Abstract
In this paper, we present the first theory-based and empirically-aligned framework to provide an integrated, multi-disciplinary siting approach for industrial decarbonization hubs. The paper and associated panel discussion explore opportunities and challenges related to developing regional hubs for industrial decarbonization, with a focus on identifying social science research questions around coordinated siting. Drawing on energy facility siting literature, the paper and presentation examine economic, environmental, and process factors that can influence hub siting. A review of existing social science frameworks and siting approaches will serve as the basis for discussion of future research needs.

A social science framework to assess industrial hub siting outcomes

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Introduction

Governments and industry are planning and implementing regional industrial decarbonization hubs to achieve national and regional decarbonization goals. Because industry remains a key contributor to overall domestic greenhouse gas (GHG) emissions, decarbonizing regional industrial hubs aims to decrease GHG emissions in the production and supply of key materials. Although the transition of existing industrial centers and the development of new regional industrial decarbonization hubs present opportunities for economic development as well as improved environmental and energy justice, there remain challenges related to developing industrial decarbonization hubs aligned with those priorities.

An example of a regional industrial decarbonization hub in the United States is the H2Houston Hub. Houston has extensive industrial facilities (a total of 193), including facilities for chemicals, petrochemicals, metals and minerals, steel, gas processing and power, and other material production and processing, which collectively produce 156.2 million metric tons (Mt) of $CO2_2e$ annually (GPI 2022). This hub contains 14 hydrogen (H_2) production facilities, which can serve as an alternative energy source for facilities, and transportation infrastructure, which can serve as a distribution network for low-carbon fuels—and has the potential for carbon capture and storage. Efforts are underway to develop and implement strategies and partnerships to transition this existing industrial hub into a center that applies clean energy technologies to decrease industrial carbon emissions and realize economic growth (World Economic Forum [WEF] 2024a).

In this paper, we present a theory-based framework that provides an integrated, multi-disciplinary siting approach for regional industrial decarbonization hubs. We explore opportunities and challenges related to developing regional hubs for equity focused industrial decarbonization, with a focus on identifying social science research questions around coordinated siting. Drawing on energy facility siting literature, we examine economic, environmental, and process factors that can influence hub siting and propose a research agenda and associated guiding questions.

Background

Industry accounts for roughly one-third of energy-related CO_2 emissions in the United States (Energy Information Administration [EIA] 2021). Regional industrial decarbonization hubs integrate clean technologies into industrial processes, apply clean technologies as energy sources, and co-locate facilities—therefore, hubs can reduce industrial GHG emissions. Industrial decarbonization can involve the transition of existing facilities or the development of new ones (Devine-Wright 2022). Fundamentally, the multiple and traditionally carbon-intensive energy sources that drive industrial processes pose both an opportunity and a challenge for a shift to decarbonization, with industrial emissions largely coming from carbon-based fuels, electricity generation and demand, chemical processes, and product life cycles (U.S. Department of Energy [DOE] 2022). Integrating clean technologies to provide alternatives to these fuels and processes presents technological, logistical, and social challenges and risks, such as distributed siting of industrial facilities with multiple transportation routes for high-risk products and supplies. Regional industrial decarbonization hubs present potential opportunities as co-localized governments and companies cooperate to adopt and implement shared goals and—in doing so—decrease the financial, technological, and social risks linked to the integration of new clean technologies while realizing improved economic, environmental, and social benefits.

For this paper, we consider *industry* to be a broad term that includes multiple subsectors responsible for emissions, including the five specific subsectors identified by DOE as the highest contributors of emissions (i.e., food/beverage, cement, petroleum refining, iron and steel, and chemicals; DOE 2022). We define a *regional industrial decarbonization hub* as a grouping of co-localized facilities and infrastructure for materials production and processing and energy generation, and the partnership of government and industry stakeholders, that is committed to the development and implementation of decarbonization strategies. Building on this definition, *regional industrial decarbonization hub siting* is a multifaceted and multi-phased approach for selecting industrial centers and technologies and developing and implementing strategies that require coordination among several stakeholder groups, including multiple government entities (e.g., policy makers and regulations), industry, workforce, and the broader community.

In recent years, the development and adoption of strategies for regional industrial decarbonization hubs have increased. The U.S. federal government, for instance, announced a long-term strategy to achieve net-zero GHG emissions by 2050 and, as a part of realizing this goal, has formulated strategies to advance decarbonization in industry (U.S. Department of State and U.S. Executive Office of the President 2021). DOE also developed a national roadmap for industrial decarbonization based on energy technology pillars, which recommends eight key actions, including the application of energy justice goals to engage communities in building workforce capacity (DOE 2022). As an example of the federal policies, the 2022 Inflation Reduction Act extended and modified a carbon capture and storage credit—Section 45Q—increasing the amount of the credit and including all carbon oxides, among other changes, to decarbonize industrial and power generation facilities (H.R.5376 2022; IEA 2023; Kammer et al. 2023).

Additionally, WEF's Transitioning Industrial Clusters initiative offers resources, facilitates partnerships, and provides guidance on four practical and logistical pillars of policy, partnerships, technology, and financing (World Economic Forum 2024b). This initiative has engaged 13 signatory clusters across the globe, with 4 in the United States—including the H2Houston Hub. An assessment of domestic mid-Atlantic facilities suitable for the deployment of carbon capture, utilization, and storage (CCUS) technologies by the Great Plains Institute identified 286 possible facilities across eight states and the District of Columbia that are eligible for the 45Q credit, which produce emissions of more than 100,000 Mt CO_2 per year (Kammer et al. 2023).

Siting industrial decarbonization hubs can bring about many benefits, opportunities, and risks, and the growth in interest in industrial decarbonization illuminates the need for governments, industry, and communities to think strategically about how to develop collaborative hubs while minimizing their risks and maximizing public and private benefits. Local and regional benefits include economic growth in the form of increased gross domestic product and jobs (World Economic Forum 2024a) and improved public health, such as decreased mortality (Bennett et al. 2023). Broader societal benefits include reduced carbon emissions and the deceleration of climate change (World Economic Forum 2024a). Similar to other energy development efforts but at a broader scale, risks include technological and market uncertainties, the need for investment, and impacts from having inadequately addressed energy justice. Challenges arise as we collectively learn how to provide economic opportunities equitably across the country. For example, there is concern about the potential negative impacts to communities when industrial facilities are moved from distributed communities into hubs. The risks and benefits of these transitions can be greater for private industry, supply chains, government, workforce, and surrounding communities.

Research related to regional industrial hub siting is relatively new. Therefore, we largely draw from literature on smaller-scale energy infrastructure siting (including renewable energy siting) and other facility types relevant to industrial hubs (with key distinguishing differences).

In recent years, public policy literature related to broad energy infrastructure siting, not related to a specific technology, has grown. The literature discusses the concept of community (Lesbirel, 2011), conflict and concord among policy actors (You et al., 2021), and community variables associated with project locations (e.g., demographics and political-orientation; You et al. 2002) and concerns related to waste (e.g., siting of nuclear waste; Pijawka and Mushkatel 1981)

Renewable energy siting typically focuses on the processes and support around the geolocation of new infrastructure, such as wind energy generation projects, often at the community scale. Although the development of industrial hubs is more complex, involving incorporating new technologies, facilities, and energy sources into existing industrial centers belonging to multiple companies across multiple and different industrial activities, lessons learned from renewable energy siting are relevant to industrial hub siting given that they both involve governance challenges around the interconnected nature of renewable energy with the environment, society, and the economy. The process for siting industrial decarbonization hubs requires larger-scale collaboration and commitment across local government and multiple private companies and must be multifaceted across the policy, partnership, technological, and financial pillars identified by WEF. This complexity could produce local reactions distinct to those for renewable energy siting. Nevertheless, renewable energy facilities present a reasonable simplified example on which to build.

Given the commitment of the U.S. federal government to equitably decarbonize, including the industrial sector, there is a critical need to examine the environmental, financial, and societal impacts of industrial hubs on local and global scales. Because of the complexity of the systems involved in industrial hub siting and the distributed nature of the decarbonization opportunity, coupled with differences in how industrial decarbonization is prioritized within success broad decarbonization metrics and roadmaps, a multidisciplinary approach is necessary to evaluate siting processes and to enable the highest likelihood of optimizing the most benefits (e.g., economic, environmental, and financial benefits) across the full range of stakeholders. We thus draw upon multidisciplinary social science theories and frameworks to examine the following questions:

- How might siting processes and strategies result in different outcomes for regional industrial decarbonization hubs?
- How might different social, policy, and technological factors contribute to the improved effectiveness of equity of hubs?
- How might processes and strategies identify, prepare for, and adaptively manage risk and uncertainty to achieve effective decarbonizing and equitable hubs?

To build a research agenda that aims to expand our understanding of and ability to evaluate regional industrial decarbonization hub siting processes, we draw upon existing industrial decarbonization strategies in addition to lessons learned from the siting of smaller-scale energy infrastructure to develop a Learning Framework for Industrial Decarbonization Hubs.

Developing a Comprehensive Research Framework

In this section, we present our framework: a Learning Framework for Industrial Decarbonization Hubs. We present the components of the framework and potential operationalized variables and explain their role in the processes and connections to outcomes in siting regional industrial decarbonization hubs. To develop our framework, we first examined strategies developed and applied by governments and organizations to provide guidance for planning, implementing, and assessing the impacts of regional industrial decarbonization hubs. Integrating multiple frameworks, including the Collective Learning Framework (Heikkila and Gerlak 2013) provides a structure to explore the relationships between factors, processes, and outcomes related to industrial hub siting. In this framework, specific factors serve as independent variables that shape the planning and information processing and knowledge building of siting processes. The dependent variables are the outcomes from these siting processes, including the strategies, decisions, implementation actions, and deployment of technologies. The selected factors and their connection to the siting process and outcomes shape research questions through which we can explore regional industrial decarbonization hub siting.

Published Strategies for Regional Industrial Decarbonization Hubs

Practical strategies applied by governments and organizations provide applied grounding for the framework. We assessed WEF's Transitioning Industrial Clusters initiative (WEFa, WEFb); DOE's Industrial Decarbonization Roadmap (DOE, 2022); the National Academy of Science, Engineering, and Medicine's (NASEM) report on Accelerating Decarbonization of the U.S. Energy System (NASEM, 2021); and the Great Plains Institute's (GPI's) analysis of CCUS opportunities in the Mid-Atlantic (Kammer et al, 2023). These strategies provide pillars and recommendations for industrial hub development, and the GPI CCUS report demonstrates criteria for selecting potential sites for decarbonization technologies. Table 1 outlines these strategies.

Table 1. Strategies and Pillars for Industrial Decarbonization

Strategies	**Pillars**	**Lessons Learned, Recommendations, Examples**
World Economic Forum: Transitioning Industrial Clusters initiative	Technology	• Green H_2 hubs as storage of renewable energy and source of power generation, fuels, products
	Policy	• Comprehensive policy frameworks (Inflation Reduction Act) • Promotion of renewable energy and energy security • Carbon pricing
	Partnerships	• Dialogue across government, industry, community • Workshops with community participation
	Financing	Policy: • Credit enhancement for risk mitigation • Incentives for industrial decarbonization hubs; decarbonization across supply chain • Removal of incentives for traditional fuels and processes • Grants and incentives Investing: • Provide long-term financing • Build expertise to evaluate technological options Clusters (hubs): • Resource sharing (aggregated demand improves efficiency while reducing cost) • Engagement across multiple stakeholders (community, government, industry) • Develop governance model
DOE Industrial Decarbonization Roadmap programs	Energy efficiency	• DOE Better Plants Program Energy Initiative
	Industrial electrification	• Innovation of new electric or hybrid systems
	Low-carbon fuels, feedstocks, and energy sources (LCFFES)	• Production and use of renewable fuels, including H_2 • DOE H2@Scale
	Carbon capture, utilization, and storage (CCUS)	• Provide long-term solutions to chemical processes
	Alternative approaches	• Land-use and management, including biochar and soil carbon management • Biomass-energy with carbon capture and storage (BECCS)

Strategies	**Pillars**	**Lessons Learned, Recommendations, Examples**
Accelerating Decarbonization of the U.S. Energy System report	Technological goals	• Invest in energy efficiency and productivity • Electrify energy services in transportation, buildings, and industry • Produce carbon-free electricity • Plan, permit, and build critical infrastructure • Expand the innovation toolkit
	Socioeconomic goals	• Strengthen the U.S. economy • Promote equity and inclusion • Support communities, businesses, and workers • Maximize cost-effectiveness
	Siting risks	• Timely siting of new long-distance transmission capacity
	Siting innovations	• Increased investment in research and technology to develop innovations in processes and procedures, including repurposing existing infrastructure

The pillars described in Table 1, in combination with the social science frameworks described in the next section, can inform an integrated framework for regional industrial decarbonization hub siting. The first pillars are the foundation of WEF's Transitioning Industrial Clusters initiative and reflect key dimensions of industrial decarbonization clusters: technology, policy, partnerships, and financing (World Economic Forum 2024a; World Economic Forum 2024b). These logistical pillars align with key aspects of certain social science theories and frameworks. For instance, collaborative partnerships in the Clusters initiative aligns with the role of social dynamics in collective processes around environmental governance. This alignment demonstrates the relevance of building a framework that integrates aspects of logistical pillars and social science frameworks. The pillars also have overlapping components, such as the roles of policies and partnerships in informing and defining financing mechanisms. The iterative relationships across logistical pillars are reflective of the benefit of applying social science theories and frameworks which can both capture and explain these interactions.

DOE's Industrial Decarbonization Roadmap (2022) provides pillars in the form of energy technologies that can be used as routes to decarbonize industrial processes and energy sources. The roadmap also provides recommendations for developing, applying, and integrating these technologies and for engaging communities, building workforce capacity, and building knowledge within and across agencies. These latter components also align with social science frameworks, including those developed to explain learning in environmental governance contexts.

The National Academy of Sciences, Engineering, and Medicine (NASEM) report on Accelerating Decarbonization of the U.S. Energy System (NASEM 2021) provides a basis for understanding technological and socioeconomic goals, siting risks, and innovative solutions for industrial decarbonization hubs.

GPI's analysis of carbon capture and storage opportunities in the Mid-Atlantic United States (Kammer et al. 2023) provides an understanding of siting characteristics that can be considered in site selection from a technological perspective, including incentives eligibility and carbon emissions.

Together, these strategies provide a strong contextual understanding of the overarching components of siting processes, lessons learned, and recommendations related to decarbonization hubs. Key aspects of these strategies align with social science concepts, such as the role of social dynamics in environmental governance (see Gerlak et al., 2017), and demonstrate approaches to better understand and evaluate hubs.

Literature Review: Multidisciplinary Social Science Theories and Frameworks

Drawing on key learnings from the social science literature enables the development a more holistic framework in which to consider the equitable development of industrial hubs. The bodies of social science literature included are public policy, environmental governance—particularly the collective learning framework, energy justice and social psychology.

We examined factors related to each step in the siting process (described in Figure 1).

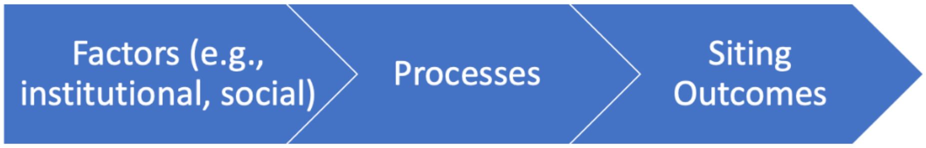

Figure 1. Continuum of siting

Throughout this paper, we considered the factors (e.g., institutional, social) that go into various siting processes and lead to siting outcomes.

Across the multidisciplinary social science literature we drew from, there are multiple levels of analysis and types of actors relevant to industrial decarbonization siting and development processes:

- Government, e.g., national, state, or regional collaboratives that span multiple localities and/or states
- Institutions, e.g., universities involved in regions regional technological and economic growth in building innovation hubs
- Industry, e.g., private partnerships and collaboratives, project developers, owners, and operators
- Stakeholder groups, e.g., labor unions, nonprofits, and educational centers
- Individuals, e.g., siting-related occupations and community member roles at individual levels.

Learning Theories and Frameworks in Environmental Governance

The nature of environmental governance—particularly around energy contexts—is complex. The intersection of social, policy, economic, and environmental factors must balance both adverse and beneficial impacts in a dynamic system.

Multiple learning theories and frameworks address adaptive management of complex environmental resource management. These include including policy learning, social learning, and the collective learning framework (Gerlak et al. 2017). Although many of the learning theories and frameworks do not fully define concepts, clarify causal factors and relationships, or provide for clear operationalization (Gerlak et al. 2017), the collective learning framework provides a structure based on clearly defined factors and processes and explains the causal relationship that results in successful products. This framework integrates key components of other theories and frameworks, including organizational learning, to provide a structure of types of factors that shape processes that in turn result in cognitive and behavioral change in the form of decisions and actions (Heikkila and Gerlak 2013). Within this integrative framework, key types of factors are social, institutional (rules), and technological, which explain how people and processes are structured, how they interact, and how the resources and systems they use impact information processing knowledge building to effect cognitive and behavioral change (e.g., policies and decisions). An application of this framework found it relevant for explaining factors involved in the consideration, evaluation, planning, and decision-making processes around proposed renewable energy siting projects (Smolinski 2021), demonstrating how the collective learning framework can be useful for other energy siting contexts.

DOE's Industrial Decarbonization Roadmap (2022) articulates the importance of coordinated environmental governance across agencies. An agency-coordinated approach to hub development allows for multiple streams of information to come together to address the challenges related to developing a complex system.

Social Psychology & Energy Justice. The beliefs, attitudes, and perceptions of participants involved in planning and decision-making frame how information is processed and applied, how knowledge is built, and can ultimately influence outcomes (Heikkila and Gerlak 2013). These concepts as applied to collective learning link back to behavioral economics (Kahneman 2003), organizational learning, and other learning perspectives (see Heikkila and Gerlak 2013). The role of social psychology factors in shaping siting processes is also reflected in community engagement best practices, which consider the different perspectives of community members throughout the energy siting process (Romero-Lankao et al. 2023).

There is broad support for increasing renewable energy development in the United States (Sharpton et al. 2020); however, local development often faces opposition (Bessette et al. 2024). The energy justice literature contextualizes this opposition by addressing distributive and procedural dimensions of justice (Baker et al. 2019). Because energy infrastructure siting, including the siting of industrial decarbonization hubs, has lasting impacts on the communities in which they are sited, incorporating energy justice into siting processes allows for long term accrual of benefits to communities, which ultimately leads to improved business outcomes. For instance, community member support and opposition for local renewable energy development are the product of several factors, many of which are related to energy justice. The extent to which siting processes are perceived by community members as procedurally and distributively just are particularly impactful on siting support (Bidwell 2016; Crawford et al. 2022; Hoen et al. 2019; Rand and Hoen 2017). Siting decision-making processes that include community members likely to be impacted by development build trust between stakeholders and are thus more likely to be supported, and further, collaborative processes that include diverse perspectives have better outcomes. Distributively, community members who perceive that energy facilities will reduce property values and increase electricity rates are less likely to support development, especially when they believe economic benefits will flow to nonlocal communities. However, when projects incorporate mechanisms for local ownership and when community members perceive energy facilities will increase local tax revenues and lower electricity rates, they are more likely to support development. The literature on renewable energy siting has also documented several additional factors that impact community support for energy siting, including impacts to the landscape and local identity as well as impacts to human health of facility development and operation (Carlisle et al. 2015; Rand and Hoen 2017).

Importantly, the literature for community support for siting industrial decarbonization hubs is less definitive in terms of impact of complex decarbonization facilitations compared to than the literature for smaller-scale decarbonization efforts such as wind and solar development. Given that industrial decarbonization hubs are more complex than single technology facility development, more research is needed to determine which factors predict community support for industrial decarbonization hub siting (research questions for which are described in Table 2). For instance, siting industrial decarbonization hubs often involves incorporating new technologies, facilities, and energy sources into existing industrial centers. The process of retrofitting existing infrastructure could be more supported by local communities in the context of industrial decarbonization hubs than developing new infrastructure; however, the process might also perpetuate historical inequities in industrial development (Devine-Wright 2022). Regardless, given the robust literature establishing the connection between energy justice principles and the incorporation of energy siting processes, industrial decarbonization hub siting should include energy justice considerations.

The framework developed from social science theory and empirical evidence informs the proposed research agenda. Future development of this framework could also more deeply examine learning theories and frameworks, the behavioral economics and organizational learning that factors into the Collective Learning Framework, and other bodies of literature focused on innovation processes, as well as behavior around uncertainty. There may be other social science theories and frameworks that could be included in future work.

A Learning Framework for Industrial Decarbonization Hubs

To orient the research framework, we categorized the factors related to industrial decarbonization hubs into five main groups according to how they might contribute to siting: 1) institutional and policy, 2) social dynamics and partnerships, 2) technological, 4) economic, and 5) environmental (see Figure 2).

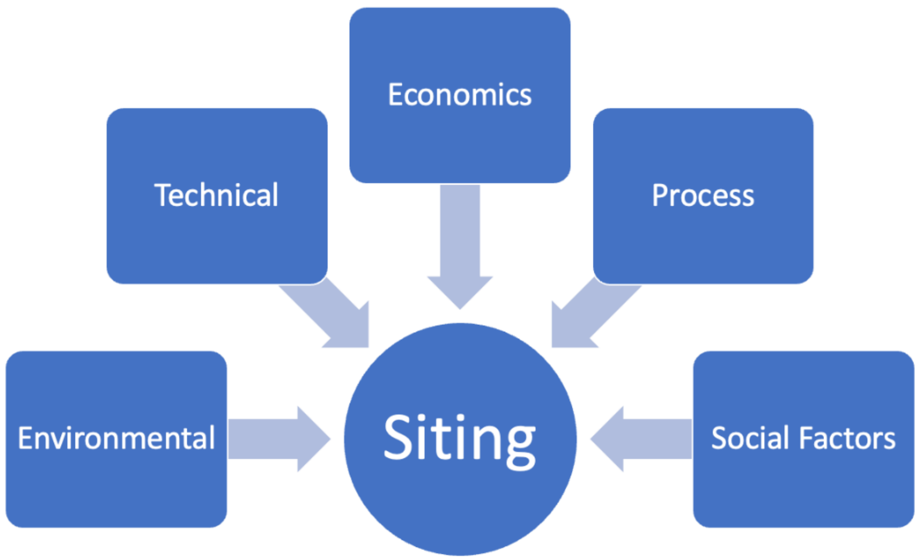

Figure 2. Key factors and their relationship to the siting process

Figure 2 summarizes the factors influencing siting. In reality, factors also influence each other. Drawing on the DOE Industrial Decarbonization Roadmap, the role of adaptive management, collective learning, and ongoing engagement and monitoring (Armitage et al. 2008; U.S. Department of the Interior [DOI] 2009; Heikkila and Gerlak 2013; Romero-Lanko et al. 2023), we consider siting to span and interact across multiple phases: planning and capacity building, site screening and assessment, and negotiation and implementation (DOE 2022).

Table 2 presents five key factors and associated variables as well as identified research questions to better understand the complexities of the siting process.

Table 2. Proposed Learning Framework for Industrial Decarbonization Hubs: Variables and Sample Research Questions

Factors	Relevant Factors, Variables, and Measures	Sample Research Questions
Institutional and policy	• Policies, rules, regulations, programs • Rules around participants, processes (e.g., who is involved, what is their expertise, power dynamics, structure, decision-making) • How institutions engage with one another (e.g., norms, rules, actors)	• How do different strategies contribute to or inhibit the effective cooperation across multiple stakeholders that is necessary for these hubs?? • How does the level at which policies are enacted (federal, state, regional) impact public support for industrial decarbonization hubs?
Social dynamics and partnerships	• Justice (recognition, distributive, and procedural) • Interactions (extent of trust, frequency, and quality of interactions) • Dialogue across government, industry, community • Social norms and interactions (trust, communication) to achieve cooperation of resource management	• Which community members and populations are likely to be impacted by industrial decarbonization hubs? • What decision-making processes can be used that include broad stakeholders (e.g., community, governmental, and industrial stakeholders) in developing industrial decarbonization hubs? • What mechanisms can be used for knowledge sharing across broad stakeholders (e.g., community, governmental, and industrial stakeholders)? • What mechanisms can be used to identify and track risks from planning through siting of decarbonization hubs? • What metrics can be used to identify and track risk? • How do hub partners structure agreements to control for technological uncertainty?

		• What do community members perceive as the benefits and risks of industrial decarbonization hubs? • What factors influence community members' support for industrial decarbonization hub siting? • How do the factors related to industrial decarbonization hub siting differ from those related to renewable energy siting? • How can the complex processes and impacts related to industrial decarbonization hubs be best communicated to community members? • How does the inclusion of various renewable energy technologies in an industrial decarbonization hub impact community support?
Technological	• Technologies, systems, programs, goals, products, pathways • Criteria for site selection: emissions, infrastructure	• What factors and mechanisms identify and track risk from planning through implementation and operation?
Economic	• Workforce capacity (supply, demand, training) • Resilience (perceived risks, economic resilience) • Long-term financing • Build expertise to evaluate technological options • Invest in energy efficiency and productivity	• To what extent can we diversify hub components to make them more resilient? • How can we track how risks and benefits evolve over time, and how can hub strategies be designed to measure these changes? • How can factors and mechanisms ensure continued agreement around the operation of hubs as risks and benefits evolve over time?
Environmental	• Air quality standards, public health indicators, National Environmental Policy Act (NEPA) processes, regulatory processes, environmental management practices	• To what extent do strategies and agreements contribute to understanding and mitigation of potential risks?

Suggested Research. Table 2 presents a intersections of existing perspectives on industrial decarbonization hub siting and the social science theories evaluated. Incorporating a crosscutting research agenda that spans society, institutions, economics, and environment enables stakeholders to explore the risks, opportunities, and benefits, of regional hubs. As such, the questions reflect that the multiple factors we set forth in Table 2 interact to shape and impact siting processes and the resulting outcomes.

Risks and Benefits**.** For example, the risks and benefits to hubs are likely to evolve over time because of changes in financial, technological, partnership, and policy conditions. Literature related to economics, agreements, and institutional arrangements can be used to develop market-based solutions (e.g., policy incentives, grants to de-risk less-proven technologies, and policy-based approaches to develop mechanisms) and answer questions that explore the social components of planning, dialogue, and industrial decarbonization risks. In particular, utilizing these bodies of literature can be used to address questions such as, "How can the risk of underperformance of a hydrogen hub (due to factors such as slow demand or cost overruns) be mitigated?".

Liability**.** Research on this topic could address liability around technological issues and project ownership and operation. The exploration of liability considerations could address questions such as, "How are liability issues planned for or mitigated in the development of industrial decarbonization hubs?". Additionally, industrial decarbonization systems might be designed to run for the long-term, but which parties are liable for potential leaks after the project period? Literature related to designing institutional arrangements—built on trust and agreements—as well as behavior economics (e.g., game theory) would be helpful lenses through which to view liability and projected scenarios over time.

Suggested Case Study. It would be beneficial to test our proposed framework to determine the extent to which the framework can explain industrial decarbonization hub siting outcomes. We believe that pursuing a holistic approach based in science that is empirically supported, through the use of our proposed or similar frameworks, would yield better outcomes that benefit a wide range of stakeholders. To gather empirical support for our assertion, the framework and research agenda we proposed can be applied to a test case, such as the H2Houston Hub. In this test case, we would use a mixed methods approach based on interview and survey data from participants as well as an analysis of environmental, technological, and partnerships to identify and characterize important factors related to siting outcomes.

Applying the Learning Framework for Industrial Decarbonization Hubs can address questions related to opportunities for realizing benefits and mitigating risks, such as:

- How are partners building strategies to identify, track, and reduce risk exposure from H_2 market uncertainties?
  - Are risk mitigation strategies being tracked against real-world market changes to evaluate the effectiveness and adjusted to respond to risk factors not previously identified?
  - What factors have shaped the development of strategies to identify and mitigate short-, medium-, and long-term risk?
  - To what extent are flexible financial investment mechanisms providing protection from technological and market risks?
- How are communities and workers being represented within the H2Houston Hub process?

    - If different stakeholders are surveyed or interviewed, how do their experiences and perceptions about procedural justice vary? What engagement structures and practices support the greatest agreement across perceptions of fairness?
    - Are community and workforce concerns and needs being considered and applied to hub strategies?
- What factors shape levels of perceived alignment across different industry partners as they collaborate to share resources, benefits, and risks?

These questions serve as a basis for a research agenda that can be used to explore how various factors contribute to the effectiveness of siting processes.

Conclusion

We present the first intentionally theory-based and empirically-aligned framework to provide an integrated, multi-disciplinary siting approach for industrial decarbonization hubs. Our goal was to contribute to industrial hub siting outcomes improving the understanding of influencing factors in hub siting processes. The framework provides an opportunity to explore the costs and benefits of siting hubs in a more holistic, empirical and theoretically-informed approach. The goal was to engage with the social science literature to develop a framework and research questions informing the understanding of the interplay of economic, environmental, and process factors influencing process siting of complex, multi-stakeholder regional industrial decarbonization hubs.

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Appendix A

Table A-1. Factors and select literature that informed our framework

Types of factors *(independent variables)*	**Factors - details**	**Select source literature**
Institutional/policy	• Policies, rules, regulations, programs (formal, informal) • Rules around participants, processes (who is involved and what are their expertise, power dynamics, structure, and decision-making)	• Collective learning framework • IAD • Organizational learning • WEF Transitioning Industrial Clusters initiative
Social dynamics and partnerships	• Interactions (extent of trust, frequency)	• Collective Pool Resource Theory (CPRT) • Collective learning framework • Social learning • Community engagement best practices
Social psychology	• Mental framing: perceptions, biases, beliefs, support, and opposition • Distributive, procedural, and recognition justice	• Collective learning framework • Behavioral economics • Energy justice literature
Technological	• Technologies, systems, programs, goals, products, pathways • Criteria for site selection: emissions, infrastructure	• DOE industrial decarbonization framework • GPI analysis of carbon storage opportunities

Economic	• Workforce capacity
	  ○ Supply (number of workers)
	  ○ Demand (number of workers needed)
	  ○ Training/capacity programs	

Environmental	• Air quality, public health	
Processes *(independent variables)*	**Processes - details**	**Select source literature**
Planning stages	• Planning stages	
Information processing and knowledge building	• Information processing and knowledge building	• Collective learning framework