Capturing the Benefits of Industrial Decarbonization for Houston and Beyond

HOUSTON ENERGY TRANSITION INITIATIVE | MISSION POSSIBLE PARTNERSHIP

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About RMI

RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut climate pollution at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; Abuja, Nigeria; and Beijing.

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Executive Summary

Texas is home to nearly a third of the country's refining and petrochemicals processing capacity, and it has the country's largest electricity generation capacity. The state also has an experienced and specialized workforce. Texas and the greater Houston area took on a leadership role in industrial decarbonization over 20 years ago, beginning with the integration of renewables. The state has a long and successful record of Scope 2 emissions reductions through electrical generation fuel switching, with coal and gas going from comprising 86% of the Electric Reliability Council of Texas's (ERCOT's) electric generation profile in 2001 to 62% in 2023, while renewables grew from under 1% to 27% in the same time period.[1] During the same time frame, coal power generation as a percentage of the total ERCOT generation profile fell by more than half even while natural gas usage remained relatively steady, highlighting a shift over time toward cleaner fuel sources.

US regulatory support mechanisms, climate legislation in other jurisdictions, and voluntary corporate net-zero goals are driving global industrial decarbonization markets that will significantly contribute to job creation and overall growth in the regional economy. By leveraging available policy support for both existing technologies and research into new solutions, Houston's industrial sector can accelerate its decarbonization efforts and continue the region's position as a global leader in the energy transition. At the same time, by embracing decarbonization, Houston can maintain its competitive advantages in a world of rapidly changing consumer preferences. Industrial decarbonization investments in the Houston area will stem from upgrades to and replacements of the existing asset base in parallel with new assets being added to the regional portfolio to address growing global demand for emissions reductions and decarbonized products.

This study focuses on facility-level strategies to tackle Scope 1 emissions from heavy industry within a 10-county region encompassing greater Houston. It maps major emissions sources and volume to begin identifying opportunities for and a potential sequence of reduction. The study reviews Scope 2 emissions impacts associated with the increased power needs of electrification as a decarbonization pathway but does not otherwise consider the region's Scope 2 emissions.

Methodology and Assumptions

Through in-depth interviews with key stakeholders in the region, including asset owners and operators, four primary levers targeting Scope 1 emissions emerged for upgrading existing facilities across major industrial sectors: (1) energy efficiency, (2) electrification, (3) hydrogen, and (4) point-source carbon capture and sequestration (CCS).

Three scenarios were developed to assess the decarbonization pathways:

- **Scenario 1 Business as Usual (BAU):** 2% gross domestic product (GDP) annual growth added to existing industrial production base
- **Scenario 2 Selective Investment (SI):** No decarbonization solutions with a cost greater than $85/ton of CO_2 abated are implemented
- **Scenario 3 Net Zero (NZ):** All emissions are eliminated — regardless of estimated cost of abatement — using a combination of the four primary decarbonization levers and direct air capture (DAC)

The implied investment opportunities and subsequent economic impacts for the Houston region between now and 2050 were then estimated for each scenario.

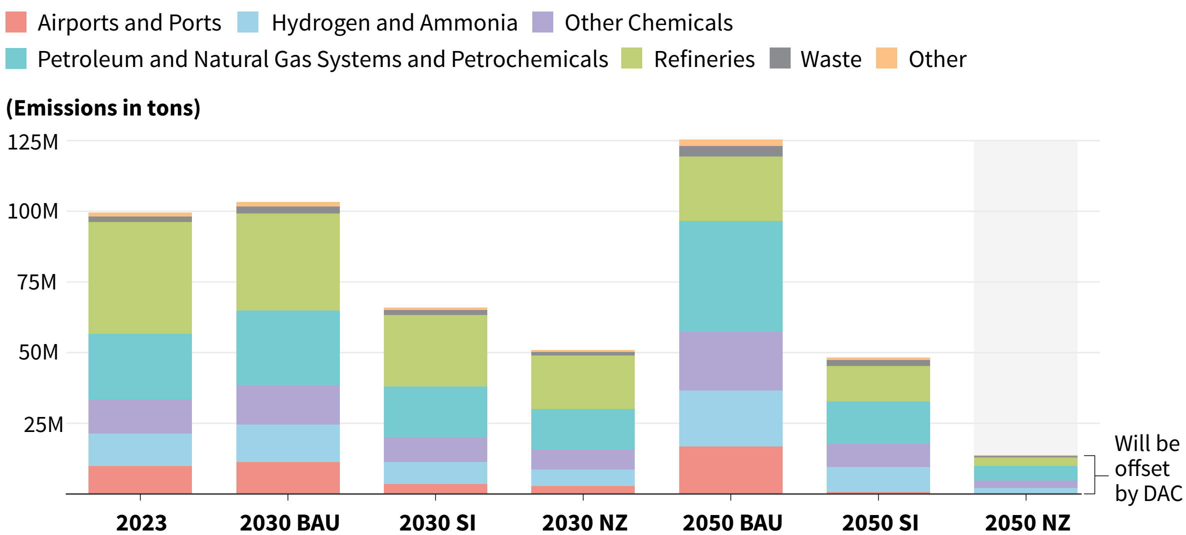
A detailed carbon abatement cost curve methodology was employed to approximate the relative cost-effectiveness of implementing each decarbonization lever. This approach allowed for development of the SI scenario, which analyzes the interplay between managing the emissions intensity of individual assets while maintaining their long-term economic viability. The total-cost-of-abatement values were then utilized as an approximation for the incremental economic impact to the region's economy resulting from investing in industrial decarbonization.

Results

Electrification emerges as the most impactful emissions reduction strategy across industries, representing most of the solution set in the SI scenario. At over 52 million tons fewer CO_2 equivalent emissions compared with regional Scope 1 emissions today, electrification in the SI scenario realizes over 76 million tons of Scope 1 emissions reductions in 2050 compared with the BAU scenario. Expected cost reductions and ongoing policy support mean decarbonization strategies are sensitive to modeling assumptions; however, both the SI and NZ scenarios also demonstrate that energy efficiency upgrades and implementation of low-carbon solutions such as clean hydrogen and CCS are necessary contributors to achieving substantial emissions reductions. Exhibit ES1 compares the Scope 1 emissions profiles of Houston's industrial asset base today, in 2030, and in 2050 for the three scenarios.

Exhibit ES1

Annual Scope 1 Emissions for the Scenarios



Note: NZ scenario emissions exclude reductions from DAC.

RMI Graphic. Source: RMI analysis

The potential economic impacts resulting from embarking on a concerted industrial decarbonization journey are considerable. In the SI scenario, it is estimated that more than 14,000 jobs per year would be created from industrial decarbonization within the Houston region; in the NZ scenario, the same region could see nearly 21,000 jobs added annually.

This study quantifies potential economic growth and emissions reduction benefits in just one region of the United States achieved by not only implementing, but also embracing and capturing energy transition opportunities. It also identifies a framework for other geographies to similarly identify pathways to lower-carbon futures.

PART 1

Houston's Energy Leadership: Driving the Global Transition to a Low-Carbon Future

Houston Is Poised to Continue Its Leadership Role in the Energy Transition

Texas is the national leader in energy production, accounting for more than a quarter of the United States' domestically produced energy, nearly 15% of the nation's total refining capacity, and more than 44% of the nation's base petrochemicals manufacturing capacity.[2] Houston, known as the energy capital of the world, is home to more than one-quarter of the country's publicly traded oil and gas exploration and production firms.[3] The city boasts a high concentration of energy expertise that is applied locally and globally,[4] playing a critical role in the worldwide operations of several international energy companies and major renewable energy developers.[5] Over the past three decades, refining, petrochemicals, and upstream/midstream industries have provided approximately 60% of the jobs in the Houston Metropolitan Statistical Area.[6]

The city's historic leadership in the energy sector, coupled with its growing innovation ecosystem driven by corporate incubators and accelerators for energy- and climate-technology startups, sets the stage for the greater Houston region — hereafter referred to as Houston or the region — to pioneer groundbreaking solutions and technologies that will shape the future of industrial decarbonization. Houston's decarbonization journey began more than two decades ago, with early investments in renewable energy leading to rapid reductions in power sector emissions. Additionally, early adoption of clean energy technologies and sustainability commitments, coupled with the region's natural endowments, laid the foundation for current efforts by Houston's industrial actors to decarbonize the energy sector. As the region continues building on prior progress, it is poised to accelerate its progress toward a low-carbon future, leveraging its experience, resources, and capabilities for innovation to drive meaningful change across the energy industry.

Houston's Decarbonization Journey Is Already Underway

Houston's journey toward decarbonization began over 20 years ago with power, as the sector managed to reduce emissions during a period of overall growth in demand. Since 2013, the carbon intensity of power generation across Texas (excluding industrial combined heat and power, or CHP) has decreased by 11%, while net generation has simultaneously increased by 26%.[7] Although the electric grid in Texas has significant room to further decarbonize, progress to date has been made as renewable generation sources increased relative to fossil energy–powered facilities.

Texas's success in demonstrating progress toward decarbonizing the power sector also laid the groundwork for Houston to develop future decarbonization-driven growth opportunities. With a solid foundation, Houston is now poised to embark on the next chapter of its energy leadership journey, focused on the decarbonization of heavy industry — representing an opportunity for the potential preservation of capital-intensive, largely immobile production facilities in the region.[8]

Houston Can Experience a Repeat "Double Bottom-Line" Benefit from Industrial Decarbonization

In the same way heavy industry has contributed to the economic growth of Houston, it has an opportunity to play a leading role in tapping the region's potential to drive future economic growth through its emissions abatement journey. Since 2021, industry leaders have announced several decarbonization projects, in some cases preceding the announcement of relevant tax and research and development incentives from the federal government. Startup companies have also clustered in Houston to leverage proximity to fellow innovative technology companies, established sector businesses, and the city's innovation and education centers.

The region has also become a hub for proposed low-carbon investments across the energy and industrial sectors in recent years, with liquefied natural gas production and export terminals, hydrogen production, and carbon capture facilities redefining the regional capital investment landscape. Additional notable examples of announced commercial projects demonstrating industry interest in a low-carbon future for the region include:

- A proposed $100 billion offshore CCS project leveraging the region's geologic storage potential[9]
- A 2022 collaboration between Linde and bp on a CCS project, seeking to leverage existing workforce and geographic benefits[10]
- A proposed ammonia export facility to support expected global growth of ammonia as a low-carbon shipping fuel[11]
- A proposed power-to-X facility for e-methanol production along the Gulf Coast,[12] enabling lower-carbon shipping routes from the region

Houston is already well positioned to maintain its existing talent pool and generate value for existing assets in a decarbonized world given inherent similarities between legacy industrial facilities and their low-carbon counterparts.

This progress and robust pipeline of investments are encouraging signals that emissions increases and economic growth in Houston are not necessarily correlated. In fact, the opposite can be true: With the right investments, the region's economic engine can continue expanding and create new opportunities for decarbonized goods and services.

Why This Research?

A combination of factors could position Houston as a decarbonization leader. This work aims to quantify the potential benefits to the region of implementing industrial decarbonization. This analysis evaluates current and potential industrial decarbonization activity across the region, examines additional solutions that can be employed, and quantifies emissions and economic impacts relative to a business-as-usual trajectory.

Commissioned by the Houston Energy Transition Initiative (HETI), this analysis leverages its ongoing work to enable Houston to capture opportunities to lead the world in industrial decarbonization pathways that deliver low-carbon energy and products affordably and reliably, drive sustainable economic growth, and create skilled jobs across the region.

Policy Support, International Demand, and Voluntary Corporate Commitments Are Already Driving Industrial Decarbonization

A combination of US regulatory support mechanisms, climate legislation in other jurisdictions, and voluntary corporate net-zero commitments are driving a global industrial decarbonization market that will contribute to job creation and overall growth in the regional economy. Policy support via federal incentives can help Houston industry seize energy transition opportunities by reducing the near-term deployment costs associated with first-mover commercial-scale projects. Available federal incentives potentially reduce the lifetime capital and operating expenditure for assets placed into service within a qualifying period, and in some cases incentives can stack across a supply chain with tax credits and grant funding to further reduce up-front investment costs.[13]

The Inflation Reduction Act (IRA) of 2022 included several new opportunities for eligible industrial decarbonization projects and created additional funding opportunities administered by the US Department of Energy (DOE) for technology demonstration, research, and development. Altogether, the policy mechanisms are designed to spur investment and construction while channeling benefits to local communities through domestic materials and local workforce requirements. Examples of federal tax credit provisions potentially benefiting the region include:

1. **IRS Section 45X:** Known as the advanced manufacturing tax credit, Section 45X provides a credit to domestic manufacturers of critical technologies, including some derived from or needed for industrial decarbonization activities. *Potential use cases for this credit include domestic manufacture of solar and wind energy components, qualifying battery materials, and applicable critical minerals*.[14]

2. **IRS Section 48C:** The Qualifying Advanced Energy Credit Program (now closed to new applicants), or Section 48C, offered project developers two rounds of tax credits for qualifying industrial decarbonization projects achieving emissions reductions of at least 20%. *At least two projects in the region have disclosed 48C awards, one for a project to reduce emissions from chemicals manufacturing and another to reduce emissions from the manufacture of electrolyzers.*[15]

3. **IRS Section 45V:** Known as the Clean Hydrogen Production Credit, Section 45V rewards clean hydrogen producers with a tax credit of up to $3.00/kg based on the carbon intensity of the production pathway. *The 45V credit is production technology neutral and can be utilized by existing and new producers of hydrogen*.

4. **IRS Section 45Q:** The Carbon Oxide Sequestration Credit, or Section 45Q, rewards CCUS developers that permanently store or utilize CO_2 with tax credits worth up to $85/ton, potentially improving project life-cycle economics. *Industrial facility, refinery, power generation, and pipeline operations all qualify as carbon oxide emissions sources for the 45Q tax credit.*

Other credits for the development of renewable energy resources can benefit industrial decarbonization projects, including **IRS Sections 48E** and **45Y**.

In addition to the incentives created through US Treasury mechanisms, opportunities created by the DOE and its Loan Programs Office play a crucial role in developing supply-side incentives for the region's private sector. Notable examples include the Industrial Heat Shot initiative for supporting commercialization of efficient high-temperature process heating, and the DOE's selection of Houston's hydrogen hub proposal, HyVelocity, for award negotiations from a national pool of Regional Clean Hydrogen Hub proposals.[16]

McKinsey & Company analysis of US Bureau of Economic Analysis data concluded that hydrogen hub development in Houston — such as the proposed HyVelocity Hub, comprising seven industry incumbents and several nonprofit organizations[17] — could generate 180,000 jobs related to a hydrogen economy by 2050, highlighting the significant potential for economic growth and job creation while reducing production costs associated with one decarbonization lever.[18]

Beyond securing competitive advantages in the region, Houston industry must also navigate climate legislation in other jurisdictions and voluntary corporate net-zero commitments, which are driving markets and creating demand for low-carbon products. Global market and regulatory forces mean Houston's industrial outputs may one day be subject to reviews such as carbon border adjustment mechanisms when exporting products to other regions. Undertaking industrial decarbonization measures sooner rather than later could combine the benefits of spreading compliance costs over time, leveraging current US policy mechanisms to gain early market share, and accessing premium markets for decarbonized products.

Implementation of industrial decarbonization measures would enable Houston to pursue emissions reductions while simultaneously growing both economic prosperity for the region and industry opportunities to service increasing global demand for decarbonized energy, transport,[19] feedstocks, and industrial products. This analysis aims to qualify the "double bottom-line" positive impacts for the region of embracing the energy transition and to demonstrate that meaningful reductions in Scope 1 emissions can be achieved in the near term.

Regions beyond Houston with similar industry agglomeration, existing infrastructure and natural resource availability can benefit from similar double bottom-line growth by leaning into decarbonization to maintain existing economic drivers while also reducing emissions and improving quality of life in their communities.

Study Parameters

This study employs scenarios to explore potential paths for industrial decarbonization in Houston. By identifying, defining, and examining various possible future states and conditions that could shape the course of decarbonization efforts, this approach helps stakeholders, policymakers, and analysts understand the different possibilities, uncertainties, and factors influencing the transition to a low-carbon or carbon-neutral future.

To facilitate this exploration, time snapshots were chosen of the years 2030 and 2050 to establish a short-to-mid-term goal and a long-term vision, respectively.[i] The selection of these years aligns with major research, significant international agreements, and climate change targets because 2030 and 2050 are often linked to key policy and technological development milestones and socioeconomic transformation. Building on Texas's decarbonization progress, particularly in renewables integration, which has lowered statewide Scope 2 emissions, this study focuses on facility-level strategies to tackle Scope 1 emissions while also emphasizing optimization and renewal of the existing industrial asset base.

A Scope 1 emissions boundary was established for this study to map and identify the major sources of heavy industry carbon emissions and carbon emissions reduction opportunities within a 10-county area including and surrounding Houston (see Exhibit 1).[ii] The study also integrates a preliminary analysis

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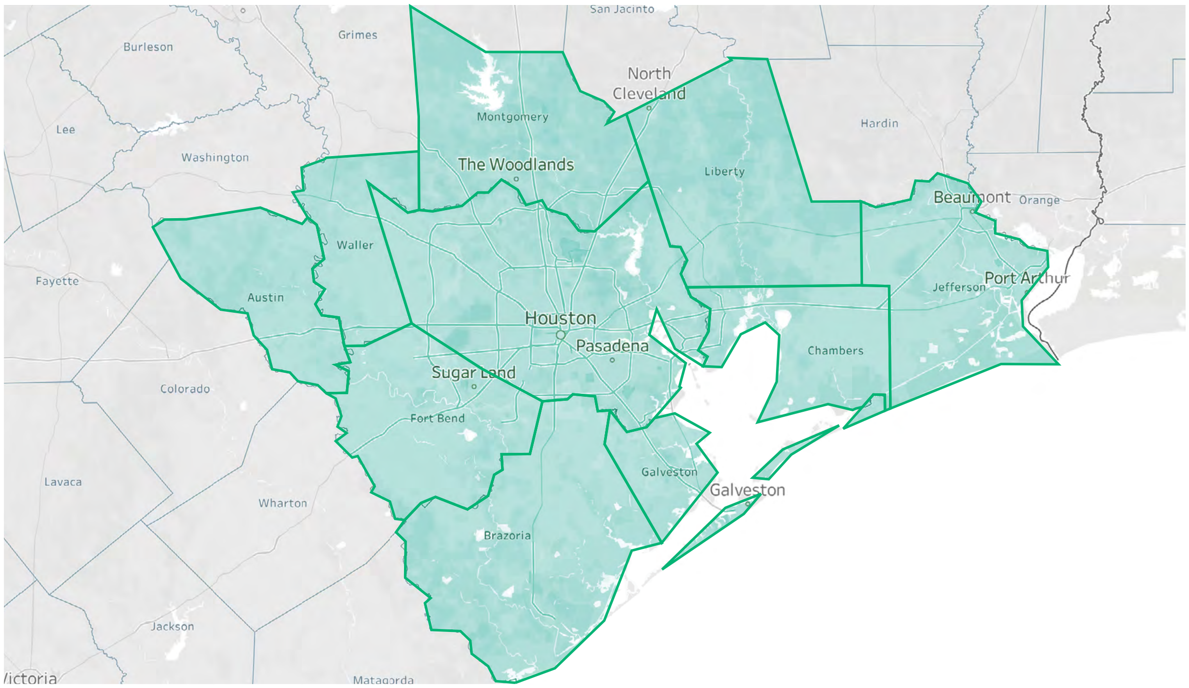
i For years between the time snapshots, the study assumes a linear progression.

ii The 10 counties are Austin, Brazoria, Chambers, Fort Bend, Galveston, Harris, Jefferson, Liberty, Montgomery, and Waller.

of the expected increase in Scope 2 emissions from the region's increase in power consumption from electrification, CCS, and hydrogen production technologies adopted in industrial decarbonization efforts. Further considerations for future research are identified in *Part 5: Houston's Paths Forward for Clean Growth*.

Exhibit 1 Map of the 10 Counties in this Study



Note: The 10 counties highlighted above were within the study's scope.
RMI Graphic. Source: RMI analysis

The sole focus on Scope 1 emissions is admittedly incomplete because it avoids analysis of the full life-cycle impact of industrial activity in the region. However, the Scope 1 analysis also presents opportunities for analyzing the specific role of the existing industrial asset base in the region's emissions profile and provides a platform for beginning to quantify the economic opportunity of continuing Houston's decarbonization journey.

PART 2

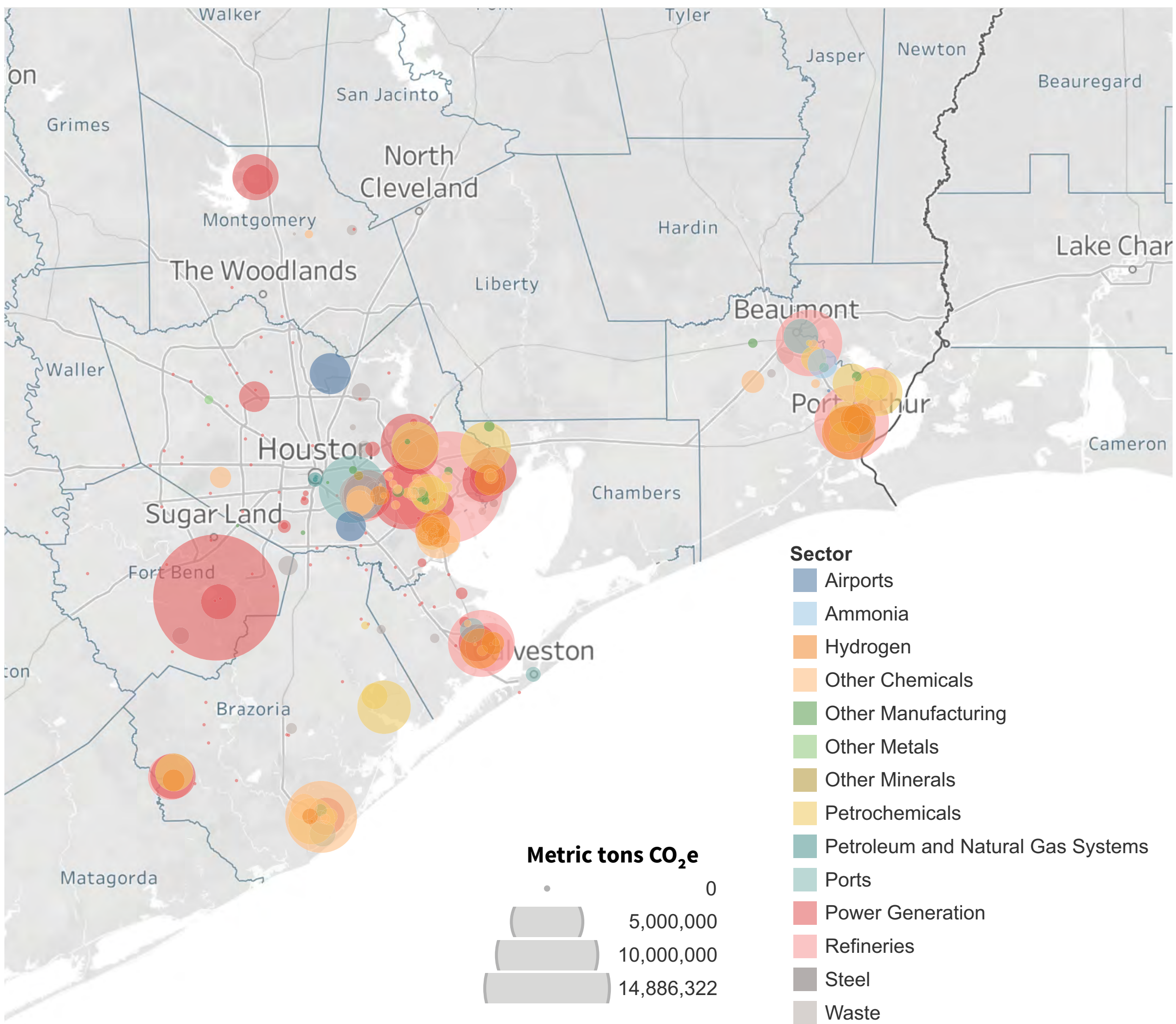
Assessment of Houston's Industrial Decarbonization Levers

Emissions Baselines

Data sets from the US Department of Environmental Protection's (EPA's) Greenhouse Gas Reporting Program, the US Department of Transportation, and Climate Trace were compiled to establish a comprehensive emissions baseline for industrial activities in the Houston area (see Exhibit 2).

Exhibit 2

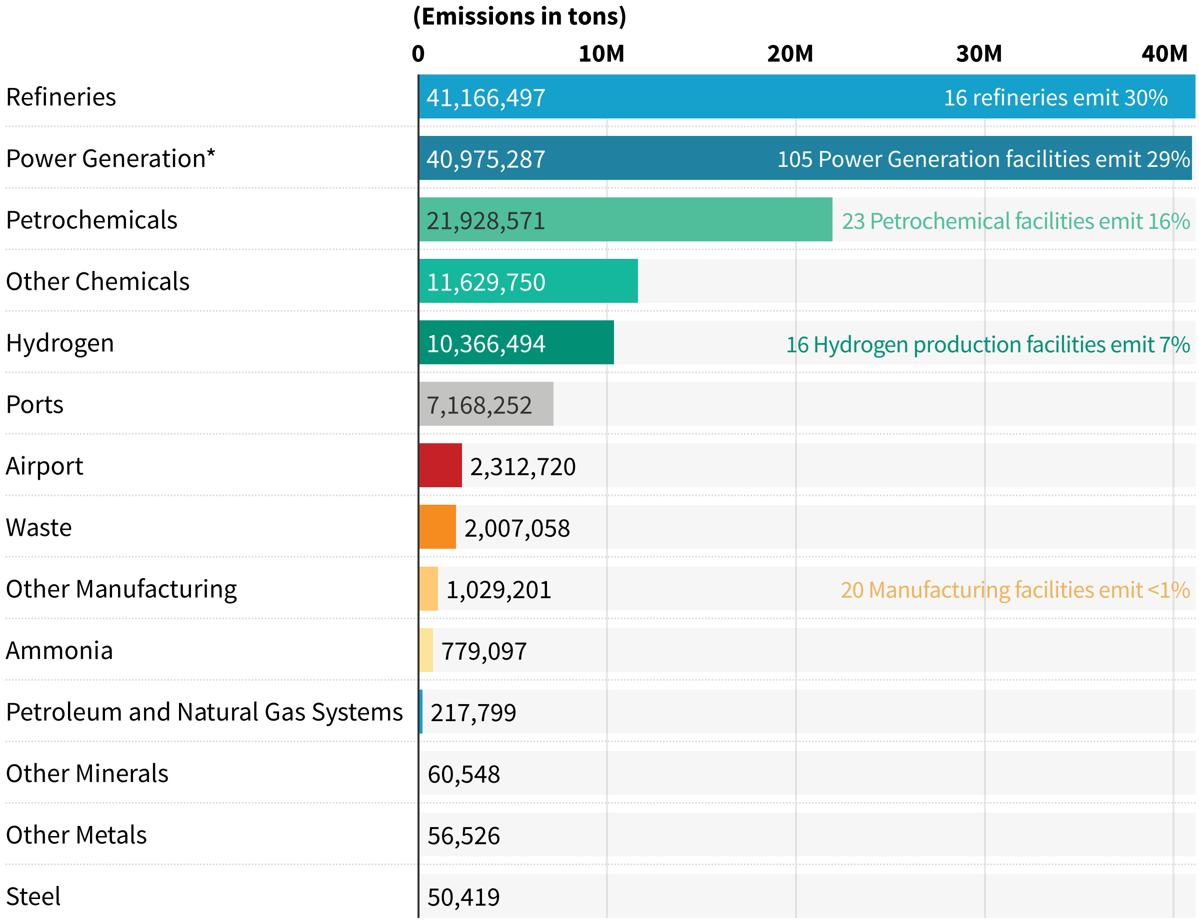
Scope 1 Emissions in the Greater Houston Region



RMI Graphic. Source: RMI analysis of EPA Flight data, 2021

This baseline serves multiple purposes: It identifies industrial activity clusters, highlights the region's most prominent industrial sectors, and provides a reference point for tracking emissions trends over time. It also is the foundation for developing a business-as-usual scenario for industrial activity and industrial emissions.

Exhibit 3 Industrial Emissions in the Greater Houston Region



* Power generation emissions are not included in this study's baseline values given the Scope I focus.

RMI Graphic. Source: EPA Greenhouse Gas Reporting Program, 2021

Exhibit 3 illustrates the breakdown of emissions in the greater Houston area. Refining and petrochemicals operations account for the largest share of industrial emissions, a result consistent with Houston's prominent role in the energy sector. Even though there has been a historic transition from natural gas to wind and solar power in Texas, Houston's power generation relies heavily on fossil fuel sources. This contrasts with the wind- and solar-dominated energy production in West and North Texas.

The Houston Ship Channel is a hot spot of industrial activity, driven by its strategic location for exports and imports. The chemicals sector stands out as a significant contributor to the region's emissions profile. Although regional freight trucking emissions data is not available, statewide figures indicate a substantial impact from heavy-duty trucking in Texas feeding the large Houston metro population and its industrial assets. Given the presence of six ports in the greater Houston area, it is likely that a considerable portion of these trucking emissions are concentrated in the region.

This baseline assessment provides valuable insights into the current state of industrial emissions in Houston, setting the stage for targeted decarbonization efforts and a variety of interventions.

Identifying Levers for Houston's Industrial Decarbonization

Extensive research, industry benchmarking, and direct consultations with key members of the Houston Energy Transition Initiative (HETI) identified four primary levers for accelerating the decarbonization of heavy industry in the region.

- **Energy efficiency measures**, such as leveraging grid renewables deployments to facilitate employing energy monitoring and control systems; recovering energy from flare gas, waste heat and power; improving steam distribution insulation; optimizing operational procedures for distillation; properly sizing motors, pumps, fans, and compressed-air equipment; and switching facility lighting to high-efficiency bulbs[20]

- **Electrification of industrial processes**, such as replacing fossil fuel–based heating systems with electric heat pumps or resistance heaters and using electric motors instead of diesel or natural gas powertrains for machinery and vehicles[21]

- **Hydrogen substitution**, for example, substituting a lower-emissions fuel source or feedstock for fossil fuels such as natural gas in chemicals or for use in e-fuels production

- **Point-source CCS**, for example, implementing technology to gather flue gases from industrial facilities for processing and sequestration[22]

The four levers define primary Scope 1 emissions reduction opportunities for the industrial asset base in Houston. The larger-scale adoption of emissions reduction technologies or the execution of decarbonization projects by asset owners will have economic considerations.

The economics of industrial decarbonization projects will be influenced by policy support to offset initial costs and create a supportive regulatory environment, long-term technology improvements and cost reductions, and shifting consumer preferences that increase demand for low-carbon products and services. The levelized cost of abatement for each solution can be used to align economic considerations with emissions reduction opportunities to develop scenarios that forecast the reductions.

Texas Structural Advantages: Accessible Renewables and Natural Gas

The cost of green hydrogen (and other industrial decarbonization solutions reliant on renewable electricity) is closely tied to the price of renewable power. Texas has a notable competitive advantage in terms of renewable power purchase agreement (PPA) prices compared with other regions in the United States. Among the major US independent system operator (ISO) regions, ERCOT boasts the lowest median PPA price, with a potential spread of nearly $20/megawatt-hour (MWh) versus the ISO with the highest-median price, PJM. As a result, Texas's renewable PPA price is estimated to be $10/MWh lower than the national average, and green hydrogen costs $0.70 less per kg than the national average. This corresponds to a carbon abatement cost of switching to green hydrogen that is $100/ton of CO_2 less than the national average.

The price advantage of renewable power in Texas also leads to an easier transition toward electrification in industrial facilities. According to a McKinsey study,[23] the break-even point for electrification versus conventional fuel consumption in industrial applications starts at process heating temperatures below 100 degrees Celsius (°C) when the price of electricity is well below $70/MWh. For process heating with temperatures between 100°C and 1,000°C, switching to electricity becomes economical when electricity prices range from $10 to $30/MWh (without a carbon tax). If a carbon tax of $100/ton is assumed, the break-even points shift to $30 to $50/MWh. Texas's renewable PPA prices fall within this break-even range without a carbon tax. Consequently, the availability of cheaper renewable energy makes electrification economically attractive in Texas.

Similar to how the renewable power price is related to the cost of green hydrogen and of electrification, the cost of blue hydrogen is closely linked to natural gas cost. Texas has a decades-long track record of low industrial natural gas prices, ranging from 7% to 30% lower than the national average. Between 2010 and 2020, the industrial natural gas price for Texas has been $0.70 to $1.0/thousand cubic feet lower than the national average. This leads to the blue hydrogen cost being $0.32 to $0.46/kg lower than the national average and in turn lowers the carbon abatement cost of switching to blue hydrogen by $53 to $75/ton.

Decarbonization Scenarios: Business as Usual, Selective Investment, and Net Zero

The development of a forecast for emissions reduction aligns with three scenarios to assess decarbonization pathways, the implied investment opportunities, and subsequent economic impacts for Houston between now and 2050:

1. Business-as-Usual (BAU) scenario
2. Selective Investment (SI) scenario
3. Net-Zero (NZ) scenario

By considering these three scenarios and their potential challenges and opportunities for emissions reduction — outlined in Exhibit 4 — stakeholders can better understand the range of possibilities and potential impacts of different decarbonization strategies on Houston.

Exhibit 4 Scenario Characteristics

Scenario	1. Business as Usual (BAU)	2. Selective Investment	3. Net Zero (NZ)
Description	Emissions growth based on general sector growth rate	Apply the four decarbonization levers (energy efficiency, electrification, hydrogen and CCS) to the BAU scenario. Then utilize a carbon abatement cost curve to decide which decarbonization levers will be implemented for each sector	A Houston-regional adoption of IEA's World Energy Outlook Net Zero scenario with high penetration rate of decarbonization levers and DAC to achieve net zero by 2050
Purpose	Understand Houston's emissions challenge because it is one of the US' and the world's manufacturing centers	Analyze the development pathway with all economically viable decarbonization solutions assuming affordability parameters	Find the remaining gap of achieving net zero in 2050
Level of Decarbonization	Low	Mid	High

RMI Graphic. Source: RMI analysis

Scenario 1: Business as Usual

The BAU scenario assumes sector emissions will align with both broader US GDP growth and expected contraction of the refinery sector. The BAU scenario assumes 2% annual GDP growth added to the existing industrial production base.[iii]

Although this assumption accounts for anticipated demand changes and the ongoing transition to alternative fuels, particularly in the contracting refinery sector, it is crucial to acknowledge that the BAU scenario does not include a detailed modeling analysis to provide a comprehensive understanding of the intricacies involved in these changes. The BAU analysis also does not account for international impacts on Houston's annualized growth.

Scenario 2: Selective Investment

The SI scenario presents a pragmatic approach to decarbonization incorporating levelized cost of abatement. This scenario considers the economic viability of decarbonization solutions and prioritizes cost-effective strategies to ensure affordability. A "cutoff" levelized cost of abatement of \$85/ton of CO_2 or less, which represents carbon trading levels in European markets as of December 2023, is used as a filter for emissions reduction implementation within this scenario.

Among all the references,[24] the DOE study on decarbonizing chemicals and refining stands out as the most up-to-date and relevant, given that a significant portion of Houston's industrial emissions are related to these sectors. When comparing the figures from the DOE study with those of other research, it becomes evident that the costs for abatement in the United States tend to align with the higher end of the cost spectrum observed in global studies. Consequently, for other sectors where this research relies on references that provide only global averages, the upper limit of the cost range is used. This approach reflects the observed trend and ensures that estimations remain relatively conservative.

To determine the most cost-effective decarbonization pathways, this scenario employs a carbon abatement cost curve, which assesses the abatement costs associated with implementing each decarbonization lever

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iii Several stakeholders interviewed for this analysis believed that overall demand for fossil fuel refineries would decline as the energy transition progresses from liquid fuels to electricity and/or hydrogen. Nevertheless, the same stakeholders surveyed anticipated sustained growth in the demand for petrochemicals, attributed primarily to the economic expansion of the Southeast Asian market.

(energy efficiency, electrification, hydrogen, and point-source CCS) across various solutions within each industry and ranks options by their cost-effectiveness.

Applying a cost cutoff line filters the decarbonization opportunities. Measures with superior cost efficiency are included in the scenario, whereas technologies above the cost cutoff line are excluded, under the assumption that they would require additional technological or policy support to become more affordable.

In all scenarios, Houston emissions from all industrial sectors are segmented into six groups and aligned with the carbon abatement costs for their respective decarbonization measures using reputable references. Exhibit 5 outlines the sector groups and the primary references used to source national or global averages for their carbon abatement costs. Although determining the precise cost value of each lever can be challenging, the cost curve gives a rough idea of the relative relationship between the emissions reduction potential and the unit cost of each decarbonization opportunity. The outcome indicates the cost-effective emissions reduction pathways for mitigating climate change, within the scenario's specific price threshold. *Integrating Levelized Cost of Carbon Abatement* provides more details about the resulting cost of abatement curve.

Exhibit 5 Sector Groups and the Primary References for Their Carbon Abatement Costs

Reference cost curve sector	Houston industrial subsectors	Reference study
Chemicals and refinery	• Ammonia • Hydrogen • Other chemicals • Refineries • Other manufacturing (mainly plastic)	• DOE's *Pathways to Commercial Liftoff: Decarbonizing Chemicals & Refining* • IEA's *Levelized cost of CO_2 capture by sector and initial CO_2 concentration*
Steel and iron	• Steel • Other metals	• EDF's *A revamped cost-curve for reaching net-zero emissions*
Petroleum and gas	• Petroleum and natural gas systems • Petrochemicals	• McKinsey's *Pathways to a Low-Carbon Economy: Version 2 of Global Greenhouse Gas Abatement Curve*
Cement	• Other mineral	• DOE's *Pathways to Commercial Liftoff: Low-Carbon Cement*
Waste	• Waste	• EPA's *Global Mitigation of Non-CO_2 Greenhouse Gases*
Building and transportation	• Airport • Port	• McKinsey's *Pathways to a Low-Carbon Economy: Version 2 of Global Greenhouse Gas Abatement Curve*

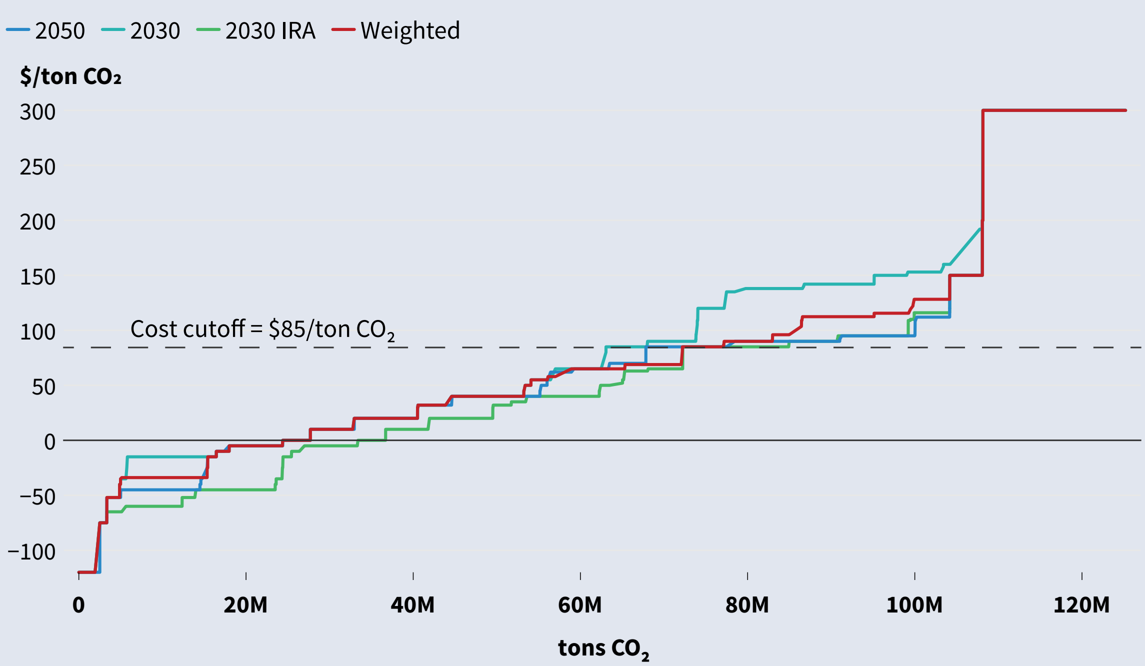
Integrating Levelized Cost of Carbon Abatement

The SI scenario utilizes a carbon abatement cost curve to assess the economic feasibility of decarbonization levers, evaluating the implementation costs of decarbonization measures for each sector and allowing for a cost-effective strategy that balances emissions reduction goals with financial viability. The cost curve reveals the interplay between policy, technology costs, and emissions reduction targets, and the methodology incorporates affordability into the decarbonization pathway, balancing environmental goals and economic considerations.

The cost curve ranks different mitigation options based on their cost-effectiveness. In Exhibit 6, the x-axis shows the reduced emissions and the y-axis represents the cost of achieving those reductions. Lower points on the curve indicate more economically efficient measures and higher points represent more expensive options. A cost cutoff line is applied to filter the decarbonization levers; measures below the cutoff are included in the scenario and those above are excluded because it is assumed that they would need further technological or policy support to become economically viable.

To account for the time-sensitive nature of abatement costs, a weighted average approach is utilized based on three estimates: 2030 costs with subsidies, 2030 costs without subsidies, and 2050 costs (naturally without subsidies). This approach factors in potential subsidies for hydrogen and CCS until 2030 under the IRA, before transitioning to cost reductions from technological improvements between 2030 and 2050. The methodology also assumes subsidies play a crucial role in deploying emerging decarbonization technologies, leading to positive feedback loops and achievement of economies of scale.

Exhibit 6 Carbon Abatement Cost Curve for Houston Industrial Sectors



RMI Graphic. Source: RMI analysis

Scenario 3: Net Zero

An ambitious forecast scenario for industrial decarbonization in Houston can be articulated by aligning assumption with the International Energy Agency's (IEA's) World Energy Outlook Net Zero scenario.[25] This comprehensive approach aims to achieve net-zero emissions by 2050 by integrating various high-impact decarbonization levers and incorporating DAC technology without the cost constraints assumed in the SI scenario.

The NZ pathway differs from the SI scenario in that it relies on market-rate solutions for development of decarbonization technology and assumes a larger role for both the application of CCS for process heating and the electrification of high-temperature process heating.

A defining feature of the NZ scenario is the pivotal role played by DAC technology. DAC addresses all remaining unabated emissions, such as incomplete capture by CCS and non-carbon emissions,[iv] ensuring any residual emissions are effectively captured and neutralized. This technology is critical in achieving the net-zero target by 2050 by abating emissions that cannot be reduced by any other means given existing decarbonization solutions.

By aligning with the IEA's Net Zero scenario target and leveraging a combination of the four decarbonization levers and DAC technology, Houston can position itself as a first mover in the global effort to combat climate change at scale. The NZ scenario represents a transformative future pathway for Houston that requires bold action, innovation, investment, and collaboration across all sectors of the economy.

iv For the waste sector, non-carbon emissions account for 50% of total emissions; therefore, modeling assumes 80% of emissions from the waste sector are hard to abate and are addressed by DAC. For all other sectors, the non-carbon emissions are insignificant and lumped into the unabated portion.

PART 3

Results by Scenario and Lever

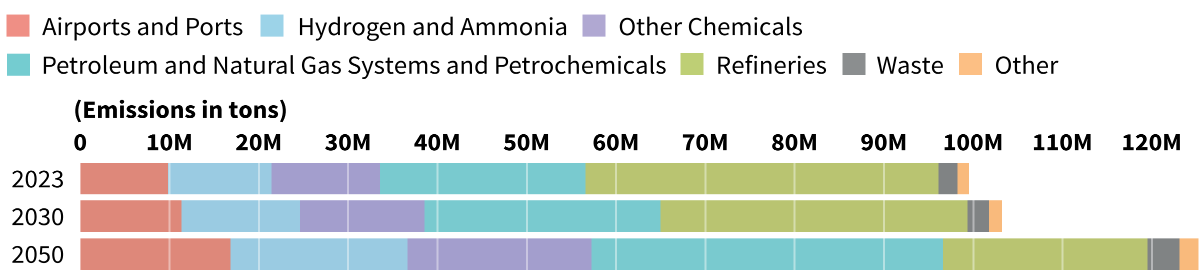
Scenario 1: Business-as-Usual Results

Exhibit 8 illustrates Houston's emissions for 2023. The refinery and chemicals-related sectors account for over 80% of Houston's industrial facility Scope 1 emissions.[v] Exhibit 7 also shows forecasted emissions for 2030 and 2050 under the BAU scenario. Under the BAU scenario, Scope 1 emissions from the industrial sectors in the Houston area are projected to increase significantly,[vi] as emissions rates and GDP growth continue to be directly correlated. In 2021, these emissions were estimated at around 99 million tons. By 2050, they are expected to rise to over 125 million tons, primarily driven by the refinery and chemicals-related sectors, even when assuming a modest contraction of the refinery sector.

The BAU scenario anticipates that the share of emissions from refining and chemicals will decrease from 88% in 2023 to 83% in 2050. This reduction aligns with the assumption that refinery capacity will shrink 2% annually owing to less dependence on fossil fuels. Despite that emissions decline, these sectors will continue to be the dominant contributors of industrial emissions in the region. Emissions from the remaining sectors — airports, ports, steel, other metals, other minerals, and waste — are anticipated to grow 2% annually, in line with expected GDP growth, slowly but steadily increasing their share of total industrial emissions.

The projected increase in overall Scope 1 emissions and the persistent dominance of the refinery and chemicals-related sectors despite the refinery production assumption highlight the significant challenges Houston's industrial sectors will face in the coming decades to address these sector emissions. These estimates emphasize the critical need for targeted emissions reduction strategies and the importance of focusing on the key refinery and chemicals-related sectors to achieve meaningful progress in decarbonization efforts.

Exhibit 7 Business-as-Usual Scenario Scope 1 Emissions Outlook for Houston



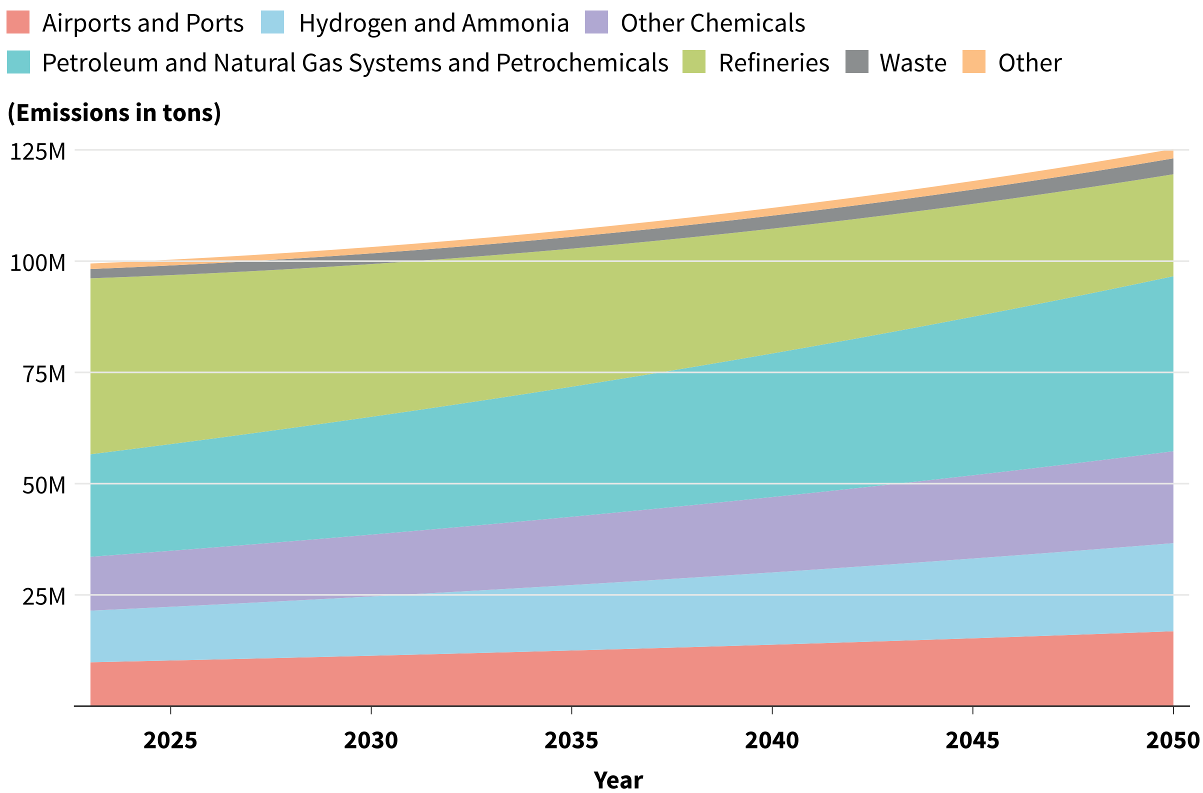
RMI Graphic. Source: RMI analysis

v Refinery and chemicals-related sectors in the Houston area include the ammonia, hydrogen, petroleum and natural gas systems, petrochemicals, other chemicals, other manufacturing, and refinery sectors.

vi The sector categorization follows EPA's Greenhouse Gas Reporting Program, which includes airports, ports, steel, other metals, other minerals, waste, ammonia, hydrogen, petroleum and natural gas systems, petrochemicals, other chemicals, other manufacturing (e.g., major plastic manufacturing), and refineries.

Exhibit 8 illustrates the year-on-year forecast of industrial emissions under the BAU scenario assumptions. The assumed regional economy annual growth rate of 2% is directly correlated to CO_2 outputs, leading to continually increasing emissions.

Exhibit 8 Business-as-Usual Scenario Emissions in Houston



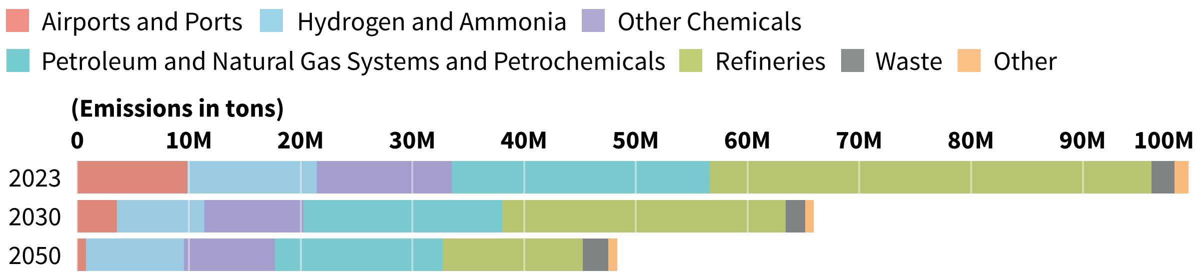
RMI Graphic. Source: RMI analysis

Scenario 2: Selective Investment Scenario Results

The SI scenario represents a significant step forward in Houston's decarbonization efforts, demonstrating the potential for cost-effective emissions reductions across various industrial sectors. The projected emissions reductions provide a clear roadmap for stakeholders to prioritize and implement decarbonization strategies that deliver both environmental and economic benefits.

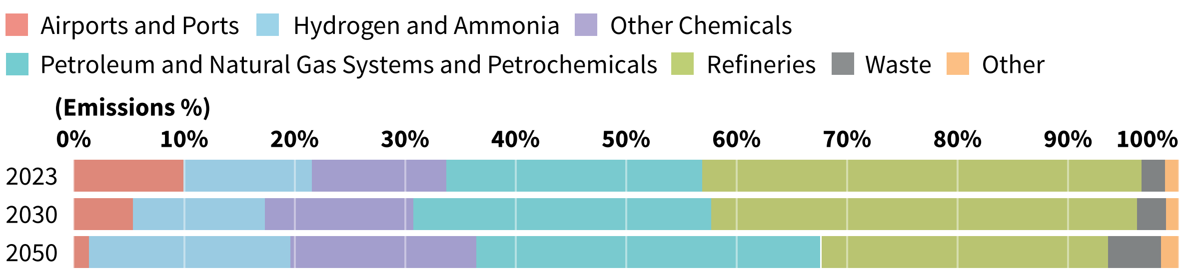
Exhibits 9 and 10 illustrate the change in sector emissions from 2023 to 2030 and 2050 using the SI scenario assumptions. If targeted industrial sectors make selective decarbonization investments, Scope 1 emissions in Houston are projected to decrease by 61% by 2050 compared with the BAU scenario. Accordingly, Scope 1 emissions are expected to decrease to 66 million tons in 2030 and 48 million tons in 2050.

Exhibit 9 Selective Investment Scenario Scope 1 Emissions



RMI Graphic. Source: RMI analysis

Exhibit 10 Share of Overall Scope 1 Emissions in the Selective Investment Scenario



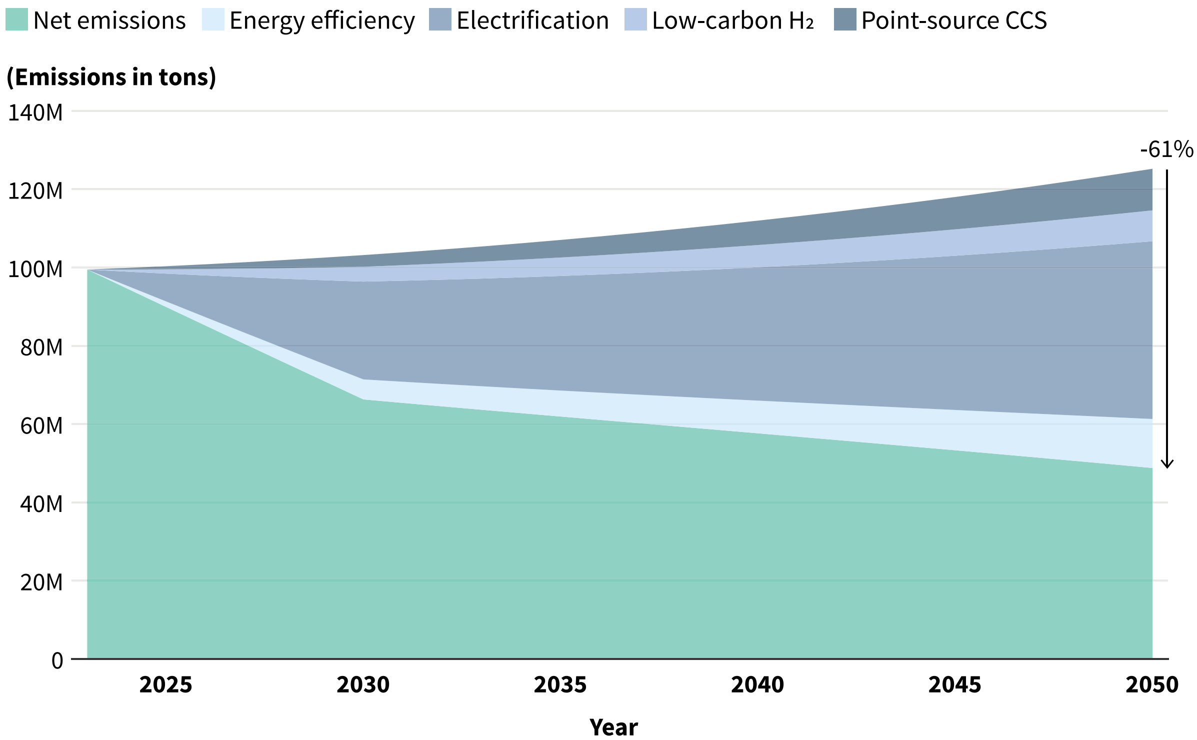
RMI Graphic. Source: RMI analysis

The refinery and chemicals-related sectors, which currently represent the largest share of industrial emissions in Houston, are expected to see significant reductions under the SI scenario. Other industrial sectors, such as steel, cement, and plastics, are also projected to contribute to emissions reductions under the SI scenario, although to a lesser extent due to the smaller proportion of the existing asset base they represent. Additionally, implementing CO_2 reduction measures achieves steep decarbonization between 2024 and 2030, with steady but less steep reductions between 2030 and 2050.

In the SI scenario, electrification combined with energy transition in the power sector emerges as the most significant contributor to emissions reductions, as shown in Exhibit 11. By 2050, electrification is projected to result in over 45 million tons fewer emissions compared with the BAU scenario, accounting for 36% of the total 61% reduction in Scope 1 emissions resulting from this scenario.

Although a substantial portion of Houston's industrial emissions originates from high-temperature process heating, technologies such as machine-drive, non-process, and low-temperature process heating still contribute significantly to Scope 1 emissions. This is particularly evident in sectors such as airports and ports, where all Scope 1 emissions stem from building energy consumption and ground transportation.

Exhibit 11 **Selective Investment Scenario Scope I Emissions Reduction**



RMI Graphic. Source: RMI analysis

Electrification presents a promising solution for reducing emissions from non-high-temperature process heating based on the assumptions in this analysis, as electric motors and heat pumps demonstrate higher energy efficiency compared with their natural gas counterparts. Coupled with the anticipated decarbonization trends in the power sector and anticipated technology improvements over time, electrification becomes the most effective decarbonization strategy for Houston's industrial sector.

Electrification Takes the Lead in Emissions Reductions

The efficiency and effectiveness of this decarbonization lever is largely dependent on access to a low-carbon grid. This research posits that a significant fraction of industrial emissions might be mitigated through electrification, underpinned by the optimistic prospects of renewable energy. This perspective is informed by the historical trajectory of decarbonization within the power sector, which suggests a viable pathway for reducing emissions through the adoption of renewable power sources. Although all major research agrees that power sector emissions will reduce rapidly with the deployment of renewable generation, establishing a clean power system still faces challenges and needs a parallel set of efforts and collaboration from various stakeholders.[26]

Electrifying high-temperature process heat still faces technical challenges and carries high uncertainty regarding costs. As a result, electrification for high-temperature heat processes in most industrial sectors is not included in the SI scenario.

How Cost Reduction Forecasts for Emerging Technologies, Including DAC, Affect Decarbonization Pathways

Most energy efficiency and electrification levers considered in this analysis are relatively mature and do not depend on technology improvements to drive implementation. For example, this study indicates that Houston can achieve a 54% reduction in emissions by leveraging a portfolio of existing lowest-cost, technologically mature energy efficiency and electrification solutions.

Compared with the BAU scenario, implementation of certain energy efficiency levers results in a negative cost of carbon abatement; in other words, this implies that savings are generated from implementing solutions from existing portfolios of energy efficiency technologies. Although this suggests technology improvement is not a barrier to implementation, additional barriers may exist elsewhere, such as access to capital, competing investment opportunities, and misaligned corporate incentive structures.

Electrification solutions from most low-temperature process heat are also technologically mature, with a corresponding low cost of carbon abatement. However, this study assumes most high-temperature process heat will be addressed by clean hydrogen and carbon capture solutions. Unlike the previous examples, the cost of implementing high-temperature process heat solutions is highly dependent on technology improvements and solving ecosystem bottlenecks beyond this study's scope, including customer willingness to pay and supply chain development. In addition, hydrogen solutions are highly dependent on regulatory support mechanisms and could stagnate in the long term without rapid technology improvements and extensions of current federal subsidies.

CCS applications in most industrial sectors are currently on the higher end of the cost of carbon abatement spectrum (see Exhibit 6, page 19) and are therefore excluded from the SI scenario because they are above the predetermined $85/ton cost cutoff threshold, even when applicable subsidies are accounted for. However, the economics of CCS in the natural gas sector, which has significantly lower capture costs relative to other industries due to the high-purity emissions present in most assets, means it is included in the SI scenario.

Another major uncertainty affecting this study's results is the development speed of DAC technology, which is crucial for addressing the 14% of emissions with no clear alternative abatement solution. DAC costs represent the highest range of the cost curve used in this analysis (see Exhibit 6, page 19), assumed to be a weighted average of $300/ton between 2030 and 2050. A review of current literature on the subject yields a wide range of DAC cost estimates and varies by the assumed methodology and time period. For example, the IEA estimates costs at $125 to $335/ton of CO_2 removed, whereas World Resources Institute estimates costs at $250 to $600/ton of CO_2 removed.

DAC costs could decrease significantly with additional policies, regulatory support mechanisms, technology development, and repeated deployment. Future DAC costs are projected to eventually settle around $100/ton, in part through government initiatives such as the DOE's Carbon Negative Shot, which aims to reduce the cost of carbon removal technologies to $100/ton CO_2 over the next decade. However, because of the expected high costs of current and future DAC solutions, they are excluded from the SI scenario, which assumes only an economical subset of climate solutions are implemented. The NZ scenario relies on DAC solutions for the hardest-to-abate emissions, implying the total investment needed for full decarbonization of the region will be highly sensitive to the actual costs of implementing specific DAC technologies and assets.

Under the SI scenario, electrification contributes to a reduction of nearly 25 million tons of Scope 1 emissions in the industrial sector by 2030 and over 45 million tons by 2050. This translates to an increase in power consumption of over 40 million MWh in 2030 and 79 million MWh in 2050 for the power sector. However, energy transition efforts in the power sector are ongoing. The SI scenario assumes that the carbon intensity of Texas's grid power decreases from today's 0.4 kg CO_2/kWh to 0.3 kg CO_2/kWh in 2030 and to 0.04 kg CO_2/kWh in 2050, aligning with the global average carbon intensity of the power sector under the Announced Pledges scenario in the IEA's World Energy Outlook 2023.[vii] Thus, increased power consumption will only lead to a rise in power sector emissions of 11 million tons in 2030 and 3 million tons in 2050, which is significantly outweighed by the emissions reductions benefits generated in the industrial sector.

Energy Efficiency Improvement Is a Low-Hanging Fruit

Energy efficiency is widely acknowledged as an established and cost-efficient means of reducing carbon emissions in the industrial sector. It offers substantial potential for emissions reductions while also yielding economic and operational advantages. Numerous proven technologies and methods, including installing energy-efficient lighting, enhancing insulation, upgrading machinery to more efficient models, and implementing advanced control systems, can markedly decrease energy consumption and emissions with relatively short payback periods.

Furthermore, energy efficiency can yield various additional benefits beyond emissions reductions, such as increased productivity, enhanced competitiveness, and reduced operational expenses. These advantages further enhance the appeal of energy efficiency as a decarbonization tool in the industrial sector. In the SI scenario, efficiency improvements resulted in over 5 million tons of emissions reductions in 2030 and 12 million tons in 2050, constituting 10% of the total 61% reduction in Scope 1 emissions.

Low-Carbon Hydrogen: A Powerful Decarbonization Tool for the Houston Area

Low-carbon hydrogen presents a significant advantage in decarbonizing industrial sectors in Houston. The Houston area is home to many facilities in the refinery, petrochemicals, and chemicals industries, where a considerable portion of energy consumption arises from high-temperature process heat that could be addressed by transitioning to hydrogen. Additionally, Houston and the broader US Gulf Coast region have structural advantages for producing low-cost hydrogen, as detailed later in this report in *Maximizing Subsidies and Navigating Risks in Decarbonizing Houston*.

vii The Announced Pledges scenario in the IEA's World Energy Outlook 2023 (**https://www.iea.org/reports/world-energy-outlook-2023**) uses a more aggressive decarbonization transition of the US power sector, in which the carbon intensity of electricity decreases to 0.11 kg CO_2/kWh in 2030 and becomes negative in 2050. This study uses the global number as a relatively conservative assumption.

The cost of low-carbon hydrogen is expected to decrease rapidly with the support of IRA subsidies, technological advancements, and economies of scale. In the SI scenario, low-carbon hydrogen is included as a decarbonization lever in the chemicals and refinery sectors, reducing nearly 4 million tons of Scope 1 emissions by 2030 and 8 million tons by 2050. This constitutes 6.3% of the total 61% reduction in Scope 1 emissions this scenario targets. The transition will require approximately 0.7 million tons of low-carbon hydrogen locally in the Houston industrial sector by 2030 and 1.3 million tons by 2050.[viii]

Beyond the chemicals and refinery sectors, the carbon abatement cost of hydrogen in other sectors closely approaches the economic feasibility criteria set in the scenario. If the cost of hydrogen declines more rapidly than assumed in these sectors, the emissions reduction potential of low-carbon hydrogen could exceed 7 million tons by 2030 and 15 million tons by 2050 while also generating an annual local hydrogen demand of 1 million tons in 2030 and 2.1 million tons in 2050.[ix]

Point-Source Carbon Capture and Sequestration: Great Potential, but Cost Challenges Remain

Point-source CCS holds significant potential but still faces cost challenges. Initially, it will be utilized primarily in the natural gas and petroleum industries because of their high-purity carbon emissions streams and relatively low capture costs.[x]

Although CCS is a topic of interest in other industrial sectors and could offer substantial benefits, its costs remain relatively high and subject to significant uncertainty across different research findings. In the SI scenario, due to cost considerations, point-source CCS is included only for the natural gas and petroleum sectors. This still results in a reduction of nearly 3 million tons of CO_2 in the industrial sector by 2030 and over 10 million tons by 2050, representing 8.5% of the total 61% reduction in Scope 1 emissions targeted by this scenario. If the cost constraints of point-source CCS are removed and the lever is applied to all industries in this scenario, then emissions reduction could increase to over 10 million tons in 2030 and 28 million tons in 2050, underscoring the technology's significant potential.

Because of the power consumption associated with CCS, the potential of transferring emissions from the industrial to the power sector exists. However, based on the research conducted for this analysis, the increased emissions from CCS power consumption are unlikely to outweigh CCS's emissions reduction benefits, even using current grid emissions factors and DAC parameters. This is especially true given the expected energy transition in the power sector and the higher efficiency of industrial point-source CCS. In the SI scenario, point-source CCS will consume nearly 0.3 million MWh in 2030 and 1 million MWh in 2050, resulting in a slight increase in power sector emissions of just over 0.8 million tons in 2030 and 0.4 million tons in 2050.

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viii According to RMI analysis, replacing natural-gas-sourced industrial heat with 1 kg of zero-emissions hydrogen results in a reduction of 7 kg CO_2 emissions.

ix The hydrogen demand discussed here pertains solely to the decarbonization efforts within the focused industrial sectors in the Houston area. This is distinct from a widely recognized McKinsey & Company work, *Houston as the epicenter of a global clean hydrogen hub*, on clean hydrogen demand, which states that "demand for clean hydrogen in Texas could reach 21 MT by 2050." This broader estimate includes hydrogen demand from the building, power, and transportation sectors, as well as hydrogen for export markets across the entire state of Texas.

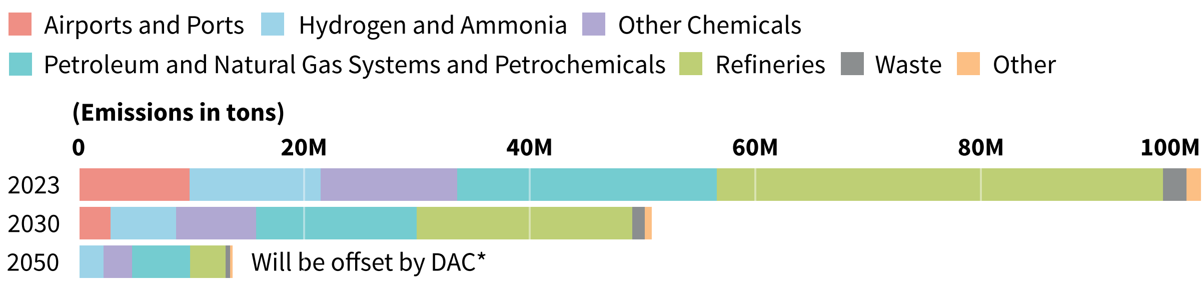
x According to a 2021 IEA analysis, ***Is carbon capture too expensive?,*** CCS of high-purity emissions from natural gas processing and ammonia, for example, cost less than $50/ton in 2019.

Scenario 3: Net-Zero Scenario Results

The NZ scenario represents the most ambitious pathway for Houston's industrial decarbonization, requiring significant investments in low-carbon technologies, infrastructure, and research and development. Although challenging, this scenario demonstrates the potential for Houston to become a global leader in industrial decarbonization.

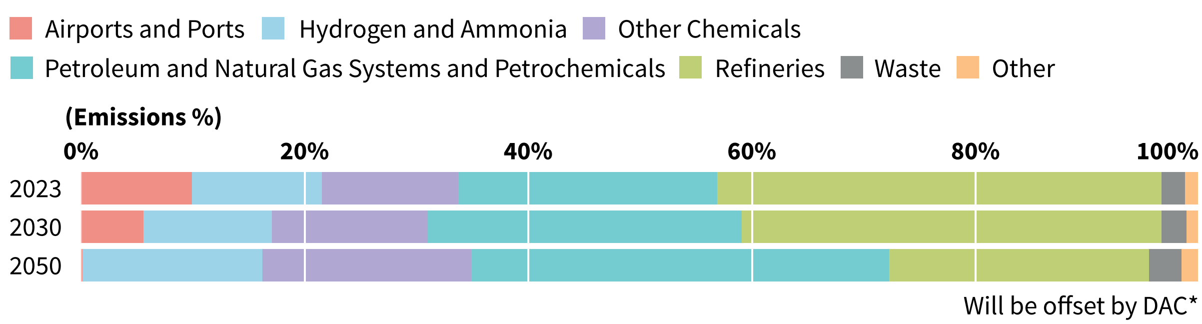
Exhibits 12 and 13 illustrate the change in sector emissions from 2023 to 2030 and 2050 using the NZ scenario assumptions. Under the NZ scenario, Houston's industrial sectors achieve zero Scope 1 emissions by 2050. This ambitious target results from comprehensively implementing all available carbon reduction measures, including energy efficiency, electrification, hydrogen, point-source CCS, and DAC technology. Notably, even with a comprehensive plan to upgrade the existing asset base, it will remain technically unfeasible to convert several hard-to-abate industrial processes to net zero. This means investments in DAC will be necessary to offset these emissions. In this scenario, DAC alone is expected to help abate an estimated 13.7 million tons of CO_2 by the year 2050.

Exhibit 12 Net-Zero Scenario Scope 1 Emissions



RMI Graphic. Source: RMI analysis

Exhibit 13 Share of Overall Scope 1 Emissions in the Net-Zero Scenario



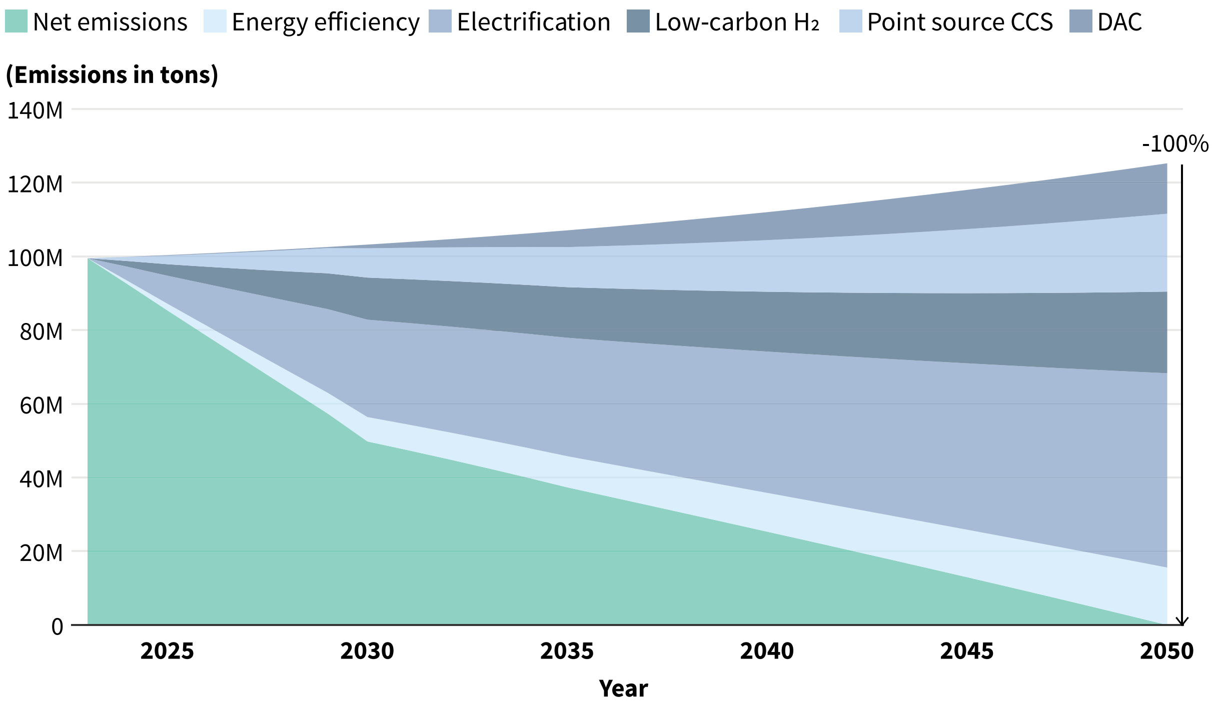
RMI Graphic. Source: RMI analysis

Other industrial sectors, such as steel, cement, and plastics, will also implement a range of decarbonization strategies, including energy efficiency improvements, process electrification, and the use of CCS and DAC technology. These efforts will contribute to the overall goal of achieving net-zero emissions across Houston's industrial landscape.

The NZ scenario relies on the BAU scenario's emissions growth and the SI scenario's assumption that Houston's industrial sectors will employ the four primary decarbonization levers to address their emissions. However, the NZ scenario couples the sectors' remaining activities with utilization of CCS, widespread adoption of low-carbon hydrogen as a fuel source, and DAC technology, as previously mentioned. Exhibit 14 illustrates the emissions reduction by lever associated with the assumptions in the NZ scenario.

Exhibit 14

Net-Zero Scenario Scope 1 Emissions Reduction by Lever



RMI Graphic. Source: RMI analysis

Energy Efficiency

The NZ scenario fully leverages energy efficiency's potential, resulting in emissions reductions of approximately 6 million tons by 2030 and 15 million tons by 2050. These reductions constitute 12% of the Scope 1 emissions this scenario targets.

Electrification

Electrification is the most effective decarbonization strategy in the NZ scenario. It reduces over 26 million tons of Scope 1 emissions in the industrial sector by 2030 and 52 million tons by 2050. For the power sector, this translates to an increase in power consumption of over 45 million MWh in 2030 and 116 million MWh in 2050. However, the NZ scenario assumes the power sector achieves net zero by 2035, which means additional annual power sector emissions resulting from increased consumption related to this electrification never exceeds 8 million tons at its peak in 2030 before eventually declining to zero. Moreover, the emissions burden transferred from other industrial decarbonization levers to the power sector is minimized.

Hydrogen

Because economic feasibility is not the primary consideration in the NZ scenario, both low-carbon hydrogen and point-source CCS are more broadly adopted compared with the SI scenario. Switching to low-carbon hydrogen reduces Scope 1 emissions by over 11 million tons in 2030 and 22 million tons in 2050, constituting 18% of the Scope 1 emissions reductions this scenario targets. This transition generates a local hydrogen demand of 1.6 million tons annually in 2030 and 3.1 million tons in 2050 for the conversion of the existing industrial asset base alone.

Point-Source Carbon Capture and Sequestration

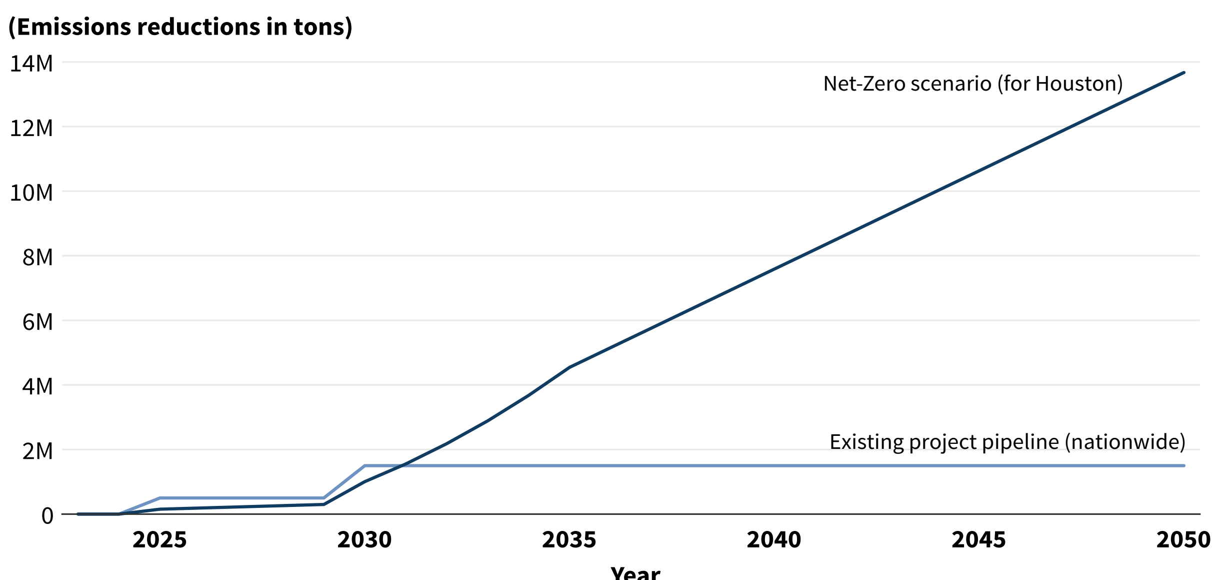
Point-source CCS plays a significant role in the NZ scenario, reducing nearly 8 million tons of CO_2 in the industrial sector by 2030 and over 21 million tons by 2050. This represents 17% of the Scope 1 emissions targeted by this scenario. The power consumed by this decarbonization lever will reach nearly 0.8 million MWh in 2030 and over 2 million MWh in 2050. However, the increase in power sector annual emissions never exceeds 0.2 million tons because the power sector itself reaches net zero by 2035 in this scenario.

Direct Air Capture

Exhibit 15 illustrates the emissions reduction handled by DAC in the NZ scenario forecasted to 2050. The functionality of DAC extends beyond merely addressing otherwise unabated emissions. DAC is also part of a dynamic interplay among other high-cost carbon abatement measures, such as electrifying high-temperature processes for the chemicals and petrochemicals sectors. If DAC's carbon abatement cost is lower than specific decarbonization methods in a certain sector — for example, electrification with long-duration energy storage/thermal energy storage and heat-generation in refining — companies may opt to use DAC to offset sector-specific emissions. Additionally, the realization of a net-zero power sector is identified as a prerequisite for unlocking the full potential of DAC on a large scale, underscoring the interconnectedness of various elements within the NZ scenario.

Exhibit 15

Role of Direct Air Capture in Emissions Reductions for Houston Versus Existing Project Pipeline Nationwide



RMI Graphic. Source: RMI analysis

PART 4

Economic Outcomes of Decarbonization

The decarbonization of industrial sectors in Houston will provide economic benefits to the region beyond the reductions in carbon emissions. The investments in decarbonization technologies that either reduce emissions or directly capture carbon from the atmosphere with CCS will also support the growth of jobs, GDP, labor income, and tax revenue over time.

This growth happens through direct, indirect, and induced impacts. These economic impacts can be an important consideration in choosing the scale and timing of specific investments.

This assessment considers the economic impacts across 13 industries in two decarbonization scenarios between 2025 and 2050: the NZ scenario and the SI scenario.[xi] The assessment includes the four decarbonization levers (i.e., energy efficiency, electrification, hydrogen, and point-source CCS) and assesses impacts within 10 counties around Houston. There are two types of investments or expenditures made by the industries measured in this study:

- **Capital expenditures (CapEx):** industrial decarbonization capital costs
- **Operating expenditures (OpEx):** facility annual operating and maintenance (O&M) costs (including fuel and power)

This analysis uses IMPLAN, an economic input-output (I-O) model, to estimate the change in economic activity from investments in certain decarbonization levers. I-O models estimate the total change in demand for goods and services (in this case, one-time demand for decarbonization levers and ongoing decarbonization expenditures).[27] They quantify the interindustry relationships within an economy (i.e., how output/activity from one sector in an economy becomes an input in another sector and their interindustry effects).

IMPLAN relies on multipliers, which quantify interactions between firms, industries, and social institutions within a local economy. Each industrial or service activity within the economy (e.g., ports, refineries, steel) is assigned to an economic sector.[xii] The model starts with a "shock" to the economy, expressed as either a change in the number of jobs in an industry (e.g., 100 jobs for construction of a pipeline) or a change in expenditures (e.g., the dollar amount spent on construction). A change in expenditures (e.g., an investment) can be broadly divided into purchasing goods and services and purchasing labor. Both types of investment set off repeated rounds of economic activity (a multiplier effect). The additional jobs, GDP,

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xi This economic assessment was conducted by ERM, a global sustainability consultancy, using RMI emissions reductions and carbon abatement analysis inputs.

xii IMPLAN uses data from the US Bureau of Economic Analysis, Bureau of Labor Statistics, US Census Bureau, and other sources. IMPLAN also uses detailed US Department of Commerce information that relates the purchases of goods and services each industry makes from other industries to the value of output in each industry. As such, IMPLAN describes the supply chain of each industry in terms of output, value added, labor income, employment levels, and state and local tax revenue. The latest version of IMPLAN data currently includes 536 sectors and regional detail at the state, county, and ZIP code level.

labor income, and tax revenue generated by interindustry spending are called the indirect impact, whereas the impact from household spending is the induced impact. The sum of the direct, indirect, and induced impacts equals the total economic impact. The multipliers vary by location and sector depending on the makeup of the local economy.

For this economic analysis, IMPLAN treats the decarbonization investment as a shock and estimates how each industry drives economic activity (i.e., jobs, GDP, income, taxes). IMPLAN estimates three types of impacts:

- **Direct impact:**: the initial change in the value of the output, employment, and labor earnings from the decarbonization investments
- **Indirect impact:** the increase in the output, employment, and labor earnings in the industries supporting the decarbonization investments
- **Induced impact (or household spending impact):** the increase in the spending of workers in the direct and indirect industries

IMPLAN estimates the distribution of economic impacts on local economies and industrial sectors. It is important to note IMPLAN results are not a benefit-cost analysis and do not evaluate whether a project provides an overall net benefit to society. IMPLAN does not estimate the impact of any changes in prices, such as electricity prices from power plants investing in decarbonization, which may affect production, output, and jobs in other industries. In addition, IMPLAN does not evaluate the opportunity costs of private investment or public funds.[xiii]

xiii Opportunity costs refer to the value of the next-highest-valued alternative use of that resource. For example, although investments in CCUS create economic benefits, the economic impacts do not take into account the next best use of those funds, which presumably would provide economic benefits in the absence of CCUS activities.

Job Impacts for the Houston Region

As a means of demonstrating the double bottom-line benefits to Houston, this analysis considered the economic impacts of industrial decarbonization for the region, primarily via the number of direct and indirect jobs created by the investments made within the target geography and resultant supply chain transactions, respectively.

IMPLAN analysis of the Houston 10-county region considered in this study concludes that decarbonization activity will benefit the region, annually creating more than 21,000 jobs in an NZ scenario and more than 14,000 jobs in an SI scenario.[xiv] This analysis focuses only on the specified Houston region and does not review national-level impacts. It also does not consider job creation under a BAU scenario.

This analysis considers job creation from both CapEx, for example, facility startup costs, and OpEx, for example long-term costs. Exhibit 16 shows average annual job growth impacts by investment type in the SI scenario.

Exhibit 16 Average Annual Job Impacts by Investment Type for the Selective Investment Scenario

Impact	CapEx	OpEx	Total
Direct	1,771	1,284	**3,056**
Indirect	1,540	4,931	**6,472**
Induced	2,608	2,690	**5,298**
Total	**5,921**	**8,905**	**14,826**
Total job creation in the SI scenario to 2050			**370,650**

RMI Graphic. Source: ERM analysis

Exhibit 17 shows average annual job impacts by investment type in the NZ scenario.

Exhibit 17 Average Annual Job Impacts by Investment Type for the Net-Zero Scenario

Impact	CapEx	OpEx	Total
Direct	2,560	1,884	**4,485**
Indirect	2,167	6,935	**9,102**
Induced	3,783	3,901	**7,685**
Total	**8,551**	**12,721**	**21,272**
Total job creation in the NZ scenario to 2050			**531,800**

RMI Graphic. Source: ERM analysis

xiv This analysis does not supersede or dispute McKinsey research previously prepared for HETI regarding job creation projections for the Houston region — modeling that was also based on IMPLAN. ERM and McKinsey model results may not align perfectly based on several factors, including input assumptions and CapEx/OpEx percentage splits, among other inputs.

Selective Investment Scenario

Exhibit 18 shows the average annual economic impacts of decarbonization under the SI scenario.

Exhibit 18 Average Annual Direct, Indirect, and Induced Impacts for the Selective Investment Scenario

Impact	Average Annual Jobs (thousands)	Average Annual GDP ($ millions)	Average Annual Labor Income ($ millions)	Average Annual Output ($ millions)	Average Annual State and Local Taxes ($ millions)
Direct	3.1	1,717	684	4,785	58
Indirect	6.5	1,595	681	3,202	130
Induced	5.3	576	312	977	48
Total	**14.8**	**3,887**	**1,577**	**8,963**	**236**

RMI Graphic. Source: ERM analysis

Net-Zero Scenario

Perhaps expectedly, the NZ scenario results in more substantial job creation activity for the region than the SI scenario given the higher investment value across the associated life cycle of industrial decarbonization projects. Based on the average annual growth per year, more than 530,000 total jobs are created across the region between 2025 and 2050 in an NZ scenario. Exhibit 19 details the average annual economic impacts of decarbonization in the NZ scenario.

Exhibit 19 Average Annual Direct, Indirect, and Induced Impacts for the Net-Zero Scenario

Impact	Average Annual Jobs (thousands)	Average Annual GDP ($ millions)	Average Annual Labor Income ($ millions)	Average Annual Output ($ millions)	Average Annual State and Local Taxes ($ millions)
Direct	4.5	2,516	841	7,049	87
Indirect	9.1	2,307	993	4,661	203
Induced	7.7	835	453	1,416	67
Total	**21.3**	**5,656**	**2,287**	**13,126**	**357**

RMI Graphic. Source: ERM analysis

PART 5

Houston's Path Forward for Clean Growth

Texas has structural advantages for decarbonization of energy and industrial systems — both within its own borders and internationally. Houston has an opportunity to capitalize on its position as a global leader to leverage the energy transition for its own economic growth and reduction of emissions in coming decades. Economic benefits to Texas from industrial decarbonization could potentially spill over to neighboring states with similarly industrial economies, and in many cases they would likely also benefit from the federal policy mechanisms available across the country.

The development of key features for economic enhancement of clean energy alternatives, such as demand growth through the development of greater scale of production, transparent pricing for the cost of carbon, and hydrogen and its derivatives, are valuable market developments needed to enhance the adoption of lower emissions processes and fuels.

Emerging technologies have a large part to play in Houston's industrial decarbonization journey, and continued development of the region's innovation ecosystem will depend in large part on support through policy and corporate innovation investments to commercialize and scale the best solutions for achieving double bottom-line success in reduced emissions and economic growth.

Recommendations for Future Considerations

Beyond questions of cost related to mobilizing industrial decarbonization, local impacts to communities must also be considered. Community impacts not measured in this body of work should be analyzed in more depth because they are critical to ensuring successful development and transition for the region's industry projects. Community acceptance, inclusion, and support for Houston's decarbonization will be key to ensuring successful design, permitting, and operation of updated facilities.

It is also important to recognize the changing technology readiness levels and their role in unlocking future solutions at scale using market tools from across the Houston innovation ecosystem.

Not reflected in this analysis but worthy of separate research are consumer preferences and willingness to pay for products and services produced in lower-carbon environments such as what Houston could offer through industrial decarbonization. If industry approaches to decarbonizing sectors such as aviation are any indication, Houston manufacturers could position their products to benefit from a green premium over non-decarbonized alternatives.

Finally, market conditions and the longevity of policy enablers and incentives have potential impacts on the viability of industrial decarbonization projects and should be further studied, especially for CCS projects and clean hydrogen production.

Conclusion

This analysis underscores the strategic opportunity that energy-efficient industrial decarbonization investments present for the region's industrial stakeholders. These investments, by facilitating the continuation of operations while mitigating environmental impacts, can reinforce Houston's leadership in the energy sector. By capitalizing on Texas's ongoing power sector decarbonization, Houston's industry players can accelerate their own electrification and decarbonization initiatives, leveraging large-scale investments already underway.

The development and scaling of carbon capture technologies will be pivotal in achieving net-zero emissions within the region's heavy industries. While energy efficiency measures, electrification, and hydrogen decarbonization strategies can deliver significant emissions reductions, the full decarbonization of heavy industry necessitates the widespread adoption of CCS technologies. With sustained research, development, and scaling efforts, these technologies have the potential to achieve cost-effectiveness. Until such advancements are realized, prioritizing other decarbonization levers will be crucial in the strategic planning of industrial operations.

Potential Next Steps

This study's focus on the Houston region and the surrounding 10 counties, encompassing population centers in cities from Galveston to Beaumont, highlights the significance of regional analysis in understanding decarbonization opportunities. Each region's distinct industrial composition, policy landscape, and community engagement necessitate tailored approaches to decarbonization. This research and stakeholder interviews identified Houston's desire to maintain its leadership in the global energy sector as a key motivator for pursuing decarbonization. Leveraging such regional motivations can expedite and streamline decarbonization efforts.

However, a regional perspective alone may not suffice. Decarbonization must be addressed at multiple scales, particularly at the asset level, where site managers and project developers play a critical role. The interplay between asset-level assessments, regional studies, and global strategies is essential for comprehensive decarbonization planning. These levels of analysis are interconnected, particularly in areas including supply chains, recycling systems, and power infrastructure. Asset-level studies, supported by robust baseline data, are vital for providing targeted decarbonization recommendations. To facilitate these studies, transparency in production volumes and processes is imperative, enabling precise, asset-specific strategies.

The success of decarbonization efforts hinges on the engagement and collaboration of a diverse set of stakeholders, including asset managers, financial institutions, external investors, and procurement officers across supply chains. Their involvement is not just important, it is integral. Additionally, the role of local and regional policymakers is critical in fostering an enabling environment for decarbonization. Ensuring alignment and shared understanding among these stakeholders is essential for successfully executing decarbonization strategies. RMI's Climate-Aligned Industries team and the MPP Industrial Hubs program are vital to convening policymakers, financial institutions, and heavy industry project developers to address decarbonization challenges collaboratively. Through these efforts, RMI's experts in key sectors, such as cement and concrete, hydrogen, chemicals, aviation, heavy-duty trucking, and marine shipping, work closely with stakeholders to identify effective decarbonization levers and facilitate the transition to lower-carbon products and commodities.

Asset-level analysis and multistakeholder engagement represent the initial steps toward comprehensive industrial decarbonization. To catalyze systemic change, strategic convenings and engagements in critical regions such as Houston may be necessary to jump-start a more holistic approach to decarbonization. Additionally, introducing more stringent data transparency measures or regulatory requirements for asset-level reporting, similar to European practices, could enhance decarbonization efforts by enabling detailed analysis and informed decision-making.

The Houston region has the potential to become a global leader in decarbonized industrial production, mirroring its status as a leader in the traditional energy sector. Achieving this vision will require a shared commitment and coordinated efforts from stakeholders across all levels and industries, supported by forward-looking policies and investment frameworks. By fostering collaboration, transparency, and innovation, Houston can secure its economic future and contribute significantly to global decarbonization efforts.

PART 6

Technical Appendix

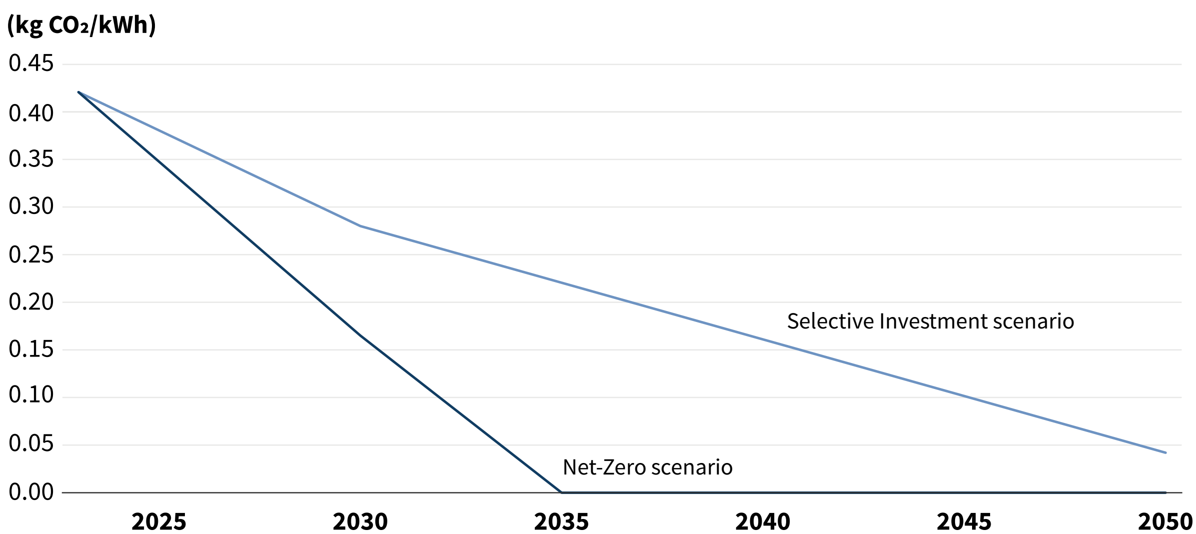
Scenario Detail

Exhibit A1 **Summary of Key Scenario Variables by Technology or End Use**

Sector	Technology or end use	Primary scenario variable	Notes
Industry	Process heat, machine drive, other facility needs (e.g., office heating, ventilation, and air conditioning)	Percent of total emissions addressed by efficiency improvement, electricity, hydrogen power, or point-source CCS	Each sector will have different emissions breakdowns for different end uses (e.g., process heat, machine drive)
	Carbon abatement cost of efficiency improvement, electricity, hydrogen power, or point-source CCS for different sectors	\$/ton CO_2 abated	Weighted average for 2030 cost with subsidy, 2030 cost without subsidy, and 2050 cost
	Low-carbon hydrogen for fuel switching	Breakdown between green hydrogen and blue hydrogen	—

RMI Graphic. Source: RMI analysis

Exhibit A2 **Forecasted Carbon Intensity of the Power Sector**



RMI Graphic. Source: IEA

Industry Emissions Reduction Methodology

Emissions Breakdown by End Uses for Each Sector

We use **US Energy Information Administration (EIA) 2018 Manufacturing Energy Consumption Survey (MECS) data Table 5.2** “Energy Consumed as a Fuel by End Use” for each facility’s North American Industry Classification System code to calculate energy demand from three main end uses that we electrify to various degrees in the scenarios:[28]

- Process heat: 84% of “CHP and/or Cogeneration Process” (see Assumption 1) + Conventional Boiler Use + Process Heating
- Non-process direct use: 16% of “CHP and/or Cogeneration Process” (see Assumption 1) + Facility HVAC + Facility Lighting + Other Facility Support + Conventional Electricity Generation + Other Non-process Use
- Machine Drive

For each sector, we calculate emissions for each of these end uses using the emissions factor of different fuels (see Exhibit A3):

- Scope 1 Emissions from [end use a] = sum all fossil type [emissions factor_fossil fuel x *fossil fuel x consumption_end use a]
- Scope 2 Emissions = sum all end uses [emissions factor of grid *electricity consumption_end us a]

We split emissions from process heat into temperature, <100°C and >100°C (see Assumption 2):

- Emissions from high-temp process heat = 23% * total emissions from process heat
- Emissions from low-temp process heat = 77% * total emissions from process heat

We then calculate the percentage of emissions for each of these end uses in the total emissions (see Exhibit A4).

Exhibit A3 Emissions Factors

Target category	Approximate category	Emissions factor	Unit
Net Demand for Electricity	ERCOT ALL (Market-based 2019)	0.42062	kg CO_2/kWh
Residual Fuel Oil	Residual Heating Fuel	11.24	kg CO_2/gallon
Distillate Fuel Oil and Diesel Fuel	Diesel and Home Heating Fuel (Distillate Fuel Oil)	10.19	kg CO_2/gallon
Natural Gas	Natural Gas	54.87	kg CO_2/thousand cubic feet
Hydrocarbon gas liquids (excluding natural gasoline)	Propane	5.75	kg CO_2/gallon
Coal (excluding Coal Coke and Breeze)	Coal (All types)	1,764.83	kg CO_2/short ton

RMI Graphic. Source: EIA

Exhibit A4 Emissions Breakdown by End Uses for Each Sector

Sector	Scope 1 emissions				Scope 2 emissions
	Machine drive	Non-process	High-temperature process heat	Low-temperature process heat	Emissions from electricity
Airports	18%	82%	0%	0%	0%
Ammonia	2%	9%	55%	16%	17%
Hydrogen	0%	9%	16%	5%	71%
Other Chemicals	3%	9%	36%	11%	41%
Other Manufacturing	0%	9%	11%	3%	77%
Other Metals	1%	6%	20%	6%	68%
Other Minerals	5%	7%	35%	11%	42%
Petroleum and Natural Gas Systems	1%	6%	45%	14%	34%
Petrochemicals	4%	8%	50%	15%	22%
Ports	61%	39%	0%	0%	0%
Refineries	1%	6%	46%	14%	34%
Steel	0%	8%	30%	9%	53%
Waste	1%	10%	28%	8%	52%

RMI Graphic. RMI analysis of IEA MECS 208 data

Scope 1 Emissions for BAU Scenario

The emissions baseline data is sourced from the EPA FLIGHT tool, which provides Scope 1 emissions data for 2021.[29] We calculate the forecasted Scope 1 emissions for each sector using sector growth rates (see Assumption 3). Then, we multiply the percentage of emissions by end uses in each sector to derive Scope 1 emissions by sectors, by end uses, and by year in the BAU scenario.

Scope 1 Emissions Reduction Overview

For each decarbonization lever, we define 2030 and 2050 snapshots of their parameters, and then fill in the years in between in a linear manner.

The BAU Scope 1 emissions are first adjusted based on the efficiency improvement rate by end uses by sector:

- Emissions after efficiency_sector 1_end use a = BAU emissions_sector 1_end use a * (1-efficiency improvement rate_sector 1_end use a)

Then the remaining emissions are divided into addressable emissions and emissions that cannot be covered by any in-facility decarbonization levers.

- Emissions addressed _ sector 1_end use a = after efficiency_sector 1_end use a * (1- uncovered emissions rate_ sector 1_end use a)

Finally, addressable emissions are assumed to be addressed through electrification, low-carbon hydrogen, and point-source CCS, with their emissions reduction potentials listed in Exhibit A5:

- Emissions addressed_decarb lever i_ sector 1_end use a = Emissions addressd _ sector 1_end use a * emissions reduction potentials_decarb lever i_ sector 1_end use a

Since these decarbonization levers are not perfect and may result in incomplete emissions reduction or additional emissions associated with their operation, any side-effect emissions are added back to the Scope 1 emissions of the scenario. Alternatively, they may be calculated separately to identify the increased Scope 2 emissions that can be directly attributed to the implementation of these decarbonization levers.

Exhibit A5 Variables Used to Calculate the Emissions Reduction Potential of the Decarbonization Levers

Decarbonization Levers	Decarbonization scenario (base for Selective Investment scenario)		Net-Zero scenario	
	2030	2050	2030	2050
Energy efficiency	Median number in research for 2030	Median number in research for long term	Upper end in research for 2030	Upper end in research for long term
Uncovered emissions (% of total emissions after efficiency)	17% of high-temperature heat process emissions for energy-intensive industries, 0% for others			
Electrification (% of total emissions after efficiency and uncovered)	Overall 27%: Machine drive 26%, Non-process 100%, High-temperature heat process 8%, Low-temperature heat process 28%	Overall 49%: Machine drive 90%, Non-process 100%, High-temperature heat process 20%, Low-temperature heat process 70%	Overall 25%: Machine drive 45%, Non-process 100%, High-temperature heat process 3%, Low-temperature heat process 30%	Overall 50%: Machine drive 98%, Non-process 100%, High-temperature heat process 20%, Low-temperature heat process 70%
Fuel switch to hydrogen (% of total emissions after efficiency and uncovered)	Overall 2%: Machine drive 0%, Non-process 0%, High-temperature heat process 15%, Low-temperature heat process 0%	Overall 17%: Machine drive 0%, Non-process 0%, High-temperature heat process 30%, Low-temperature heat process 0%	Overall 15%: Machine drive 0%, Non-process 0%, High-temperature heat process 26%, Low-temperature heat process 0%	Overall 25%: Machine drive 0%, Non-process 0%, High-temperature heat process 45%, Low-temperature heat process 0%
Clean hydrogen mix (% of total hydrogen)	80% blue; 20% green	50% blue; 50% green	35% blue; 65% green	27% blue; 73% green
Post-combustion capture (% of total emissions after efficiency and uncovered)	Overall 14%: Machine drive 0%, Non-process 0%, High-temperature heat process 20%, Low-temperature heat process 12%	Overall 33%: Machine drive 0%, Non-process 0%, High-temperature heat process 50%, Low-temperature heat process 30%	Overall 10%: Machine drive 3%, Non-process 0%, High-temperature heat process 15%, Low-temperature heat process 10%	Overall 25%: Machine drive 3%, Non-process 0%, High-temperature heat process 36%, Low-temperature heat process 28%
Carbon capture rate	90%	90%	90%	90%
Direct air capture	Existing pipelines in Houston 0	Existing pipelines in Houston 0	Existing pipelines in United States 1.5 million	Remainder/existing pipelines in United States

RMI Graphic. Source: RMI analysis

Scope 1 Emissions Reduction from Efficiency Improvement

The study relies on the Advanced System Studies for Energy Transition (ASSET) Study on Technology Pathways in Decarbonization Scenarios as a reference for medium- and high-efficiency improvement cases as shown in Exhibit A6.[30]

Exhibit A6 2030 and 2050 Efficiency Improvement Rate by End Uses for Each Sector

End use	Medium Case						High Case					
	Machine drive		Non-process		Heat process		Machine drive		Non-process		Heat process	
	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050
Airports	6.54%	13.04%	18.41%	26.62%	N/A	N/A	11.50%	18.03%	21.45%	32.67%	N/A	N/A
Ammonia	6.25%	13.04%	18.41%	26.62%	9.29%	13.59%	10.97%	17.35%	21.45%	32.67%	12.07%	16.64%
Hydrogen	6.25%	13.04%	18.41%	26.62%	9.25%	13.33%	10.97%	17.35%	21.45%	32.67%	12.07%	15.86%
Other Chemicals	6.25%	13.04%	18.41%	26.62%	9.25%	13.33%	10.97%	17.35%	21.45%	32.67%	12.07%	15.86%
Other Manufacturing	6.25%	13.04%	18.41%	26.62%	6.10%	8.67%	10.97%	17.35%	21.45%	32.67%	7.83%	10.71%
Other Metals	6.25%	13.04%	18.41%	26.62%	8.85%	12.23%	10.97%	17.35%	21.45%	32.67%	10.87%	15.17%
Other Minerals	6.25%	13.04%	18.41%	26.62%	8.04%	11.49%	10.97%	17.35%	21.45%	32.67%	9.90%	16.12%
Petroleum and Natural Gas Systems	6.25%	13.04%	18.41%	26.62%	9.54%	13.59%	10.97%	17.35%	21.45%	32.67%	12.07%	16.64%
Petrochemicals	6.25%	13.04%	18.41%	26.62%	9.54%	13.59%	10.97%	17.35%	21.45%	32.67%	12.07%	16.64%
Ports	6.54%	13.04%	18.41%	26.62%	N/A	N/A	11.50%	18.03%	21.45%	32.67%	N/A	N/A
Refineries	6.25%	13.04%	18.41%	26.62%	9.54%	13.59%	10.97%	17.35%	21.45%	32.67%	12.07%	16.64%
Steel	6.25%	13.04%	18.41%	26.62%	11.15%	15.51%	10.97%	17.35%	21.45%	32.67%	13.93%	19.16%
Waste	6.25%	13.04%	18.41%	26.62%	12.22%	18.26%	10.97%	17.35%	21.45%	32.67%	15.95%	23.73%

RMI Graphic. RMI analysis of ASSET Study on Tech Pathways

For end uses such as machine drive and non-process, we utilize the efficiency improvement rate of horizontal process technology from the ASSET study. Efficiency improvement in machine-drive energy consumption pertains to the enhancement of large-scale, midsized, and small motors' efficiency. Non-process energy use improvement involves the enhancement of cooling, refrigeration, lighting, and air ventilation efficiency.

For end uses such as heat processes, we use the efficiency improvement rate of sector-specific vertical processes from the ASSET study. Since the classification of sectors does not match one-to-one, we choose the closest sector available in the reference for approximation (see Exhibit A7).

Exhibit A7 Efficiency Improvement Rate Approximate Sectors

Houston industrial sectors	Approximate sector
Airports	Motors large scale
Ammonia	Fertilizers
Hydrogen	Inorganic and basic chemicals
Other Chemicals	Inorganic and basic chemicals
Other Manufacturing	Engineering and equipment industry
Other Metals	Ferroalloys
Other Minerals	Other nonmetallic minerals
Petroleum and Natural Gas Systems	Petrochemicals
Petrochemicals	Petrochemicals
Ports	Motors large scale
Refineries	Petrochemicals
Steel	Integrated steelworks
Waste	Food, drink, and tobacco

RMI Graphic. Source: ASSET

Scope 1 Emissions Reduction from Electrification

Electrification will directly transfer Scope 1 emissions from the industrial sector to the power sector. Hence, the reduction in Scope 1 emissions due to electrification equals the addressable emissions covered by electrification:

- Scope 1 emissions reduction from electrification_ sector 1_end use a = Emissions addressed_ electrification_ sector 1_end use a

However, we are also interested in the increased electricity demand resulting from this electrification process and aim to quantify the associated Scope 2 emissions because they are directly attributed to industrial decarbonization.

To calculate the electricity demand for electrification, we first need to convert its direct Scope 1 emissions reduction into avoided natural gas consumption using the natural gas emissions factor. Then, we determine the energy value of the replaced electricity by considering the efficiency difference between natural gas and electricity.

- Natural gas end-use efficiency (ng_eff) and electric end-use efficiency (elec_eff)
  - We need both natural gas and electric end-use efficiency. When we calculate natural gas energy demand from emissions, essentially what we are getting is the amount of natural gas a facility might use
  - As shown below, we multiply natural gas energy demand first by natural gas efficiency. This gives the amount of useful energy used for the process.
  - We then divide by the electric efficiency, which accounts for losses involved with using the device.
  - See Assumption 4 for assumptions about natural gas and electric device efficiencies

We calculate increased electricity demand from electrification in year x for all end uses and sectors:

- Electricity demand increased form electrification_ sector 1_end use a= Emissions addressed_ electrification_ sector 1_end use a/NG emissions factor $* \frac{ng_{eff}}{elec_{eff}} * \left[\frac{0.293\ MWh}{mmbtu}\right]$

Subsequently, the increase in Scope 2 emissions from industrial electrification is calculated by multiplying the increased electricity demand of year x by the grid emissions factor of year x, assuming that the energy transition of the power it uses will be similar to that of grid power.

Scope 1 Emissions Reduction from Switch to Low-Carbon Hydrogen

When transitioning to low-carbon hydrogen, the emissions addressed by green hydrogen result in a complete direct reduction in Scope 1 emissions. This is because we can assume that green hydrogen uses renewable power that matches hourly demand, resulting in near-zero Scope 1 and Scope 2 emissions. However, for the emissions addressed by blue hydrogen, the reduction is not completely equivalent to the Scope 1 emissions reduction because it involves a capture rate. The portion of emissions that cannot be captured is added to the unabated emissions for DAC to manage in the NZ scenario:

- Scope 1 emissions reduction from hydrogen_ sector 1_end use a = Emissions addressed_hydrogen_ sector 1_end use a * green hydrogen share + Emissions addressed_hydrogen_ sector 1_end use a * blue hydrogen share * CCS capture rate

We are also interested in the increase in local Scope 2 emissions resulting from the transition to low-carbon hydrogen. This increase occurs only with blue hydrogen production because grid power consumption is assumed. Therefore, we need to estimate the locally produced hydrogen in the Houston area, which is associated with, but conceptually different from, local hydrogen consumption.

Our calculation of hydrogen production is based on the “Mix Fuel Houston” scenario developed by the HETI Power Management working group, representing a deep decarbonization vision. This scenario is derived from the **hydrogen report published by HETI and Center for Houston’s Future**.[31] Exhibit A8 shows total production numbers from the report for Texas and what is assumed to be produced in the CenterPoint service territory for a deep decarbonization scenario. For our targeted SI and NZ scenarios, we scale up or down the deep decarbonization vision proportionally based on the emissions addressed by green and blue hydrogen.

Exhibit A8 Hydrogen Production for an Extended Area

Scenario	Texas hydrogen production in 2050 (Mt/y)	CenterPoint hydrogen production in 2050 (Mt/y)	Houston hydrogen production in 2050 (Mt/y)
Calculation base: Mix Fuel Houston scenario	20	10	3.6

RMI Graphic. Source: Houston Energy Transition Initiative, Center for Houston's Future, 2022

We assume that blue hydrogen will initially scale faster than green hydrogen, with 80% of hydrogen being blue by 2030. By 2050, the production method is split evenly in the SI scenario, leaning toward green in the NZ scenario, following the pattern outlined in the IEA World Energy Outlook. Exhibit A9 shows Houston's blue and green hydrogen production by scenario and year.

Exhibit A9 Hydrogen Production by Year, Scenario, and Method in Houston

Scenario	Year	Blue hydrogen production (Mt)	Green hydrogen production (Mt)
Calculation base: Mix Fuel Houston scenario	2030	0.96	0.24
	2050	1.8	1.8
Selective Investment scenario	2030	0.88	0.22
	2050	1.04	1.04
Net-Zero scenario	2030	0.97	1.82
	2050	1.42	3.83

RMI Graphic. Source: Houston Energy Transition Initiative, Center for Houston's Future, 2022; and RMI analysis

We use an electricity intensity of blue hydrogen (see Exhibit A10) to calculate non-net-zero-emissions electricity demand for the blue hydrogen systems:

- Electricity demand increased form hydrogen_ sector 1_end use a= Emissions addressed_hydrogen_ sector 1_end use a * blue hydrogen share * blue hydrogen_electricity intensity $\left[\frac{\text{MWh}}{\text{t H}_2}\right]$

Subsequently, the increase in Scope 2 emissions from switching to low-carbon hydrogen is calculated by multiplying the increased electricity demand of year x by the grid emissions factor of year x, assuming that the energy transition of the power it uses will be similar to that of grid power.

Scope 1 Emissions Reduction from Carbon Capture and Sequestration

CCS directly reduces Scope 1 emissions by capturing and storing CO_2 instead of emitting it. However, the reduction is not equivalent to all addressable emissions covered by CCS because it needs to be multiplied by a capture rate, which is less than 100%. The portion of emissions that cannot be captured will be added to the unabated emissions for DAC to manage in the NZ scenario:

- Scope 1 emissions reduction from CCS_ sector 1_end use a = Emissions addressed_CCS_ sector 1_end use a * CCS capture rate

Similar to electrification and low-carbon hydrogen, CCS also transfers some emissions burden to the power sector. To roughly estimate that burden, we use an electricity intensity of capturing CO_2 (see Exhibit A10) to calculate electricity demand for the point-source CCS systems:

- Electricity demand increased form CCS_ sector 1_end use a= Emissions addressed_CCS_ sector 1_end use a * CCS_electricity intensity $\left[\frac{\text{MWh}}{\text{t CO}_2}\right]$

Subsequently, the increase in Scope 2 emissions from industrial electrification is calculated by multiplying the increased electricity demand of year x by the grid emissions factor of year x, assuming that the energy transition of the power it uses will be similar to that of grid power.

Direct Air Capture

In the NZ scenario, DAC addresses any remaining Scope 1 emissions. To determine the increase in Scope 2 emissions from DAC, we use the electricity intensity of DAC (see Exhibit A10) to calculate its electricity demand. We then multiply this by the grid emissions factor of the year, assuming that the energy transition of the power used by DAC will be similar to that of grid power.

Exhibit A10 Electricity Intensity of Decarbonization Levers

Decarbonization levers	Electricity intensity	Source
Blue hydrogen	3.58 MWh/t H_2	ATR-CCS number in "Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions"
CCS	0.1 MWh/t CO_2	RMI research
DAC	2 MWh/t CO_2	World Resources Institute[32]

RMI Graphic. Source: RMI, World Resources Institute, *Energy Conversion and Management*, 2022

Assumptions

1. We assume 84% of energy for CHP and/or cogeneration process from **EIA 2018 MECS data Table 5.2** is used to make steam and 16% is used for electricity. This is based on the useful energy (excluding losses) in the **Onsite Generation DOE Sankey Diagrams of 2014 MECS data**.

2. We assume 23% of total energy demand for process heat is <100°C and 77% is >100°C. This is aligned with data on the chemicals industry in Europe (see Figure 6 of this **Renewable Thermal Collaborative report**). This also aligns with total global process heat demand across all industries according to the **IEA's report on the Future of Heat Pumps** (see Figure 1.16).

3. Sector growth/shrink assumptions are as follows:

    a) The refineries sector shrinks depending on differing levels of vehicle electrification in the scenarios. For the high-electrification scenario, we assume the refineries sector gets smaller by 4.5% per year. This is how much oil supply reduces per year globally now to 2050 in the IEA's Net Zero scenario from the **2022 World Energy Outlook**. For the other scenarios that are more focused on decarbonization through hydrogen, we assume the refineries sector gets smaller by 2% per year. This is based on the Further Acceleration scenario from the **hydrogen report published by HETI and Center for Houston's Future**.

    b) All other sectors grow by 2% per year in all scenarios. All other sectors grow by 2% per year in all scenarios, in alignment with the **Texas Energy Policy Simulator** pathway for the state.

4. We assume natural gas and electric device efficiencies for the directly electrified end uses as shown in Exhibit A11.

Exhibit A11 Industrial End-Use Efficiencies

End use and device	Natural gas efficiency	Electric efficiency	Sources
Heat pump	80%, based on steam generation from conventional boilers and CHP/cogeneration	Coefficient of performance of 3	DOE 2018 MECS Footprint for Chemicals (natural gas) RTC Heat Pump Decision Support Tool (electricity) ACEEE Industrial Heat Report (electricity)
Thermal energy storage	80%, based on steam generation from conventional boilers and CHP/cogeneration	95%	Correspondence with thermal energy storage startups (electricity)
Cracker	35%	55%	Shell presentation to Institute for Sustainable Process Technology,[33] Slide 5 (natural gas and electricity)
Machine drive	35%	94%	DOE 2018 MECS Footprint for Chemicals (natural gas) Table 1, DOE Advanced Manufacturing Office (electricity)
Direct non-process use	33%	100%	Assumed

RMI Graphic. Source: DOE; Renewable Thermal Collaborative; ACEEE; and Institute for Sustainable Process Technology

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