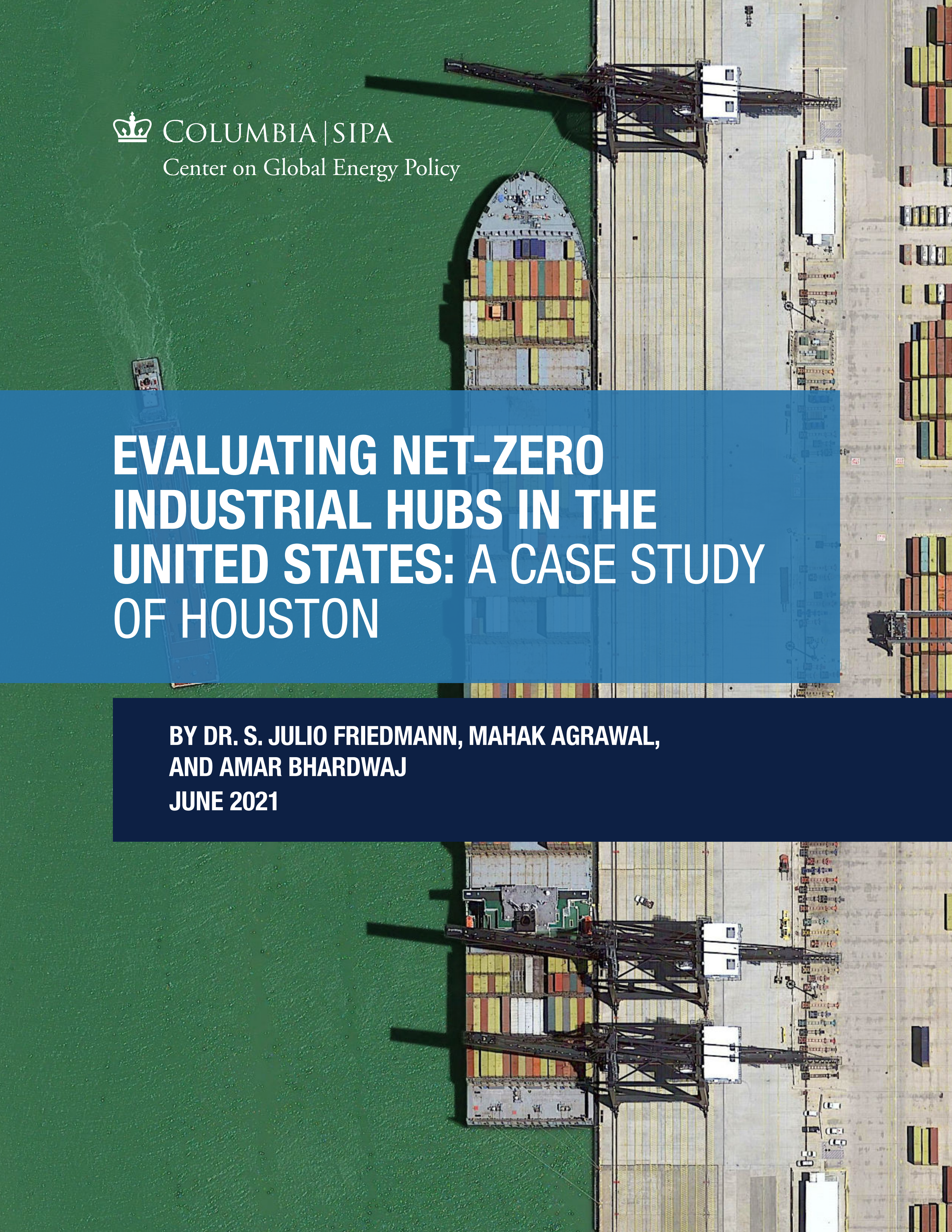

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EVALUATING NET-ZERO INDUSTRIAL HUBS IN THE UNITED STATES: A CASE STUDY OF HOUSTON

BY DR. S. JULIO FRIEDMANN, MAHAK AGRAWAL, AND AMAR BHARDWAJ

JUNE 2021

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ACKNOWLEDGMENTS

This work was made possible by the support of the Cynthia George Mitchell Foundation and benefited greatly from stakeholder workshops facilitated by the Greater Houston Partnership. We are grateful for the comments of a half dozen anonymous reviewers, who substantially improved the clarity and content of the report. Finally, the research and publications teams within the Center on Global Energy Policy provided Herculean support to bringing this report to print under very difficult circumstances—we are in your debt.

This paper represents the research and views of the authors. It does not necessarily represent the views of the Center on Global Energy Policy. The paper may be subject to further revision.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

New legislation, corporate action, and public interest have created both an imperative and opportunities associated with rapid and profound CO_2 reduction and removal. Net-zero industrial hubs present a pathway to focus investment, innovation, and public policy to create industries and infrastructure toward achieving that goal. Such a hub would require building facilities, plants, and linked infrastructure that would reduce and eventually eliminate greenhouse gas emissions through the application of advanced clean energy, emissions control technology, and possibly CO_2 removal technology. This concept, while relatively new, has already gained interest from some nations and companies, most notably in the United Kingdom around net-zero hubs like the Teesside collective.

This paper, part of the work from the Carbon Management Research Initiative of Columbia University's Center on Global Energy Policy, examines Houston as a potential net-zero hub location. Houston, a major US refining and petrochemical center, possesses a high concentration of industrial sites and fossil-fueled power plants. Regional CO_2 storage capacity, low-cost energy, infrastructure like the Port of Houston, and a large skilled labor pool also suggest a possible opportunity for investment, trade, and greenhouse gas reduction in this area. The paper also makes recommendations for policy makers should they seek to pursue a net-zero hub in the Houston area.

Key findings of the paper include the following:

- Infrastructure development is a core feature of net-zero hubs. The authors estimate the possible costs of green hydrogen infrastructure (electolyzers), CO_2 capture infrastructure, new renewable power supplies and transmission, and an ammonia export terminal in Houston will require an initial investment of about $28 billion for 25 million tons per year of annual emissions reduction capacity.

- Based on studies of similar industrial sites, this amount could involve a combination of public and private funds. A competitive federal granting program on the order of $1.5–$2.5 billion of government funding per net-zero hub could attract the private capital needed for development. In order to accelerate investment and reduce risk of failure, the competitive program could be paired with market-aligning incentives such as a hydrogen production tax credit or augmented 45Q.

- Ultimately, developing a net-zero hub and achieving deep CO_2 emissions reductions would likely require a combination of civic and corporate leadership, regional cooperation across sectors, and community engagement. Efforts could include a deliberate focus on equity and environmental justice, including platforms for community involvement, with a focus on creating local benefits.

INTRODUCTION

The global drive to decarbonization is a race for competitiveness and for market share. Any transition to a net-zero world, as required by legislation around the world and set forth by the Paris Agreement, will create opportunities for new fuels, markets, businesses, and trade. This has sparked a global race to capture future economic opportunities in a carbon-constrained world, reflected in policies in nations, trade blocks, and key economic sectors (e.g., in chemicals and steel). Already, the valuation of assets and companies reflects current and future liabilities that come from carbon intensity of manufacturing, products, and services.[1,2] Innovation and investment lie at the heart of the transition,[3] and these are reflected in business plans and national strategies. In addition to investment and innovation, a third "i" is required: infrastructure. New infrastructure is needed to fuel vehicles and vessels and to move electrons, molecules (like carbon dioxide, or CO_2, and hydrogen), and low-carbon goods and cargo. These requirements have led to the concept of **net-zero industrial hubs** as potential engines of development.

> **A net-zero hub, or net-zero industrial hub, is a concentrated set of facilities, plants, and linked infrastructure dedicated to near-term reduction and long-term elimination of greenhouse gas emissions through the application of advanced clean energy and emissions control technology and possibly CO_2 removal technology.**

In concept and in practice, net-zero hubs may become the locus of investment and innovation (in both technology and business model) in the next 20 years of energy transition. Net-zero hubs in key locations, especially ports with large cargo and industrial production, can provide regions and nations with a differentiated competitive edge in a carbon-constrained world. Today, there are parts of the US, Texas, and Houston economies that are carbon and trade exposed—where carbon policies (e.g., border carbon adjustment) could lead to loss of revenue or market share[4]—and investment in net-zero hub facilities and infrastructure could help bring stability to those sectors. It could also bring and maintain high-quality jobs and anchor an innovation ecosystem that will further attract human capital and investment. This study identifies opportunities for net-zero hubs in the United States with a focus on Texas and Houston and proposes discrete recommendations to finance and develop hubs. Houston has a high-potential opportunity for accelerated action through investment, with specific thoughts for local engagement and development.

THE VALUE OF INDUSTRIAL HUBS

Industrial hubs and clusters, as an economic and planning concept, are well known.[5] In contrast, net-zero hubs are fairly new[6,7] but have gained interest and momentum, in particular over the last few years.[8] This is in part because they can address several economic and political concerns simultaneously:

- They can provide a focus for maintaining and growing jobs through public-private partnerships and infrastructure development.
- They can provide support for core infrastructure that is modern, efficient, and low carbon.
- They can provide a pathway to accelerate energy transition and profound decarbonization, particularly for hard to abate sectors.
- They can integrate multiple technologies across multiple sectors (power, manufacturing, transportation, and shipping), which may help provide broad political support.
- They can reduce cross-chain risk when development engages multiple sectors or markets.
- They can more readily achieve economies of scale than distributed systems due to the concentration of infrastructure and resource, reducing overall cost.
- They can make good advantage of local skilled labor pools, including planning, operations, and safety.

In short, net-zero industrial hubs combine a construction agenda with a reduction agenda—building new facilities and critical energy and manufacturing infrastructure in a way that can attract additional manufacturing and investment. If done well, hubs can also be an opportunity to reduce pollution, provide important public services, and redress environmental and equity concerns.

At their heart, net-zero industrial hubs provide a platform to develop three parallel clean energy pathways that are commercially available at scale today: carbon capture, use, and storage (CCUS), zero-carbon electricity, and low-carbon hydrogen. Some include elements of waste-to-energy conversion and biomass. Since many net-zero hub proposals involve ports, they also provide development opportunities for synthetic fuels and electrification as well as trade-related investments (e.g., export of low-carbon ammonia).[9] These pathways require dedicated, new infrastructure essential to project development and achievement of key goals:

- CO_2 transportation and dedicated storage: Captured CO_2 is transported by pipelines or boats to dedicated CO_2 storage sites, most importantly deep saline formations (to maximize storage capacity and minimize carbon footprint).
- Electric transmission expansion: New and enhanced transmission and distribution

power systems could link to zero-carbon electricity generation (most importantly renewable electricity but potentially nuclear, hydro, geothermal power, or fossil with CCUS) that could charge electric vehicles, electrify some industrial and operational processes, or produce green hydrogen.

- Hydrogen production and distribution: New production could include green hydrogen (made from zero-carbon electricity with electrolyzers) or blue hydrogen (made from fossil fuels with CCUS). These could be used locally to decarbonize transportation in the port (trucks and ships) for industry like chemicals and steel or could be converted to zero-carbon fuels like ammonia.
- Port infrastructure: For hubs associated with ports, investment could include new export terminals for zero-carbon goods and cargo produced and manufactured in the net-zero hub[10] and might include docks, storage tanks, distribution systems, and infrastructure for safe and sustainable operations. They might also include airports, with opportunities to produce and disburse low-carbon or sustainable aviation fuels.

Many nations and districts have recognized the potential for net-zero industrial hubs to deliver the benefits discussed above. In addition to the six hubs proposed in the UK, there are many hubs in development worldwide, including those proposed in the EU[11] in the Netherlands, Belgium, Germany, Norway, Italy, and additional net-zero hub proposals in Saudi Arabia[12] and Singapore.[13] This interest is also reflected in the recently announced Global Hydrogen Port Coalition announced at the 2021 Clean Energy Ministerial,[14] which has already confirmed 30 ports around the world as members.

Teesside Project as a Model for Houston

The UK government announced a hub and cluster competition in 2020, with the goal of selecting four sites to receive a total of £800 million funds as part of a public-private partnership. One of the locations competing for these funds is Net-Zero Teesside, one of the longest-lived consortia developing an industrial hub in Europe or anywhere.[15] According to the Net Zero Teesside website, the project "aims to decarbonise a cluster of carbon-intensive businesses by as early as 2030 and deliver the UK's first zero-carbon industrial cluster."[16] The proposal for achieving these outcomes will require multiple kinds of new infrastructure, including the commissioning of trunk CO_2 pipelines to offshore storage, new and retrofit blue and green hydrogen facilities, new zero-carbon power generation inside the port, and other infrastructure enhancements. Toward this end, Teesside won several small grants from the UK government to design and pilot portions of the necessary hub plan[17] as well as substantial funding to begin infrastructure work.[18]

In many ways, Teesside is like Houston. It contains the UK's largest chemical and refining cluster and with it the largest associated greenhouse gas emissions (for comparison, Houston is the largest in the United States).[19] As such, it contains assets from many sectors, including refining, hydrogen production, steel, waste-to-energy, biorefining, and pharmaceuticals. It is adjacent to geological carbon storage options in the near-by offshore—carbon capture and storage (CCS) is at the heart of the Teesside project. Finally, Teesside has sufficient existing infrastructure to provide a starting point for additional development to serve a net-zero economy.

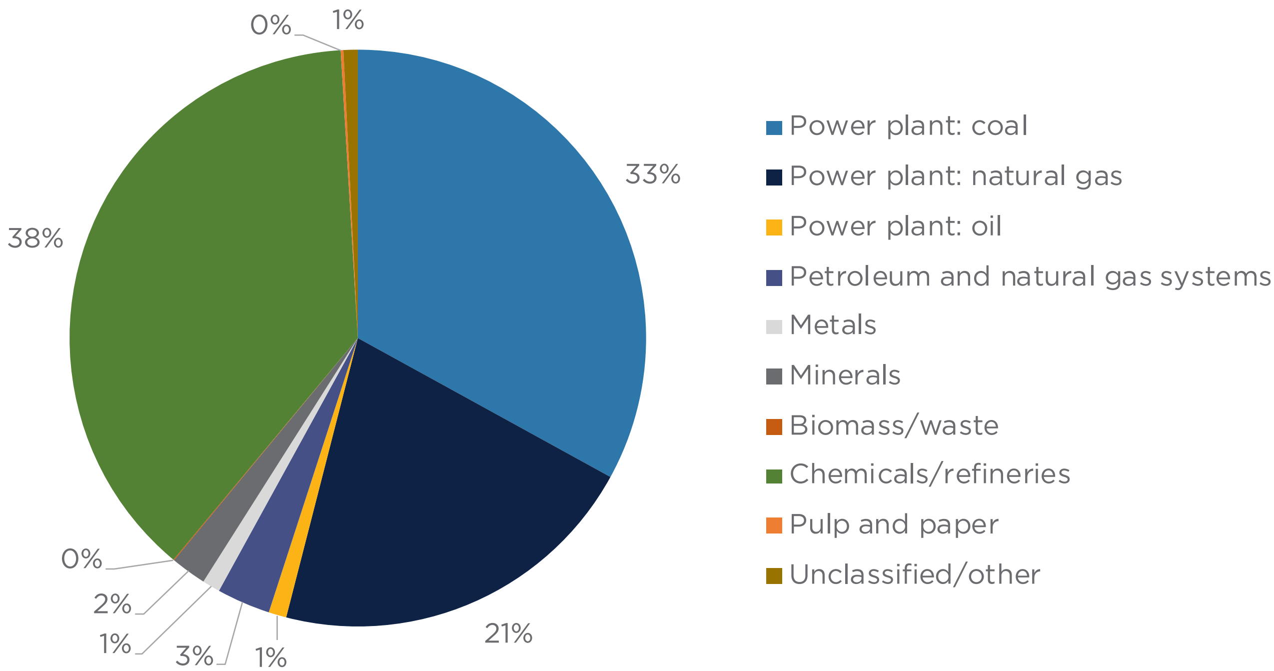
INDUSTRIAL HUBS IN THE TEXAN CONTEXT

Texas is the second largest US manufacturing state, holds some of America's largest manufacturing centers, and is home to diverse industries and logistics centers.[20] Key infrastructure, natural resources, international ports (air, rail, and sea), well-trained human capital, and low taxes (some of the lowest in the United States) make Texas an attractive site to establish and expand industrial and business hubs. Additionally:

- Texas is the second largest economy as a state in the United States. If it were a nation, it would be the ninth largest global economy, with over $1.9 trillion in annual economic activity.[21]
- Texas exports $316 billion in goods every year.[22]
- Texas represents 10 percent of US manufacturing productivity—$230 billion of output each year—and the second largest US manufacturing workforce.[23]

These and other features have led to rapid economic and population growth in Texas. It has also made Texas the largest GHG emitter in the United States—if it were a nation, it would be the seventh largest emitter.[24] It is the largest emitter in both power and industrial emissions, with many large sources clustered in the Greater Houston area (Figure 1). The emissions sources, including from heavy industry and a combination of coal and natural gas power, rank Texas as the 40th state for air quality and 48th for pollution-related health effects.[25] Many of these emissions (both criteria pollution and GHGs) come from large point sources; the largest fraction and largest sources are from chemical and refining, including sources like catalytic crackers, combined heat and power systems, and hydrogen production units. After that, large coal and gas plants are the second largest set of sources.[26]

Figure 1: Share of CO_2 emissions by sector in Texas, with chemicals and refining as the single largest fraction

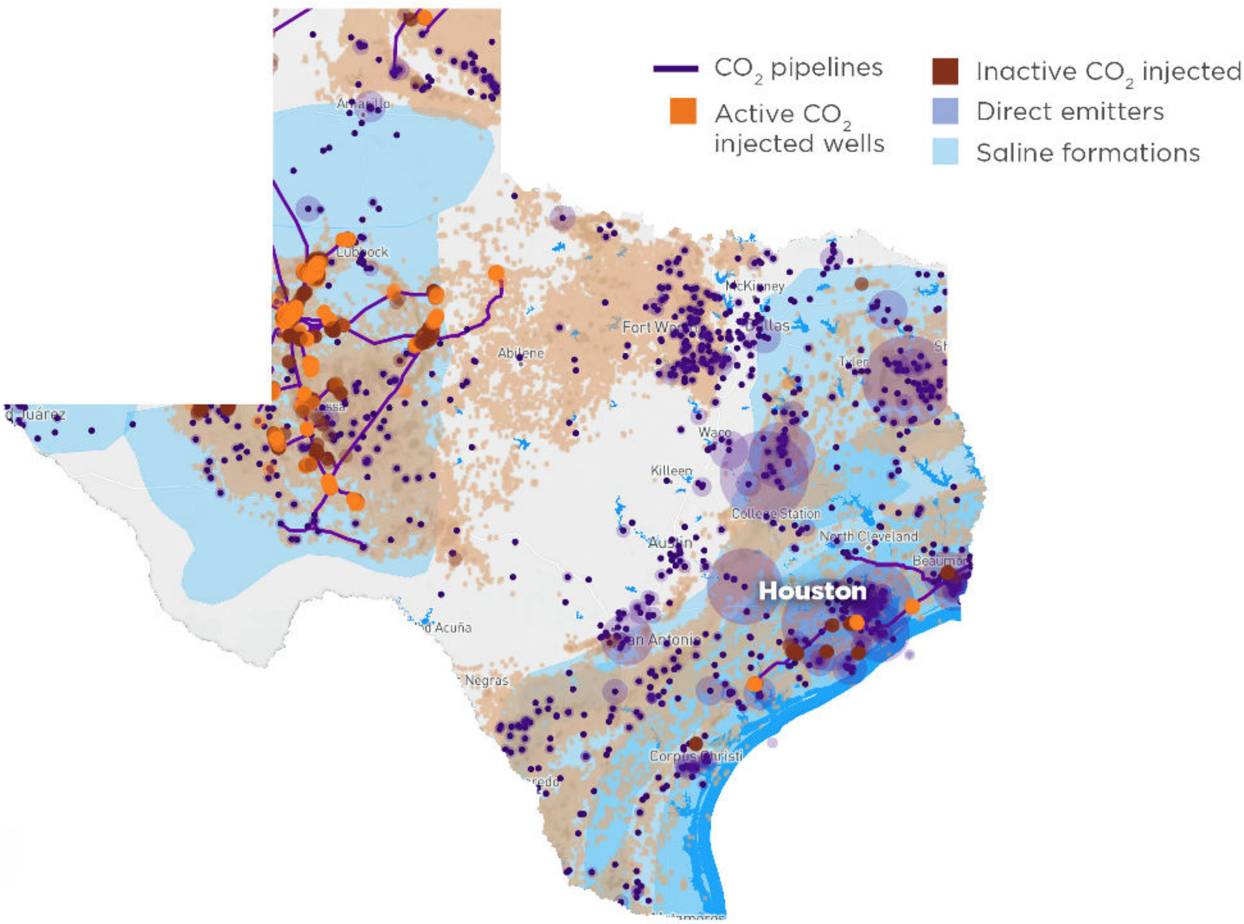


Source: National Petroleum Council, "Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage in the United States," (Washington, DC: National Petroleum Council, 2020), https://dualchallenge.npc.org/downloads.php.09.

Within the region, Houston hosts the largest and largest concentration of emissions sources.[27] While in Texas coal power is the second largest CO_2 source, in Houston natural gas power plants represent the second largest share of CO_2 emissions.[28] The clustering of sources provides pathways to minimize footprint and cost for CO_2 retrofit—just the steam-methane reforming units in Houston produce 5.7 Mt/y CO_2, of which ~4 Mt/y is already highly concentrated (>90 percent CO_2 purity).

Texas is also home to an important natural resource required for a net-zero industrial hub: subsurface pore volume for CO_2 storage. The combined onshore and offshore saline formation capacity along the Gulf Coast alone is estimated above 1 trillion tons capacity[29]—more than 10,000 times the annual emissions of Houston—and the Gulf of Mexico pore-volume storage resources is the largest in the United States. Much of this natural resource is available near Houston (Figure 2), including the Eocene Wilcox and Claiborne units, the Oligocene Frio-Vicksburg Formation, and Lower Miocene formations, and in the near-offshore shelf units in the Middle and Upper Miocene. Both scientific pilots and large commercial facilities have demonstrated that these formations can safely and effectively store CO_2.[30,31,32,33] Since Texas is the only state that controls and owns the first 10 miles of shelf from the shoreline (three times what most states own), the state has an outsize legal authority to develop this large natural resource for use in development of a net-zero hub.[34]

Figure 2: Composite map of the CO_2 storage capacity in saline formations and active oil fields in Texas



Source: Medlock and Miller (2021), with data from NETL/NATCARB and the Gulf Coast Carbon Center. See endnote 33 for more details.

Because excellent geological storage resources are proximal to concentrated anthropogenic carbon sources (i.e., CO_2 emissions from refining, chemicals, and other energy intensive industries), the need for expansion of pipelines and other transportation infrastructure can be minimized.[35] The human capital of the oil and gas industry provides both experience and technical expertise required to build and operate a net-zero hub, including for carbon capture, transport, and storage retrofits, and new net-zero fuel production, use, and shipping (as well as the planning, safety, and implementation).[36.37]

While these characteristics are true of Texas, many are true as well in Louisiana. On a national basis, the Gulf of Mexico region could host multiple hubs that would accelerate decarbonization and improve competitiveness on a national basis. On a regional basis, Louisiana and Texas could be seen as competitors for the same labor pools, capital, and trade opportunities. In this context, it is noteworthy that Louisiana as a state has shown leadership around low-carbon refining[38] and access to carbon storage resources.[39]

INFRASTRUCTURE COSTS FOR A HOUSTON NET-ZERO INDUSTRIAL HUB

To better understand the possible costs for net-zero hub infrastructure, we applied a set of assumptions to representative infrastructure components. These assumptions are meant to help estimate the order-of-magnitude costs involved; these are rough estimates, not precise figures, which may be too generous or conservative depending on project specifics. The specific size of systems is keyed to Houston in terms of present energy and material demands. The ammonia terminal was added to reflect one substantial trade opportunity.

- Green hydrogen synthesis for local use: We assumed a 1 Mt/y hydrogen facility (~2800 t/day H_2). This would require 14 GW of electrolyzers running at a 40 percent capacity factor. We assume $800/kW, which is below market prices today but consistent with near term projections.[40]
- CO_2 pipelines: To move 20 Mt/t, we assumed 10 new dedicated pipelines (8 onshore, each $24.6 million, and 2 offshore, each $28.4 million), each carrying 2 Mt/y and 30 miles in length.[41,42] This reflects the current sources of CO_2 in Houston (roughly 25 Mt/y) and the expectation that there will be a mix of sized and onshore-offshore configurations.
- Electricity upgrades: We assumed 50 TWh/y, including transmission and new renewable generation (an even split of solar, onshore wind, and offshore wind) with average overnight capital costs of $820/kW and an average 40 percent capacity factor.[43,44] This would be sufficient to provide zero-carbon electricity for either all of green hydrogen production or some green hydrogen with other renewable loads flowing to fuel electric vehicles in the port and city and electrify a fraction of industrial steam production, and it represents a 15 percent increase in Texas's generating capacity and a near doubling of non-hydropower renewable generation.[45]
- A new ammonia terminal: We assumed a new terminal, excluding ammonia and hydrogen synthesis, capable of exporting 1.3 Mtpa of ammonia. This would include docks, ammonia storage systems, and dedicated fueling systems for export. The estimated cost is $1 billion, with assumptions based on a recent study of a comparable ammonia terminal in Galveston.[46,47]

Given these assumptions, we estimated the costs in Table 2. Naturally, none of these assumptions represents a detailed optimization for a given configuration. Rather, they are meant to provide some sense of the magnitude of investment needed to bring a handful of elements to a net-zero hub. Depending on the configuration, this infrastructure mix could reduce GHG emissions roughly 25 Mt/y at a cost of $28 billion. In short, a megaton of annual CO_2 abatement capacity costs a gigadollar.[48]

Table 1: Representative costs for key infrastructure elements in a Houston net-zero hub

Item	**Dimension**	**Estimated Costs** ($ millions)
Hydrogen—new production, all green	1 Mt/y H_2 14 GW electrolyzer capacity ($800/kW)	$11,000 electrolyzers
CO_2 pipelines—existing source focus	20 Mt CO_2/y—30 miles • 10 pipelines (2 Mt/y) • 8 onshore, 2 offshore	~$500
Electricity—zero-carbon electricity for green hydrogen and port electrification	50 TWh/y • 40 percent capacity factor • Even split: solar / onshore wind / offshore wind	$4,000 transmission $12,000 new generation
Port infrastructure	1.3 Mt/y ammonia (including storage tanks, dedicated docks, ammonia pipelines, and dredging	~$1,000 (full facility) ~$100 docks etc.

These numbers are consistent with other estimates, including ExxonMobil's recent estimate for an expansive version of a Houston regional hub. Their estimate was 100 Mt/y for $100 billion.[49] Importantly, the majority of funds to finance retrofits, infrastructure, and new projects would be private—also the expectation in the UK competition and the ExxonMobil study. However, public incentives, specifically grants, are essential to attract private capital into net-zero hubs in general. In that exact context, ExxonMobil's Houston proposal points out the need for additional policy support to attract investment.[50] This matches the expectations of the UK industrial hubs: government funds provided to Net-Zero Teesside and Humber Net-Zero are expected to attract and anchor investment from corporations, financiers, and banks. Specifically, the £1 billion funds from the UK government are projected by the government to attract £10 to £20 billion of private investment.[51]

This suggests a minimum cost of $1.5 billion of public investment for a large hub in Houston and arguably $2.5 billion of investment to de-risk projects and attract the necessary private capital, with the expectation of attracting $12 to $40 billion as private capital investments based on prior DOE project and infrastructure match rates. Constituencies that seek to develop a net-zero hub should actively engage with federal and local lawmakers to express their vision, clarify their development goals, and provide input to the legislative process around key bills, including constituencies in Texas, Houston, and Harris County.

EXISTING AND EMERGING POLICIES

Bringing clean energy to market commonly requires multiple market-aligning policies and investments. This is particularly true for infrastructure, wherein sole investor-owners have little incentive to provide benefits to multiple commercial parties or the public. For net-zero hubs, a mix of federal policy supports exists that helps reduce cost and risk to investors and operators, which can be enhanced by state and local policy.

The rapidly evolving policy landscape creates possibilities to support net-zero hub development directly and indirectly. Although these provisions are not yet law, it appears that some material provisions may be enacted in 2021.[52] Chief among proposals is the American Jobs Plan proposed by the Biden administration.[53] It includes a set of provisions that support net-zero hub development, in some cases in reference to drafted bills:

- $25 billion of funding to upgrade airports and $17 billion for seaports
- $20 billion of funding for clean transportation investment and infrastructure, with a focus on disadvantaged communities
- Funding for resilient infrastructure, including those affected by Hurricane Harvey
- Funding for 10 large-scale industrial decarbonization projects, including hydrogen and CCS projects, in disadvantaged communities
- Support for electric infrastructure development, including new transmission, electric vehicles charging infrastructure (which may include hydrogen fuel-cell vehicles)

These provisions could help fund specific projects and associated infrastructure in Houston, which could receive support through competitive grant solicitations, congressional earmarks, or bespoke public private partnerships. In particular public-private partnerships have proven important in deploying clean energy projects in general[54,55,56] and in the United States.[57]

Extended and expanded tax credits could play an important role as well. In particular, Section 45Q of the federal tax code[58] provides a performance-based tax credit for carbon capture projects.[59] The 45Q was expanded and reformed via the Bipartisan Budget Act of 2018 to grow the tax credit to $35 per ton CO_2 captured and used for enhanced oil recovery or other beneficial uses and to $50 per ton for saline formations storage.[60] A number of new federal bills seek to enhance 45Q crediting but may still be insufficient to activate private markets.[61]

The existing wind production tax credit and solar investment tax credit have played an enormous role in sustaining and attracting investment in renewable generation infrastructure, including in Texas. In the context of a net-zero hub, hydrogen production and investment tax credits could play an additional role in attracting private capital to produce low-carbon fuels. Proposals include a 10-year hydrogen production tax credit (PTC) indexed to speed of deployment and carbon intensity, starting at $3/kg H_2.[62] Other proposals include hydrogen-based electricity support[63] and new loan guarantees for hydrogen infrastructure.

A more comprehensive bill, the CLEAN Future Act,[64] would provide both financial support and regulatory directives that could support US net-zero hubs. Specifically, the act proposes these key provisions among others:

- A 100 percent clean electricity standard by 2035, allowing rate recovery as a mechanism to finance zero-carbon electricity
- $100 billion funding for a clean energy and sustainability accelerator program
- Additional grants and loans for infrastructure investment, including $50 billion for charging and clean fueling infrastructure and $10 billion for efficiency and GHG emission reduction upgrades

Other new legislative proposals support CO_2 infrastructure directly. These include the SCALE (Storing CO_2 and Lowering Emissions) Act to enable CO_2 transport and storage infrastructure through support from the US Department of Transportation.[65,66]

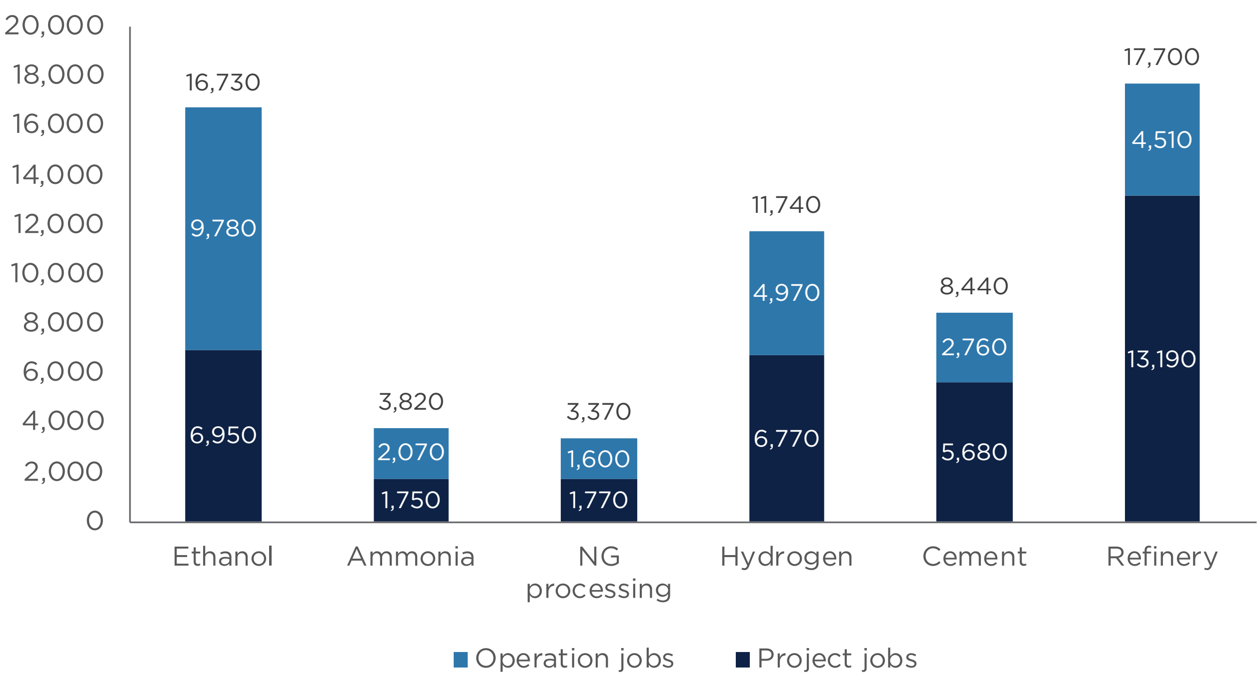
Finally, some local and federal policies provide support to developers and entrepreneurs. One example, economic opportunity zones, reduces the tax burden for companies and projects that establish themselves in areas designated as economic opportunity zones, specifically with the goal of locating high-paying permanent jobs in disadvantaged communities.[67] In considering a net-zero hub, other local or regional policies of this sort that can further activate, accelerate, or support hub development.

BENEFITS OF AN INDUSTRIAL HUB IN HOUSTON

Houston's first ever Climate Action Plan, launched in 2020, aims to reduce GHG emissions by 40 percent by 2030 and achieve carbon neutrality by 2050.[68] In realizing this vision, a net-zero industrial hub for the Greater Houston region could play a pivotal role. Houston provides diverse opportunities for the industrial net-zero hub in terms of CO_2 emissions sources, infrastructure and geology, strategic partnerships with industries, and an ecosystem for implementation and value creation.

One dimension is jobs. Recent analysis suggests that deployment of CCS with enhanced 45Q credits could generate over 60,000 jobs before 2035 in the industrial sector alone (Figure 3), with roughly 40,000 of those jobs in Texas.[69] These numbers are consistent with estimates from the UK government for similar projects in that country.[70]

Figure 3: Total job years from carbon capture retrofits with 45Q enhancements, by industry



Source: Ben King, Whitney Herndon, John Larsen, and Galen Hiltbrand, "Opportunities for Advancing Industrial Carbon Capture," Rhodium Group, 2020, https://rhg.com/research/industrial-carbon-capture/.

A study by the UK's Energy Research Centre highlights those investments in new renewable generation capacity and net-zero systems generate more jobs in the short run than investing an equivalent amount in fossil-fuel-powered systems—with the magnitude of difference being of the order of one job per annual GWh produced.[71] While it may be that renewable job and net-zero hub job creation is not strictly analogous, the experience of renewable job creation provides a sense of the magnitude of opportunity. In the medium to longer-term period, employment opportunities may unlock in the production of (and research and development related to) hydrogen electrolysis production, storage, and transmission as well as other components of CCUS and hydrogen production. In essence, transition toward a net-zero hub can drive economic growth and employment by creating and sustaining jobs, amplifying economic growth via new net-zero industries and innovation spillovers, enabling infrastructure reuse and facilitating just transition by alleviating geographic and temporal imbalances.

Industrial net-zero hubs and carbon capture could create opportunities and avenues for new companies and industries in which CO_2 is recycled into fuels, building materials, and other products—a circular carbon economy.[72] CO_2-based products could potentially be worth $800 billion and use captured CO_2 for synthetic fuel production, enriching concrete, and power generation.[73] With global abatement from CO_2, recycling could achieve several gigatons per year.[74] In essence, a range of new industries and companies—testing products with variable emission mitigation potential and at varying stages of market development and deployment—are coming up or could soon crop to tap the captured CO_2.[75] In the case of Houston, development of a net-zero hub could serve as a magnet for entrepreneurs and if well designed could include test beds, incubators, and training programs for low-carbon manufacturing and operations focused on CO_2 recycling and circular carbon economy.

In some cases, investment in net-zero hub infrastructure could provide infrastructure hardening against sea level rise or coastal storms. For federally funded projects, there is increased desire to assess climate related risks in infrastructure spending.[76,77] While dedicated weather and climate risk reduction systems (e.g., the "Ike Dike")[78] would fall outside of net-zero hub investment, other components of the energy, port, and pipeline system could be designed with extreme weather and sea level in mind. This topic is of high relevance to Texas following the 2021 winter events that led to widespread power shortages.[79]

Finally, deployment of industrial net-zero hub could reduce air pollution in key industries and several other sectors. The European Environment Agency identified reductions for key air pollutants of sulfur dioxide (SO_2), particulate matter (PM), and nitrogen oxides (NOx) and ammonia (NH_3) with the deployment of CCUS.[80] A net-zero hub could further reduce criteria pollution through reduction of diesel use from ships and trucks (through hydrogen fueling or electrification) and reduction of VOCs and PM through substitution of natural gas with hydrogen for industrial heat and processes. This would bring concrete health benefits through reduced pollution and decarbonization,[81] in particular to communities disproportionately affecting disadvantaged by close proximity to power and industrial facilities. Note: care must be taken to avoid increasing NO_x pollution, which can occur through poor mixing of hydrogen into existing pipelines or facilities, especially where disadvantaged communities would see increased pollution loads. This can be managed with existing technology and should be integrated into any net-zero hub's planning, design, and operation.

While a net-zero industrial hub could provide these benefits, the converse is also true—failure to develop a hub actively could result in missed opportunities, including loss of market share in a carbon-constrained global market. Though Houston brands itself today as the "Energy

Capital of the World," it is possible that loss of benefits could be long lived or permanent, with associated loss of trade, aging of facilities, risk of future regulation, and continued health and environmental damages from uncontrolled pollution. While it may be possible to mitigate those effects through delayed investment, it is also possible that such investments may prove more expensive and ineffective.

Public Acceptance and Environmental Justice Considerations

Local stakeholders in civil society are critical stakeholders in their own right. They include environmental groups (e.g., NRDC, Air Alliance of Houston, Sierra Club) as well as local universities (e.g., Rice, University of Houston, Texas Southern University), regional innovation centers (e.g., HARC, Greentown Labs, the Cannon), and local chambers of commerce (e.g., Greater Houston Partnership).

Increasingly, the recognition of the high health and environmental burden paid by communities near industrial facilities has elevated the subject of environmental justice and the need for greater equity.[82] Commonly, and as is the case in the Greater Houston area, these communities are homes for economically disadvantaged populations comprising underserved minorities. These communities are subjected to safety failures as well, including facility explosions and release of highly toxic substances.[83] These communities and populations are not homogeneous and represent many needs, perspectives, and constituencies. Critically, these communities too frequently lack adequate voice or representation when infrastructure and major project investment decisions are being made.

Early engagement with key environmental, civic, and commercial stakeholders locally will be essential for any community aiming to develop a net-zero hub anywhere in the United States, and certainly in Houston. To help make sure that important benefits manifest in a just and equitable way, civic leaders should consider developing active engagement strategies that provide agency and voice to these communities so that their needs and issues can be considered. Ideally, business, political, and civic leaders would call upon leaders of impacted communities to better understand their thoughts and concerns and to identify potential solutions. There may be many pathways to address these concerns through policy, regulation, and investment, but these pathways cannot be explored without discussion and consideration. Alignment of needs and vision across many stakeholders is critical to successful planning and development.

FINDINGS AND RECOMMENDATIONS

Finding 1: Investment in net-zero hubs could help make the United States more competitive. In a carbon-constrained global economy, net-zero hubs can serve as anchors of industry, trade, and innovation. Other countries (including the UK, Canada, Norway, Netherlands, Italy, Saudi Arabia, and the UAE) have made public commitments to the development of net-zero hubs with a mixture of public and private funding and policy support. The United States risks loss of market share, market access, and competitiveness without major infrastructure investments in and policy support for net-zero hubs.

Finding 2: Houston is well positioned to become a best-in-class net-zero hub. The asset base, natural resources (including geological CO_2 storage resource), and human capital in the Greater Houston area are well positioned to build on existing local, state, and federal policy as well as some existing infrastructure (e.g., the Port of Houston). The environmental and economic benefits could include >20 Mt/y CO_2 reduction, substantial pollution reduction, and the creation of thousands of new jobs. Moreover, the hub could serve as a magnet for new and emerging industries, innovators and entrepreneurs, and investment in energy transition companies and resources. Failure to develop a hub could lead to loss of these benefits and opportunities.

Finding 3: Specific challenges face a net-zero hub initiative in Houston. First and foremost, policy support today is insufficient to finance a net-zero hub within the United States or in Houston. Substantial public and private capital is required, as is alignment across multiple industries and stakeholders. The current infrastructure provides a platform to begin but is insufficient to achieve decarbonization targets or key economic goals of the region. Dedicated CO_2 transportation pipelines and storage facilities, electric transmission and power upgrades, port infrastructure (including docks, new fueling facilities, and fuel storage systems), and new manufacturing facilities stand among the most pressing and important infrastructure elements, and the substantial estimated cost of associated infrastructure is unlikely to be met through voluntary markets and existing policy measures alone. Similarly, public engagement is necessary, most importantly in communities that might host infrastructure and disadvantaged communities near existing or planned hub components. There is a deficit of trust that will likely prevent or limit hub development.

Finding 4: Substantial public policy support would be needed to attract the private investment to develop a net-zero hub. Critical components of the needed infrastructure require direct public investment and financial support. Market failure and risks necessitate additional market aligning policies, such as public funds for infrastructure, tax credits, contracts for differences, clean energy standards, and even border tariffs. Without direct support or market-aligning policies, any US hub (including Houston) would not attract the private investment necessary to build new assets and facilities and to operate reliably and sustainably, thereby missing the potential economic and environmental benefits.

Recommendation 1: The US Congress should enact financial supports for net-zero hubs. A competition for hubs nationwide, akin to the UK hub competition and the Department of Energy's Regional Carbon Sequestration Partnerships, would build on precedent and provide cash for common and critical infrastructure[84] such as electricity upgrades and CO_2 pipelines.

- A competition should provide a minimum of $1.5 billion for each hub, and arguably greater sums for higher ambition (up to $2.5 billion), focused on net-zero enabling infrastructure.
- For greatest benefit, this should be paired with market-aligning policies (e.g., hydrogen PTC, enhanced 45Q) that would stimulate investment and innovation to support the manufacture of low-carbon fuels, manufacturing, goods, and services.

Recommendation 2: Texas, Houston, and Harris County should prepare a net-zero hub plan and proposal. The hub leadership should be independent of government and industry (e.g., a new nonprofit entity or within an existing nonprofit community entity) and would require a strong and experienced leader to succeed through convening, strategy development, and federal engagement.

- The hub leadership should begin at once to engage with civic leaders, local government, organized labor, regional technical experts, academia, and corporate leaders to build a team, prepare detailed plans, and formalize commitments (institutional or financial).
- This leadership and its constituencies should focus on securing expansive financial support, including federal and state grants and market-aligning policies.
- Local communities and stakeholders should have active roles and platforms and processes to voice ideas, perspectives, and concerns, with dedicated platforms to discuss questions of equity and environmental justice.

Proactive engagement by Houston and Harris County could help identify potential barriers and hurdles to development of a hub and would provide a model to other US and international cities that might be considering net-zero hubs. Finally, Houston should consider developing a sister-city network with other net-zero hubs to share information, assess practice, and stimulate political and economic activity.

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