>
<td>8.8 kg CO₂ equivalent per MMBtu</td>
<td>Aligned with Clean Hydrogen (1 kg CO₂ per kg H₂)</td>
</tr>
</tbody>
</table>

>85% Lower Emissions

2035
Industrial Heat Shot – Pathways to Reduce Emissions from Thermal Systems

Goal: Reduce the amount of heat and/or emissions from heat to make cleaner products

Generate Heat from Clean Electricity

Reduce Emissions:
- electrify equipment & use clean electricity, improve energy efficiency

Examples:
- heat pumps, microwave heating, resistive heating, etc.

Integrate Clean Heat from Alternative Sources

Reduce Emissions:
- switch to low-emissions heat sources and increase thermal storage

Examples:
- solar thermal, nuclear, geothermal, hydrogen, some sustainable fuels, etc.

Innovative Low- or No-Heat Process Technologies

Reduce Emissions:
- new chemistry and emerging approaches to reduce heat demand

Examples:
- advanced separations, electrolysis, ultraviolet curing, biobased manufacturing, etc.

Enabling technologies and systems: e.g. energy storage, materials, modeling, data analytics, etc.

www.energy.gov/eere/industrial-heat-shot
Decarbonization of process heating will require a multi-modal strategy.

Process heating represents more than 50% of manufacturing end-use energy, but less than 5% of process heating is electrified.

Over 50% of process heating demand is low temperature (<150°C) – prime candidate for electrification, while other high temperature process heat needs will require alternative thermal processing technologies.

<table>
<thead>
<tr>
<th>Thermal process</th>
<th>Industrial sector</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Iron and steel</td>
</tr>
<tr>
<td>Calcining</td>
<td></td>
</tr>
<tr>
<td>Bonding, curing and forming</td>
<td></td>
</tr>
<tr>
<td>Drying</td>
<td></td>
</tr>
<tr>
<td>Fluid heating</td>
<td></td>
</tr>
<tr>
<td>Heat treating (metal and nonmetal)</td>
<td></td>
</tr>
<tr>
<td>Metal and nonmetal reheating</td>
<td></td>
</tr>
<tr>
<td>Metal and nonmetal melting</td>
<td></td>
</tr>
<tr>
<td>Other heating: processing</td>
<td></td>
</tr>
<tr>
<td>Reactive thermal processing</td>
<td></td>
</tr>
<tr>
<td>Smelting, agglomeration etc</td>
<td></td>
</tr>
<tr>
<td>Steam generation</td>
<td></td>
</tr>
</tbody>
</table>

Blue = low temperature (<800°F);
Orange = medium temperature (800°F to 1,400°F);
Red = high temperature (>1,400°F).

**Thermal considerations:**
- Higher process heat needs requiring combustion fuel?
  - Cement
- Are alternative heating technologies (e.g. electrification) technically challenging or cost-prohibitive?
  - Glass

**Process considerations:**
- Is this a process that traditionally requires direct-fired heating?
  - Melting and forming

*Source: Decarbonization Options for Process Heating, Arvind Thekdi, 2022*
Industrial Decarbonization is also a systems challenge

Landscape of major RD&D investment opportunities for industrial decarbonization between now and 2050.

LCFFES = Low Cost Fuels, Feedstocks, and Energy Sources; CCUS = Carbon Capture Utilization and Storage

Source: Industrial Decarbonization Roadmap

What are the implications of:
- Expanded H₂ generation & use
- New thermal energy sources & systems
- Smart manufacturing, automation, & data analytics
- Transition to clean electricity
- Policies
DOE Industrial Decarbonization – Clean Hydrogen Opportunities

Intersectoral Collaboration

- **Clean H₂ generation** - renewables, nuclear power, or fossil resources with carbon capture can reduce emissions of existing demand sectors.

- **Clean H₂ and low-carbon electricity demand** - will increase significantly by 2050. R&D efforts will be needed to improve the efficiency of electrolyzers.

- **Novel technologies for H₂ use** - heavy-duty vehicles, metal refining, synthetic fuels production, and stationary fuel cells can further enable emissions reductions.

- **H₂ supply for grid services** - to increase resiliency.

- **H₂ infrastructure advancements** – e.g. compression, pipeline and chemical carrier transport, and bulk storage

**Examples of hydrogen use by industrial subsector:**

<table>
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<tr>
<th>Industrial Subsector</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron &amp; Steel</td>
<td>Alternative reductants – e.g., Clean H₂ in direct reduced iron (DRI) and blast furnaces</td>
</tr>
<tr>
<td>Chemicals</td>
<td>Clean H₂ use as fuel or feedstock</td>
</tr>
<tr>
<td>Food &amp; Beverage</td>
<td>Clean H₂ use for medium temp process heat</td>
</tr>
<tr>
<td>Refining</td>
<td>Desulfurization using clean H₂</td>
</tr>
<tr>
<td>Cement</td>
<td>Clean H₂ as fuel</td>
</tr>
</tbody>
</table>
Global Hydrogen Value Chains

Current \( H_2 \) demand ~ 90 MMT

2030 forecast demand: 200 MMT

https://www.iea.org/reports/the-future-of-hydrogen
U.S. Hydrogen Demand Estimates

Current hydrogen production is ~10 MMT

U.S. National Clean Hydrogen Strategy and Roadmap forecast 50 MMT hydrogen production in 2050.

- Total 2050 Net Zero Hydrogen Demand for 6 EEII sectors is over 12 MMT
- Chemicals and Refining are largest consumers
  - >90% of total industrial hydrogen use
- In 2050 hydrogen remains more valuable as a feedstock than as a combustion fuel

Note: food & beverage and cement report negligible hydrogen demand under the net-zero scenario

PRELIMINARY DATA. DO NOT CITE.
The U.S. Chemicals Sector

- The U.S. chemical industry contributed over 25% to the total GDP in 2022, valued at $486 billion.
- It manufactures **70,000+ distinct products across 11,000+ facilities**.
- In 2022, the U.S. ranked as the world’s second-largest chemical producer, meeting nearly 13% of global demand.
- The sector **employs approx. 4.1 million individuals**, directly or indirectly.
- It consumes **25% of total primary energy** within U.S. manufacturing.
- Responsible for **28% of GHG emissions in U.S. manufacturing**.
- Historical data shows a **16% growth in chemical production from 2010 to 2020** ...
- ... and projections **suggest a further 20% growth** in basic chemical production between 2020 and 2050.
Emissions Across Chemicals Sector

- Petrochemicals: 17%
- Other Basic Organic Chemicals: 22%
- Plastic Materials and Resins: 14%
- Ethyl Alcohol: 9%
- Synthetic Rubber: 1%
- Synthetic Rubbers and Filaments: 1%
- Artificial and Synthetic Fibers and Filaments: 1%
- Industrial Gases: 6%
- Other Basic Inorganic Chemicals: 13%
- Nitrogenous Fertilizers: 11%
- Pharmaceuticals and Medicines: 3%
- Ethylene: 9%
- Ethanol: 8%
- Chlorine: 7%
- Ammonia: 7%
- Benzene: 6%
- Soda Ash: 5%
- Ethylene Dichloride: 5%
- Sodium Hydroxide: 4%
- Nitrogen: 2%

**Early Uses**
- ✓ Process heat (especially high temperature)
- ✓ Blending with current H$_2$
- ✓ Ammonia (if energy for H$_2$ decarbonized)

**Later Uses**
- ✓ Methanol
- ✓ Ethylene
- ✓ Ammonia (H$_2$ from energy via decarbonized grid)

**Key message:** If electrolysis – H$_2$ using grid-based electricity is applied too rapidly as a feedstock by 2030, CO$_2$ emissions could increase above BAU, whereas if its use as a feedstock is delayed until the electric grid is fully decarbonized, the increased emissions above BAU could be avoided. Direct use of renewable energy to supply the energy for H$_2$ generation could also avoid this issue.
Approximately 90% of ammonia emissions are from the generation of H₂ as feedstock

- Natural gas steam methane reforming (SMR) is the primary production route in the U.S.
- Autothermal reforming (ATR) and coal gasification are also commercial pathways to H₂ production.
- IEA’s Ammonia Technology Roadmap provides a comprehensive list of lateTRL technology approaches to low-carbon hydrogen for ammonia production.

➢ Energy and emissions analysis presents interesting trade-offs

**Sources:**
- IEA, Ammonia Technology Roadmap, 2021, Table 1.2, [https://www.iea.org/reports/ammonia-technology-roadmap](https://www.iea.org/reports/ammonia-technology-roadmap)

**PRELIMINARY DATA. DO NOT CITE.**
START


db/energy/forweb/energy-efficiency/industrial-efficiency-and-decarbonization-2022/figures/DecisionTree.png

Net Zero (or Near Net Zero or Negative emissions)

Have all possible resource efficiency measures been applied beyond the boundaries of the plant?

Apply resource efficiency measures (e.g. plastics recycling, fertilizer use efficiency, etc.)

Are there high-purity CO₂ emissions (e.g., process emissions) available?

Build CO₂ transport and utilization/storage infrastructure?

Are there diluted emission streams exceeding 0.1 MMT CO₂/yr?

Have all possible resource efficiency measures, been applied beyond the boundaries of the plant?

Do plants have access to CO₂ transport and utilization/storage infrastructure?

Develop and deploy new pathways, incl. those based on low-carbon feedstocks

Are there high-purity CO₂ emissions (e.g., process emissions) available?

Is it worthwhile to capture biogenic CO₂ resulting from the use of LCFFES?

Apply CCUS measures (e.g., amine scrubbing)

Are there high-purity CO₂ emissions (e.g., process emissions) available?

Have all accessible low-carbon fuels been utilized?

Employ low-carbon fuels to their fullest potential

Is it worthwhile to capture biogenic CO₂ resulting from the use of LCFFES?

Have all accessible low-carbon fuels been utilized?

Apply electrification measures

Have all possible loads been electrified?

Do plants have access to clean electricity grids and infrastructure?

Build clean electricity grids and infrastructure?

Build CO₂ transport and utilization/storage infrastructure?

Are there unabated emissions?

Are there unabated emissions?

Biogenic emissions

Are there unabated emissions?

Net Zero

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Net Zero
Substantial Investments are Required to Meet Net-Zero Goals

**Investment scale** → In the range of **$0.7 – $1.1T**

for 8 industrial sector of focus in the IRA:

- Chemicals
- Refining
- Iron & Steel
- Food & Beverage
- Cement
- Pulp & Paper
- Aluminum
- Glass

Source: DOE Pathways to Commercial Liftoff; Industrial Decarbonization

[https://liftoff.energy.gov/industrial-decarbonization/](https://liftoff.energy.gov/industrial-decarbonization/)
Research, Development, Demonstration & Deployment (RDD&D) Continuum

Industrial Technologies across DOE: https://www.energy.gov/industrial-technologies/industrial-technologies
Closing Thoughts

Technology Investment Portfolios

- Investment strongly influences outcomes
- Too much diversification is a bad strategy
- It is essential to make targeted investments
- Should put a few eggs in the right baskets

https://doi.org/10.1016/j.jedc.2018.10.006
Thank you

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For additional information:
https://www.energy.gov/eere/iedo/energy-analysis-data-and-reports