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Original article

Reinventing the global oil capital: The sociotechnical dynamics of industrial net-zero megaprojects in Texas

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ABSTRACT

Texas, the "energy capital of the world," is undergoing a widescale technological transition in response to recent climate policies in the United States. There is immense potential for industrial decarbonization in Texas—which already has extensive experience with carbon capture and enhanced oil recovery—and thousands of miles of hydrogen and CO2 transport pipelines. Successful reorientation of its industry towards net-zero could provide a blueprint to industrial regions elsewhere. This article investigates industrial decarbonization megaprojects using the Triple-Embeddedness Framework (TEF), which emphasizes the region as a sociotechnical and industrial regime. Through a longitudinal analysis of five temporal TEF phases, we uncover significant reorientation as new constellations of industrial actors coalesce and consolidate. Nevertheless, some technological dimensions of the industry regime are resistant to systematic, whole systems change, such as blue hydrogen and CO2 capture hubs—which are tethered to fossil fuel production.

1. Introduction

Industrial decarbonization, and the ambitious goal to achieve net-zero greenhouse gas emissions (GHGs) have risen to the top of global, national, and even subnational policy agendas in recent years (Hsu et al., 2020). The marriage of climate with industrial policy is attractive because it can help kickstart industrial regions, vital to domestic economies, and create opportunities for win-wins by reducing emissions while stimulating local industry (Upham et al., 2022; Sovacool et al., 2024). "Hard-to-abate" industrial sectors, moreover, are also critical to the low-carbon technology supply chains and innovations (Griffiths et al., 2021); all clean energy technologies require industrial components and energy transition metals—e.g., steel for wind turbines, silicon for solar panels, rare earth minerals for fuel cells, graphite for nuclear reactors, or copper and lithium for electric vehicles and batteries (Svobodova et al., 2022).

The infrastructural, technological, and financial needs for industrial decarbonization are daunting, however. These include uncertainty in technical performance, liability concerns, accidents, as well as high costs of deployment and lack of a mature market (Grubert et al., 2022; US GAO, 2022; US DoE, 2023). Spatial unevenness, permitting for facilities and pipeline rights of way, as well as lack of skills and workforce development are prominent barriers (Synder, 2018). Potentially adverse outcomes include environmental impacts, residual emissions, methane or hydrogen leakage, as well as disparities in air pollution and distribution of co-impacts (Colmer et al., 2020; Wang et al., 2023). In response to the twin challenge of maintaining heavy industry and significantly reducing GHGs, dozens of countries have announced handsome subsidies targeting infrastructure and net-zero technologies, including: Norway, the United Kingdom, South Korea, Japan, and Australia, among others (Sovacool et al., 2022). This is one main motivation that underscores research into the industrial decarbonization process in different jurisdictions (Sovacool et al. 2024).

The US has recently taken an aggressive decarbonization approach, spearheaded by the Biden Administration's Inflation Reduction Act (IRA) in 2022, building on the Infrastructure Investment and Jobs Act (IIJA) in 2021 (Bistline et al., 2023). Industrial firms are potentially on the receiving end of massive tax credits, as well as related subsidies, grants, and loans on offer as part of the IRA and IIJA, collectively worth hundreds of billions of dollars. The natural resource endowments coupled with industrial assets in Texas put the Lonestar state in position to take advantage of these regulatory "carrots"—or financial rewards for decarbonization deployment: "If it's going to happen anywhere, it's going to happen in Texas" (S&P Global, 2021).

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The eventual outcome of decarbonization projects in Texas will reverberate elsewhere; should industrial decarbonization projects and technologies succeed there—the fossil fuel energy capital of the world (Brown, 2015)—it can demonstrate how fossil-fuel dependent industrial regions can transition to a net zero GHG world (Greenspon and Raimi, 2024)—especially in place-based, locational settings (Eadson et al., 2023). It might also lead to much-needed innovations and proof-of-concepts for industrial decarbonization technologies.

A complex array of sociopolitical and socioeconomic factors, nevertheless, must align for industrial decarbonization to be a success (McLaughlin et al., 2023). When viewed as a sociotechnical system through the lens of the Triple Embeddedness Framework (TEF), how is industrial decarbonization unfolding in the global oil capital? To answer this question, we draw on a range of qualitative and quantitative data, including: regulations, current and previous projects, and a longitudinal analysis of partnerships and collaborations for net zero.

This article is structured as follows: Section 2 provides a background and theoretical underpinning using the TEF. Section 3 discusses relevant US industrial decarbonization policies and introduces our case study. Section 4 presents the main part of the article, presenting the Texas industrial decarbonization transition from 1972 to 2030 along the five phases of the TEF. Finally, the conclusion provides a brief synopsis of our findings and offers future research directions.

2. Theoretical underpinning and analytical framework

Contained within the Infrastructure Investment and Jobs Act (IIJA) (2021) and the Inflation Reduction Act (IRA) (2022) are billions of dollars of subsidies for industrial decarbonization infrastructure, development, and deployment. An array of public and private actors—including not only industrial firms, but also insurance providers, law firms, investors, land prospectors, and technologies providers—are currently coming together to plan and develop "first-of-a-kind" industrial decarbonization megaprojects, defined as projects with costs exceeding $1 billion in capital expenditures (Geels et al., 2023; Sovacool and Geels, 2021). The mobilization of resources needed for industrial decarbonization megaprojects and hubs alters the strategic efforts of firms, and firms-in-industries, within the "industry regime" (Geels, 2022). Owing to these firm-related aspects of the transition, we apply the Triple Embeddedness Framework (TEF) to explore the industry regime more deeply (Geels, 2002, 2014, 2022).

2.1. The triple embeddedness framework and industrial decarbonization

The TEF draws on several diverse fields of research, including evolutionary economics, strategic management, and institutional theories (Penna and Geels, 2012; Geels and Penna, 2015; Geels, 2022). It aptly suits analysis of industrial sectors because the framework effectively encompasses infrastructure, technologies, firms, industries, policies and politics (Turnheim and Geels, 2013)—each of which fall under the remit of industrial transformation, especially those "associated with societal problems (e.g., climate change)" (Geels, 2014: 275). Furthermore, it was specifically tailored to help researchers analyse the "co-evolution and bi-directional interactions between industries and their environments" (Geels, 2014: 261), helping to shed light on industrial reorganization and revival—as well as the exploitation of windows of opportunity to "overcome lock-in mechanisms" (Geels, 2014: 261). Fig. 1 visualizes core elements of the TEF.

One of the main conceptual devices deployed by the TEF is the industry regime (Penna and Geels, 2012). During industry transitions, the "political, cultural, and normative processes" (Geels, 2014: 275) impart unidimensional changes on the industry regime—defined as "industry-specific institutions that mediate perceptions and actions of firms-in-an-industry towards external environments" (Geels, 2014: 267). The industry regime is comprised of four elements: (1) technical knowledge and capabilities; (2) mindsets and cognitive frames; (3) values, identity and mission; (4) formal regulations, laws, and standards (Geels, 2014: 267). Firms within the industry regime can be further classified according to shared knowledge, mission statements, regulations, and standards (Wesseling et al., 2022; Canal Vieira et al., 2022).

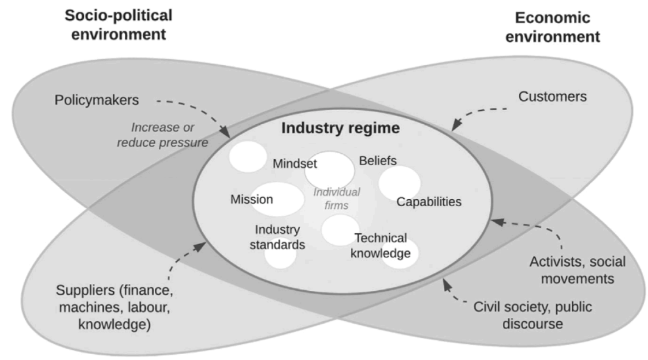

Fig. 1. Visualizing the triple embeddedness framework.
Source Canal Vieira et al. (2022).

The overall socio-political environment (policymakers, suppliers, finance mechanisms), as well as the socio-economic environment (customers, activists, civil society, and public discourse), exert pressures on the industry regime during industrial transitions (Geels and Penna, 2015; Olson-Hazboun, 2018; Luke and Evensen, 2021). In response, the industry regime embarks on *externally-oriented* strategy approaches—-which include economic positioning, corporate political strategy, discursive strategy, and issue management—as well as *internally-oriented* strategies that revolve around tacit knowledge, skills, and capabilities Geels (2014). Similarly, the TEF helps with empirical analysis of technical transitions by incorporating "the bidirectionality of relationships between the actors in a regime and its external environment" (Canal Vieira et al., 2022: 490).

When industries undergo transition, selection pressures reverberate through "institutional environments and economic (task) environments" (Geels, 2014: 266). This means that similar pressures manifest in parallel strategic responses in firms-in-industries. The firms-in-industries concept also bears down on the transition processes here because firms "share many routines and capabilities which cluster into technological regimes […] guiding and focusing their activities in certain directions rather than others" (Geels, 2014: 263). The identification of pressures, therefore, gives way to an understanding of regime strategies—strategies that are unique in capital and resource-intensive sectors with "strategic planning styles" (Geels, 2014: 264). By way of example, an empirical application of TEF to the Oil and Gas (O&G) industry is undertaken by (Canal Vieira et al., 2022). They show how the O&G industry regime, as well as the O&G from a firms-in-industries perspective, triggers variegated strategies such as resistance and reinvention of business models. This assessment is consistent with Geels (2014), Kungl and Geels (2018), Turnheim and Sovacool (2020), as well as Abraham-Dukuma (2021), and these studies play an important role in our conceptual approaches here.

2.2. Temporal phases of industrial transition

Sociotechnical transitions in heavy industry, as outlined by Geels and Penna (2015) and Geels (2014), involve underlying temporal dimensions that can be isolated into five distinct phases (see Fig. 2). Phase one is defined by resistance to change ("denial"); many firms undertake little to no significant redirection as the regulatory and technological futures are uncertain. The second phase of the TEF is characterized by an adjustment of belief systems and norms, with "local searches" coalescing around a shared vision of the future given regulatory demands and technological capabilities. Nevertheless, most firms continue to resist fundamental changes (Barker and Duhaime, 1997).

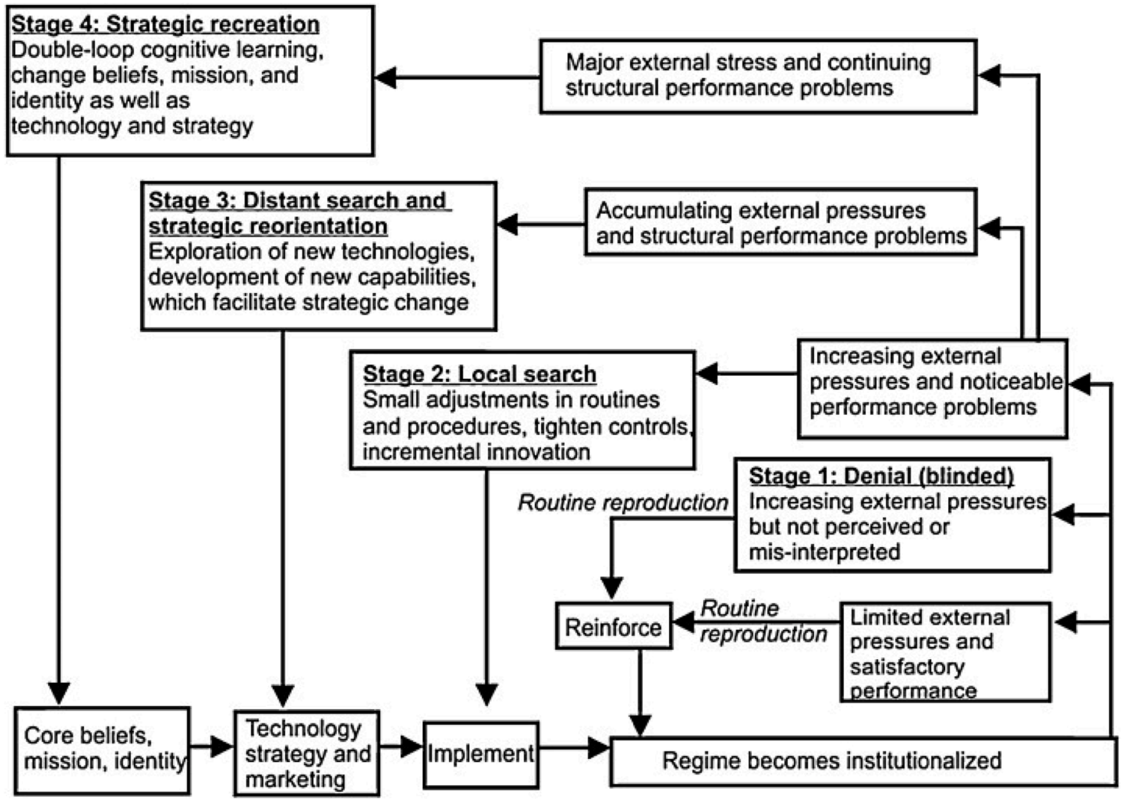

Fig. 2. The dynamic phases of the triple-embeddedness framework.
Source: Geels, 2014.

For example, emissions and climate policies can incentivize firms to make some initial cost assessments of low-carbon technologies, yet often they stop short of undertaking significant reorientation (Geels, 2022). For the industry regime, in general, the adoption of lower emissions technologies is deemed more costly than the playing a game of "wait-and-see" (Boiral, 2006; Sullivan, 2009). Rather than taking drastic reorientation efforts, the regime might exploit information asymmetries and "purposively [withhold] relevant information" about technological costs and performance of low-carbon technologies (Geels and Penna, 2015: 71).

In the third phase ("strategic reorientation"), a collective effort ensues to defend the industry regime within the confines of its existing technological capabilities (Geels and Penna, 2015; Kim et al., 2019). Entrenched and collaborative corporate political activities steer public policies in the regime's favor (Turnheim and Geels, 2012; Geels and Gregory, 2023). Technological demands—whether from policies, customers, or the wider public—are met with modest efforts. At this juncture, firms within the industry regime typically argue that substantive technological changes are too costly, or that they are too difficult in the absence of public subsidies (Besco et al., 2021). On the other hand, in the first three phases, some first-mover firms are quick to grasp the new direction of travel and, for example, experiment with decarbonization technologies, source more clean energy, and undertake costly energy efficiency upgrades well before their industry peers (Andersen and Gulbrandsen, 2020). In this phase the industry regime reorients and, importantly, "that architectural change can also take place without major disruptions to incumbent actors" (Andersen et al., 2023: 2).

In the fourth phase ("strategic re-creation"), new regulations and incentives induce the industry regime to scan the technological horizon and diversify (Geels and Turnheim, 2022). At this point, political and policy realities set in for the industry regime—"which additionally entails changes in core beliefs, identity and mission" (Geels, 2014: 274). An earnest exploration of more fundamental technological innovations begins (Steen and Weaver, 2017; Turnheim and Koretsky, 2023), supported through new partnerships and collaborations (Ruggiero et al., 2021). For industrial decarbonization, this might take the form of exploring opportunities for blue and green hydrogen production, transport, and storage.

The fifth stage is defined by significant reorientation of the industry regime ("technology strategy, marketing, and implementation"). It is marked by a recalibration "of regime elements, based on technological search activities and cognitive adjustments in core beliefs and mission" (Geels, 2014: 274). The exploration of emerging technologies ensues, new financial arrangements are developed consonant with underlying strategies (Geels, 2022; Turnheim and Geels, 2013, 2012; Grinyer and McKiernan 1990). New windows of opportunity arise, which catalyzes the revamping of business models (Geels et al., 2017). In short, should any combination of these features of the fifth phase be identified, the industry regime stands on the precipice of deep structural transformation. This is all to assume, however, that the industry regime can reach the fifth TEF phase without firms within it succumbing to bankruptcy or relocating to less stringent locations (Böhringer et al., 2017; Geels and Penna, 2015). The coal power industry, indeed, provides a salient example here: throughout many OECD economies, after failed attempts to affix modular, add-on technologies such as carbon capture and storage (CCS), countless power stations were shuttered in the previous decades (EPA, 2013).

2.3. *Large technical systems, actors, and the industry regime*

In the last part of Section 2 we situate industrial decarbonization within the broader literature on Large Technical Systems (LTS) (Hughes, 1987). LTS are "spatially expansive and capital intensive," and require "billions or even trillions of dollars of investment" (Sovacool et al., 2018: 1069)—and are "governed and legitimated by formal, knowledge-intensive, impersonal rationalities" (Joerges, 1988: 24).

They also involve a multiplicity of actors and sectors, such as "manufacturing firms, utility companies, academic research and development laboratories, and investment banks" (Hughes, 1986: 287).

Transitions in LTS, not unlike the TEF's industry regime, are defined by their "nonlinearity, variation, and complexity" (Sovacool et al., 2018: 1089). The main implication is that the industry regime for industrial decarbonization is enveloped by a wider range of technical systems—within the LTS framework—with unique characteristics "of invention, expansion, growth, momentum, and style" (Sovacool et al., 2018: 1066). By embedding industrial decarbonization within the LTS, a more fine-grained analysis of the industry regime along longitudinal (e.g., temporal) dimensions can be conducted (Brauers et al., 2020; Geels, 2014). In this sense, the industrial decarbonization industry regime can be understood as a galaxy that is part of the LTS universe, with individual firms in the industry regime represented by planets, pulled by emerging net-zero policies (the sun) and technologies (the planet's moons).

In the context of industrial decarbonization—with serious technological, infrastructural, and financial implications for the industry regime—it is unsurprising that incumbent firms often fail to deliver niche or radical innovations (Pickl, 2021). In the absence of stringent regulatory interventions, or substantial subsidies, incumbents "show reluctance to address" such costly upgrades (Geels, 2014: 275); incumbent firms are unlikely to engage with technological transitions on the sole basis of managing societal problems such as GHGs (Geels and Penna, 2015). But this does not imply that incumbent firms simply disappear, even if intransigence sets in. As Hughes (1982: 6) aptly remarks: "Old systems like old people tend to become less adaptable, but systems do not simply grow frail and fade away. Large systems with high momentum tend to exert a soft determinism on other systems, groups, and individuals in society."

In relation to that, regulators can also exert gravitational influence upon the industry regime through targeted "tariff protection, loans, cash grants, government purchases, patents, tax concessions, information and research services" (Geels, 2014: 265). Indeed, the IRA and the IIJA are set to leverage substantial "federal incentives to unlock potentially $1 trillion or more in associated private and public investment" spanning energy, infrastructure, manufacturing, and other heavy, hard-to-decarbonize, industrial sectors (Bender and Maxwell, 2023: 12). In other words, these colossal legislative packages are targeting LTS, incumbent industry, and the industry regime. Therefore, we need to dig deeper into the LTS that industrial decarbonization is embedded in. This in turn draws attention to governance of social processes, legitimation of technologies, and technological maturation (Sovacool et al., 2018; Deonandan et al., 2024), the subject we turn to.

3. Background and case selection

This section discusses essential background to our study, while the following section delves into our case study of industrial decarbonization in Texas.

3.1. US industrial emissions, technologies, and policies

Industry accounts for 23 % of total US GHGs, and 30 % if electricity is included (see Fig. 3). In the most hard-to-abate industrial sectors it is therefore imperative that government policies create space for industrial transition and transformation (Griffiths et al., 2021; Bender and Maxwell, 2023).

Though the Biden Administration's decarbonization policies and related subsidies dwarf those of previous administrations, this is not the first time the US has taken an ambitious approach towards industrial decarbonization. Already by 1997, indeed, the US Department of Energy (DoE) had launched a CO2 storage program. Shortly thereafter, the Bush Administration was surprisingly the first to initiate substantial subsidies for industrial decarbonization, specifically for carbon capture and storage (CCUS) and clean coal under the Energy Policy Act (2005). The so-called 45Q tax credit—carried forward under the Biden Administration—refers to a section of the 2008 tax code that provided subsidies and grants to energy and CCS projects (Hirsch and Foust, 2020). In total, the Bush Administration earmarked "$2 billion over 10 years in coal and related technologies for hydrogen production and carbon sequestration" (Byrne et al., 2007: 4556).

From 2006–2010, moreover, $979 million was set aside for coal research and projects under the Clean Coal Power Initiative (US Office of Fossil Energy and Carbon Management, 2022a). The Obama Administration financed eleven CCS projects to the tune of $1.1 billion, building on the Bush Administration's initial support. Three major projects were nevertheless withdrawn after receiving $745 million combined from the US DoE (The Mountaineer Carbon Dioxide Capture and Storage Demonstration, the Southern Company Carbon Capture and Sequestration Demonstration, and the Basin Electric Power Cooperative CCS). Furthermore, the US DoE provided $684 million to eight coal-CCS projects, though only two operate today, one of which is in Texas (Petra Nova, which received $167 million from the DoE, though it paused operations from 2020 – 2023 due to cost concerns). In addition, a

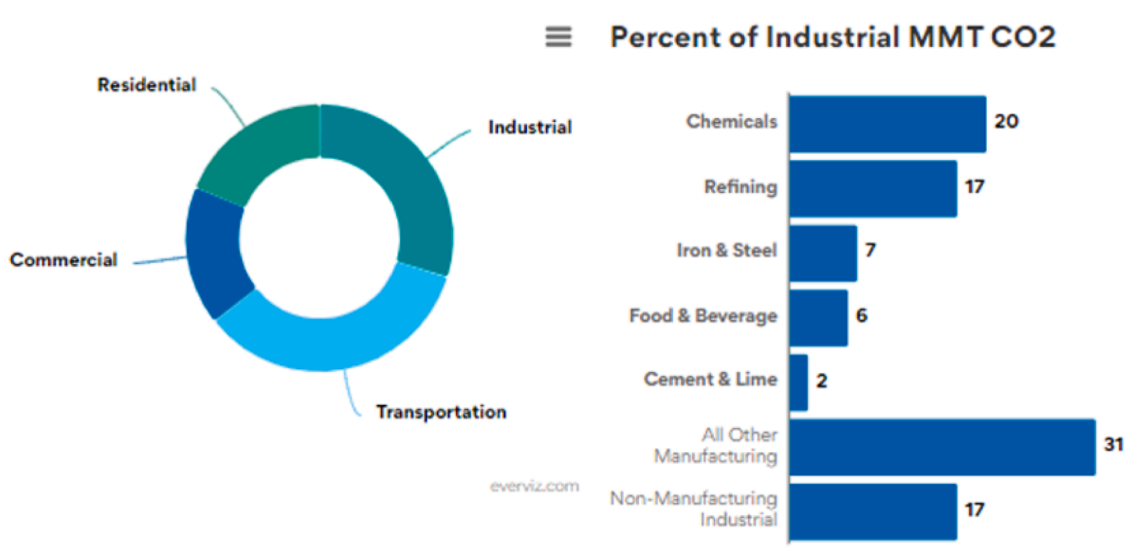

Fig. 3. Energy-related CO2 emissions by sector in the USA.
Source: US DoE Industrial Decarbonization Roadmap (2022).

costly failure was the Texas Clean Energy Project (TCEP), shuttered in 2016 after nearly $4 billion was invested, with the DoE contributing $811 million (MIT, 2016). Owing to these monumental failures, there are reasons for skepticism for industrial decarbonization technologies and projects, even should they receive substantial public subsidies.

Like CCS, this is also not the first time that the federal government has sought to subsidize hydrogen. Indeed, the first global oil shock in 1973 catalyzed the establishment of the International Association for Hydrogen Energy and the first research endeavors into hydrogen technologies at the Energy Research and Development Administration (ERDA), with average R&D at $24 million annually through the 1970s (Solomon and Banerjee, 2006). In the 1980s, hydrogen funding all but vanished, but increased again during the 1990s and early 2000s (ibid).

The Bush Administration defined clean hydrogen as “hydrogen produced in compliance with the greenhouse gas emissions standard established under section 822(a), including production from any fuel source” (Energy Policy Act, 2005: 207). This definition effectively redefined “blue hydrogen” as a low carbon solution, should it be successfully coupled with CCS. The Energy Policy Act (2005: 90), moreover, defined Regional Clean Hydrogen Hubs as a “network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity.” These definitions and regulatory conventions were carried forward into the IIJA and the IRA (Price and Shah, 2023; Bistiline et al., 2023).

The Bush Administration also launched the $1.2 billion Hydrogen Fuel Initiative (2003), and the Freedom CAR Partnership, with $1.7 billion over 5 years for hydrogen research (White House, 2003). In total, $2 billion was publicly funded for hydrogen technologies under the Recovery Act funds that expired in September 2015 (Fogler, 2016). One major DoE funded project, which received $408 million in public support, was suspended (the Hydrogen Energy California Project: Commercial Demonstration of Advanced IGCC with Full Carbon Capture). Though blue and green hydrogen were yet to fully enter the fore under the Bush and Obama Administrations—at that time, they were seen as too technologically underdeveloped (Nanda et al., 2017)—the Biden Administration has made them a central part of industrial decarbonization (Bonvillian, 2021; Rode et al., 2023).

3.2. The IIJA and the IRA: Offering significant rewards for decarbonization

Although in the past “top-down” climate regulations for emissions in industrial sectors—so-called “sticks”—largely failed, the IRA and IIJA focus squarely on so-called “carrots” (SPRU, 2023)—or rewards for compliance, and generous grants for research and demonstration. Three main pieces of legislation apply to industrial decarbonization in the US: (1) The Chips and Science Act—the “brains”—which includes $54 billion for innovation in clean technologies; (2) The IIIJA—the “backbone”—which directs $98 billion for clean technology and industrial decarbonization infrastructure; (3) the IRA—or “the engine”—which is expected to result in more than $360 billion for clean technology R&D, infrastructure, and demonstration projects (Bender and Maxwell, 2023: 12). These investments are unequivocally higher than previous Administrations; for that reason, the IRA is described as the most ambitious climate and energy policy ever (Herman, 2024).

The targeted tax rebates and grants, or “carrots,” for industrial decarbonization are as follows. First, there is an $85 tax credit for each ton of carbon stored, and $60/ton for carbon utilization—marking a substantial increase from $20/ton under the 2008 Energy Improvement Extension Act (National Petroleum Council, 2019). A more substantial $130/ton is on the table for Direct Air Capture (DACCs), with a $180/ton rebate for DACs carbon permanently sequestered (Herman and Sovacool, 2024). Carbon sequestered in geologic reservoirs will be awarded with $50 per ton, while Enhanced Oil Recovery (EOR)—using carbon capture to draw out more oil or gas—is set to receive $35/ton (an increase from and $10/ton) (see Fig. 4 and Table 1).These credits are to

(c) Captured CO_2 credit

Fig. 4. Changes to CCUS tax credits from the IIJA and IRA.
Source Bistline et al. (2023).

increase in step with the rate of inflation after 2026 (National Petroleum Council, 2019; Moch et al., 2022). In addition, should a firm not benefit from the tax rebate, the credits can be transferred to project partners—referred to as “direct pay and transferability” which enables “tax exempt entities (such as municipal, state, or Tribal governments” to receive “applicable tax credits as direct payments from the IRS (Bender and Maxwell, 2023: 15).

CCS is further supported by the following: the Carbon Dioxide Transportation Infrastructure Finance and Innovation fund; the Coordinated Action to Capture Harmful Emissions Act; the Carbon Capture, Utilization, and Storage Tax Credit Amendments Act of 2021; and the Accelerating Carbon Capture and Extending Secure Storage through 45Q Act. Several proposed Amendments are also currently being debated in Congress: the CCUS Tax Credit Amendments Act of 2021, proposing to increase the 45Q tax credit from “$50 to $120 per ton CO2 for facilities that sequester CO2 and from $35 to $75 per ton CO2 for EOR facilities” (Moch et al., 2022: 3).

Hydrogen production is set to receive a ten-year tax credit of $3 per kilogram (kg) produced. Green hydrogen, produced by electrolysis from renewable energy, will receive $4/kg (US Office of Clean Energy Demonstrations, 2022b). Separately, provisions for hydrogen support are covered by the Energy Earthshot and the Hydrogen Shot, with a goal to reduce the cost of clean hydrogen by 80 % within a decade. Support for hydrogen is also provided through hub plans and subsidies (Table 1). In addition to the generous tax rebates from the Internal Revenue Service (IRS), there are substantial cash grants and loans on offer through the Loan Guarantee Program (Hirsch and Foust, 2020). Apart from hydrogen and CCUS/CCS, the IRA also earmarks $5 billion for emissions reductions in industrial sectors.

3.3. Industrial decarbonization via hubs and clusters

Hubs and clusters make much sense for sharing the costs and risks inherent in massive industrial decarbonization technologies, such as transport of carbon and hydrogen, and geological storage of carbon onshore or offshore (Sovacool et al., 2024a,b). Place-based industrial decarbonization initiatives have indeed emerged in other countries such as the UK and Norway (WEF, 2023; Eadson et al., 2023. The prevailing view is that, through industrial hubs and clusters, firms can garner new knowledge, know-how, and innovations needed for the industrial decarbonization transition—and also share the risks and costs associated with industrial decarbonization infrastructure (Rattle and Taylor, 2023; Geels et al., 2023; Sovacool et al., 2024).

Fairly recent regulations set forth in the Biden Administration’s IIJA and IRA are already catalyzing changes to the industry regime *vis-a-vis* net-zero hubs (Rattle and Taylor, 2023). Net-zero hubs are defined as "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 CO2 removal technology" (Friedmann et al., 2021: 7). The co-location of numerous industrial firms in Texas, indeed, puts the industry regime there in a strong position to win funding for industrial decarbonization hub funding (Bistiline et al., 2023; Pisciotta et al., 2022). In Texas, perhaps more than any other industrial cluster in the country or elsewhere, there is significant "potential for CCS from linked industrial emitters," which makes it "far more promising" than other locations (Tarufelli et al., 2021: 8).

Hydrogen hubs are likewise supported with substantial public funding. For instance, the Office of Clean Energy Demonstrations (OECD-DoE) issued a $7 billion funding opportunity announcement to support six to ten hydrogen hubs as part of the Regional Clean Hydrogen Hubs (H2Hubs). The expectation is that this "will catalyze investment in the development of H2Hubs that demonstrate the production, processing, delivery, storage, and end-use of clean hydrogen—all while supporting President Biden's goal of a net-zero carbon economy by 2050″ (OECD-DoE 2023). The approach to hydrogen hubs is set to induce a diversity of projects, calling for hydrogen production attached to the following industries: (1) fossil fuels; (2) renewable energy; (3) nuclear energy; (4) electric power generation sector; (5) industrial sector; (6) residential and commercial heating; (7) transportation sector (ibid). Finally, the Regional Direct Air Capture Hubs program established DACs hub policy and subsidy support, with several megaprojects already announced in Texas. Having discussed the relevant policy mechanisms for industrial decarbonization in the US, we now dig deeper into industrial decarbonization in Texas.

3.4. Selecting Texas as a case study exemplar

Since the late 19th century, propelled by the discovery of oil in the Spindletop field 1901, Texas has been considered the global capital of the fossil fuel industry. Industries agglomerated around key ports such as Corpus Christi, Port Arthur, and Houston to supply the world with refined oil for automobiles, buses, power-plants, and any technology requiring combustion of fossil fuels. Texas today continues to be a fossil-fuel producing mecca, having led US oil production in all but one year since 1970, and home to 41 % of the country's crude oil reserves. The natural gas sector has boomed since the shale gas revolution in the early 2000s (Beauloye et al., 2021), currently supplying nearly one-third the nation's natural gas, with 171 miles of natural gas pipelines, and nearly 120,000 natural gas wells (Prozzi et al., 2011). Consistent with this gas and oil production, however, the state also consumes fifteen percent of the nation's oil, one-fifth of that consumption used by the industrial sector (US EIA, 2022).

From purely an economic standpoint, Texas is the world's ninth largest economy, with nearly $2 trillion GDP in 2022, more than most G20 countries including Australia, Canada, and South Korea. Not only does it have economic prowess, but also technological capabilities, specifically for industrial decarbonization technologies such as EOR and CCS. This expertise stems back to 1972, when the world's first EOR project launched in Sharon Ridge. In 1982 the Enid Fertilizer plant was affixed with CCS and remains operational. Today, a total of 76 EOR projects exist throughout Texas (Advanced Resources International, 2021). Texas-based firms already have extensive experience in innovation, experimentation, products, processes, and technologies that are quickly becoming central to industrial decarbonization there and elsewhere.

Geographical features bode well for industrial decarbonization in Texas. For instance, the Gulf of Mexico and the East Coast of Texas are considered an "exceptionally advantageous region for future CCS because it benefits from an emerging CO2 management, utilization, and subsurface storage industry" (Meckel et al., 2017: 4729). Indeed, it is estimated that the Gulf Coast can potentially sequester 1.4 billion tons of carbon with EOR, and store 1.5 trillion tons of carbon in saline formations (Center for Houston's Future: The Way Forward), while onshore it is estimated that 2.4 billion tons of carbon dioxide can be stored (Forbes, 2019). Surprisingly, Texas also hosts a number of optimal *onshore* carbon storage facilities in the form of saline aquifers, which complement the depleted reservoirs shown in Fig. 5. One major pipeline, the Denbury Greencore Pipeline, has the capacity to transport thirteen million tons/year from industrial emitters to these carbon storage sites (MIT, 2016). Much more CO2 infrastructure is required, however, as the US government indicates that 68,000 miles of new CO2 pipelines are needed for CCUS (Jacobs, 2021). Texas also has its own CCS/EOR incentives that include "sales tax exemptions, franchise tax credits, and severance tax reductions" (Caldwell and Kidner, 2021: 8).

Though these infrastructure and geographical assets put Texas in an advantageous position to carry out industrial decarbonization—especially for CCUS, EOR, and blue hydrogen—there remains a vital bottleneck for carbon storage wells, which require a Class VI EPA permit. In the US, only two storage sites are active and fully permitted (in Illinois), and two are pending and in pre-construction phase (in Indiana) (EPA, 2023). A total of seven are pending and in pre-construction in Louisiana, of which three can potentially connect to Texas: (1) Oxy Low Carbon Ventures (2); Gulf Coast Sequestration (3); Sempra Infrastructure. There currently are not any active or pending Class VI well applications in Texas, although five sites and fifteen wells are under initial review as of October 2023 (EPA Class VI Permit Tracker):

- Four wells in Jasper Texas (BP Carbon Solutions LLC, Jasper County Storage Facility
- One well in Chambers: Oxy Low Carbon Ventures, LLC, Bluebonnet
- Two wells in Ector (Oxy Low Carbon Ventures, LLC, Brown Pelican
- One well in Upton (Milestone Carbon Midland CCS Hub, LLC, Dusek CCS #2)
- Seven wells in Gaines (Orchard Storage Company, LLC)

Apart from EOR and CCS, two other pivotal industrial decarbonization technologies, according to some experts (Noussan et al., 2020; Lagioia et al., 2023), are blue and green hydrogen. Often the main bottleneck precluding the rollout of hydrogen in industry is pipeline infrastructure—yet this bottleneck does not exist in Texas, which already boasts 1600 miles of dedicated hydrogen pipeline infrastructure (S&P Global, 2021). Over a quarter of US hydrogen production is made in the Texas Gulf Coast region, delivered to industrial operations spanning ammonia, methanol, and other petrochemicals (Bender and Maxwell, 2023). In recognition of these unique locational and infrastructural advantages, dozens of hydrogen hubs and megaprojects are nearing final stages of planning, including Hydrogen City, LIGH2T, and the HyVelocity Hub (the latter having recently received billions of dollars of public support in October 2023).

The Lonestar state has, moreover, become a surprising frontrunner in the deployment of renewable energy—which is also critical for producing green hydrogen from electrolysis. Clean energy now accounts for 25 % of all energy consumed (Federal Reserve Bank of Dallas), while it makes up 40 % of electricity of the state's electricity (see Fig. 6). Texas is home to 30 % of total wind energy in the US, besting all but four countries in total installed capacity (American Wind Energy Association). What is more, while the wind industry accelerated, the Lone-star state retired 7400 MW of coal power generation, leading to a 36 % emissions reduction in the last decade (US, 2022). Such serious inroads into clean energy demonstrate that industry in Texas is capable and willing to accelerate the decarbonization transition. In the following Section, we trace this ambition through the five phases of the TEF, discussed in Section 2.

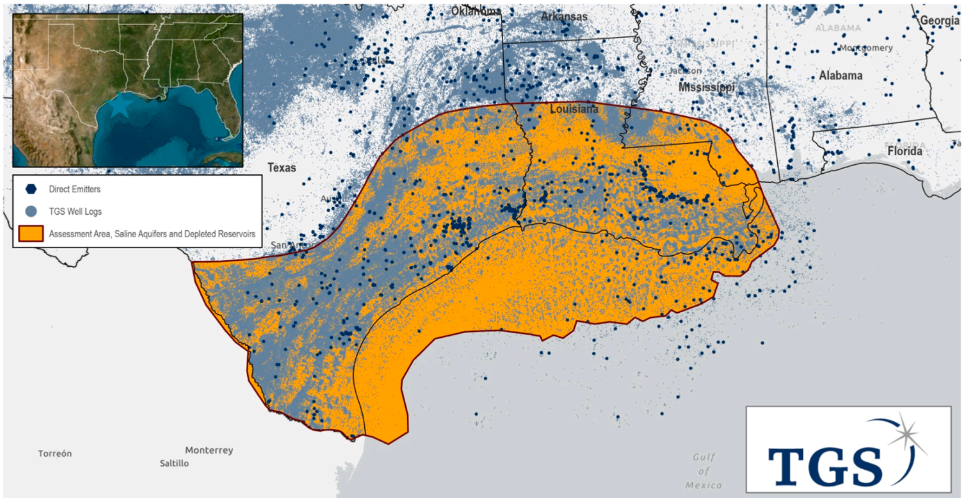

Fig. 5. Onshore and offshore carbon storage potential across the Texas, Louisiana, and Mississippi gulf coast regions.
Source: Texas Geologic Survey.

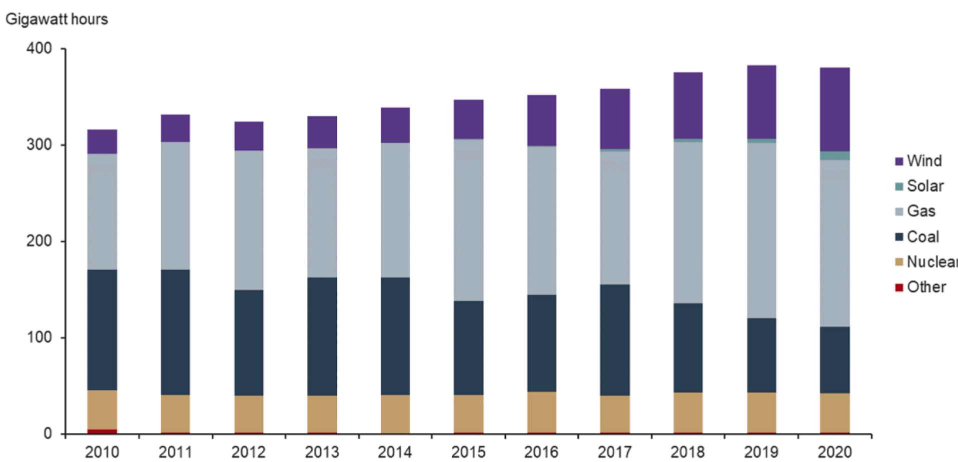

Fig. 6. Renewable energy share of power generation in Texas (2010–2020).
Source: Federal Reserve Bank of Dallas, 2021.

4. Industrial decarbonization in Texas as a triple embeddedness phenomenon

There are a considerable number of existing and planned industrial decarbonization megaprojects in Texas, which are mapped out in Fig. 7. In this section, we present our longitudinal analysis along the five temporal phases of the TEF, paying attention to policies, technologies and, more than anything else, the industry regime transition. Since TEF phases 4 to 5 are currently in progress, and several hubs await federal funding, we analyse these phases in greater detail in Section 4.2. Appendix Tables 6.1-6.3 provide further detail of the technologies, policies, megaprojects, and hubs since 1972.

4.1. The five phases of industrial decarbonization in Texas

In what follows, we map out the five distinct TEF phases, providing detail on policies, firms, and megaprojects. We close the section with a discussion of the industry regime as it currently moves from phase 4 to phase 5 of the TEF.

4.1.1. Phase 1: Proof of concepts and technological demonstration (prior to 2000)

In the absence of more stringent regulations, the industry regime largely resisted the installation of any technologies or infrastructure for decarbonization prior to 2000. There were, however, several first-mover companies and projects—for example CO2 pipelines and CCS for EOR. We fail to observe, however, any further instrumental changes to the industry regime in this period owing to the immaturity of technologies and the lack of regulation on industrial sector emissions. The focus technology was EOR and CO2 pipelines (see Projects 1–9 in Appendix Table 6.3).

4.1.2. Phase 2: Local search and project rollout (2000–2010)

The Bush Administration's Energy Policy Act (2005) provided a regulatory lever to catalyze the industry regime towards decarbonization technologies experimentation. It set in motion subsidies to first-movers in EOR, which increased prospects for CCUS, since these technologies are coupled together. Yet, aside from several first-mover companies, the industry regime remained reluctant to act without more substantial government subsidies, which were only given to several megaprojects, mainly related to coal-power CCS. The focus technology was CCUS for EOR and CCS in energy production (mainly for coal). We also draw attention to, however, the build-out of several massive CO2 pipelines (see projects 10–16 in Appendix Table 6.3).

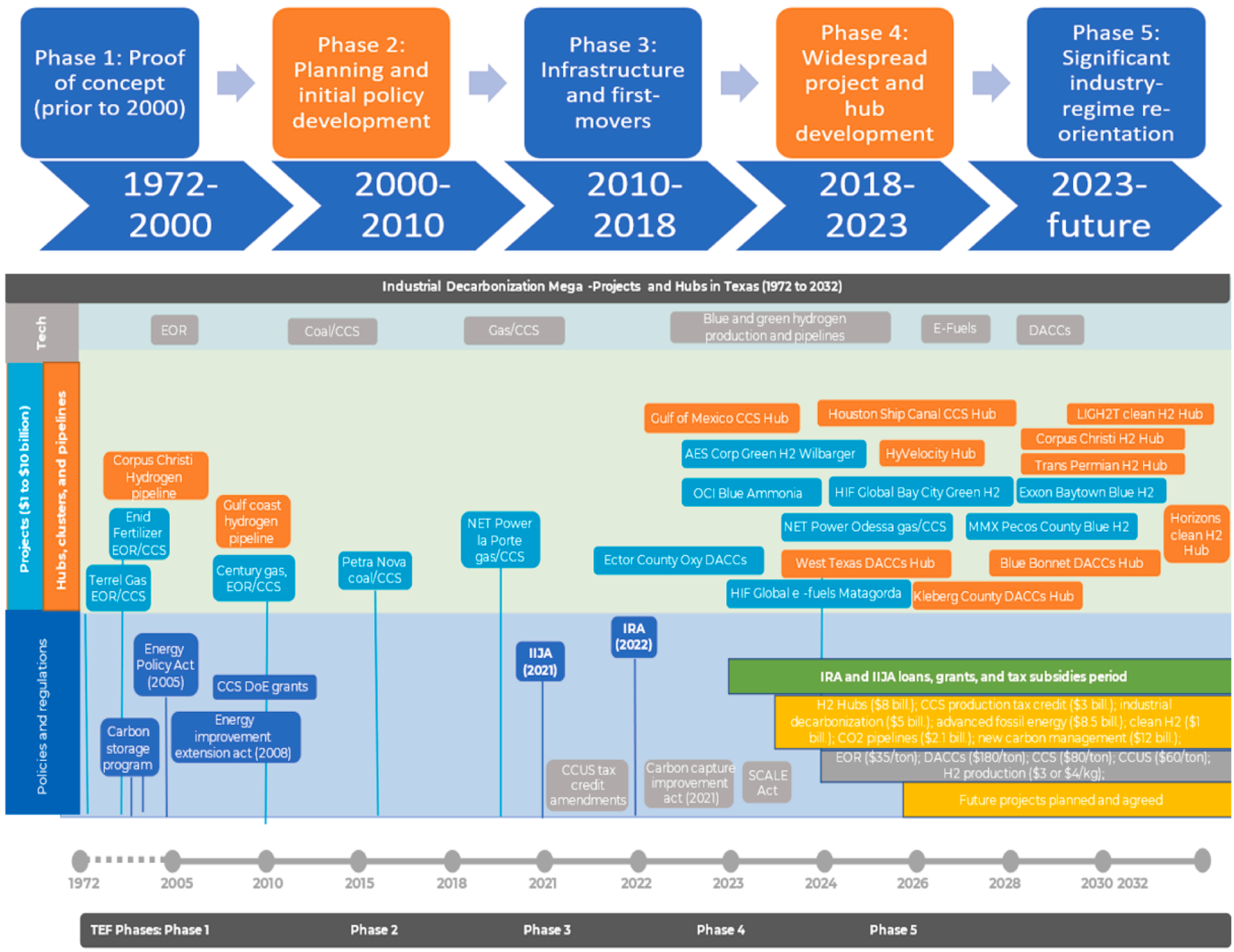

Fig. 7. Phases of industrial decarbonization in Texas and associated policies and technologies.
Source: Authors.

4.1.3. *Phase 3: Strategic reorientation and exploration (2010–2015)*

In response to generous DoE CCS grants, several major projects were initiated, specifically to decarbonize gas-fired power plants. There were some notable false starts in this period, nevertheless, as evidenced by substantial public funding to projects that eventually were shuttered. For example, Petra Nova, which received $167 million from the DoE, but its operations were paused from 2020 – 2023 due to costs. The Texas Clean Energy Project (TCEP), shuttered in 2016 after nearly $4 billion was spent, with the DoE contributing $811 million. One success was La Porte's NET power project, proving that CCS and gas could be coupled to produce low-carbon natural gas energy (i.e., a low-emission natural gas powerplant with carbon capture). The focus of technology was on CCS in energy production, specifically natural gas. In addition, several large hydrogen pipelines were constructed (projects 17–22 in Appendix Table 6.3).

4.2. *Discussion of the industry regime in TEF phases 4 and 5*

This discussion proceeds in the following order: hubs, clusters, and megaprojects for CCUS/CCS, EOR, and DACs; then a discussion of the hubs, clusters, and megaprojects for hydrogen; and, finally, a discussion of the industry regime actors and periphery firms working across these technology vectors and infrastructure.

As explained in Section 2, a main benefit of the TEF is that it enables a temporal, "modular explanatory" analysis (Geels and Penna, 2015). This is fitting in the context of the final two phases of the TEF for industrial decarbonization in Texas where we follow Geels (2021: 211) in developing a "historical narrative into an analytical causal explanation couched in explicitly theoretical forms." Indeed, CCS and hydrogen are modular add-ons within the large technical system (LTS), we envision these technologies as "moons" that are exerting gravitational pull on the industry regime "galaxy", which is turn being pulled by the LTS universe.

4.2.1. *Phase 4: Strategic recreation, learning, and innovative technologies (2015–2022)*

The industry regime began in earnest to explore innovative technologies in phase 4, to create new partnerships and collaborations even before Biden's policies toward the end of Obama's second term. Then the Biden Administration's "Build back Better Plan" sought to retrain industry and reduce GHGs by 50 % by 2032. This set the stage for the IIJA and the IRA, discussed in Section 3, with substantial rewards for industrial decarbonization. CO2 and hydrogen pipeline construction underwent further development in phase 4 (projects 22–23 in Appendix Table 6.3). In this phase, in addition, we find that incumbent firms and industries—in particular those that are connected to the spatially-expansive elements of the LTS, such as heavy industry and energy infrastructure—were beginning to meet transitions with incremental rather than radical innovations from a technological standpoint (e.g., CCS for coal and natural gas, and building out pipelines).

4.2.2. Hub, clusters, pipelines, and megaprojects (CCUS/EOR/DACs)

The first TEF phase provided proof of concept: that EOR and CCUS can work in Texas, but hubs were not yet emergent. The second and third phases demonstrated that hubs and megaprojects can come together to reduce costs in, for example, expansion of CO2 and hydrogen infrastructure to service the needs of multiple firms in the industry regime. In the current fourth phase, hubs and clusters are undergoing planning around megaprojects, with several already going forward while awaiting more public funding (see projects 24–40 in Appendix Table 6.3).

Legacy O&G majors are expressing much interest in DACCs and CCS/EOR. Since CCS and DACCs costs are daunting, only the largest industrial firms can currently participate (see Table 2). The West Texas DACCs hub (where the world's first EOR projects were constructed), as well as several massive hubs centered in the Port of Houston, provide evidence for incumbent firm's interest. Nevertheless, as mentioned above, one major bottleneck surrounds permitting for Class VI wells. Certainly, permitting delays will impact the timing and eventual success of megaproject and hubs for CCS and blue hydrogen, and to a lesser extent DACCs.

Table 1
Tax credits for industrial decarbonization under IIJA and IRA.

Technology	Credit amount / total est.	Type of reward
EOR	$35/ton	Cash rebate or tax credit
CCS	$85/ton	Cash rebate or tax credit
DACs	$180/ton; $130 ton	Cash rebate or tax credit
CCUS	$60/ton ($3 billion)	Proposal to revise to $75/ton under CCUS tax Credit Amendments Act (2021)
Hydrogen production	$3/kg; $4/kg (green)	Ten-year credit
Total credit for clean electricity generation	$131 billion	Tax credits
Production credit for CCS	$3 billion	Tax credit
Nuclear power	$30 billion	Tax credit
Clean fuels	$19 billion	Tax credit
Clean energy and energy efficiency	$37 billion	Tax credit
Clean energy manufacturing	$37 billion	Tax credit
Energy loans	$17 billion	Direct expenditure
Energy efficiency	$11 billion	Direct expenditure
Industrial decarbonization	$5 billion	Direct expenditure
Other	$66 billion	Direct expenditure
Advanced fossil energy projects	$8.5 billion	Loans and grants
Hydrogen Hubs	$8 billion	Loans and grants
Hydrogen Program's Plan	$10 billion	Investment by US Gov.
Clean Hydrogen Electrolysis Program	$1 billion	Loans and grants
Renewable energy technologies	$30 billion	Loans and grants
Emissions reduction in industrial sectors	$5 billion	Loans and grants
Direct Air Capture (DACs)	$3.5 billion	Loans and grants
CO2 Pipeline Infrastructure	$2.1 billion	Loans and grants under IIJA
DACs prize	$115 million	Loans and grants
Carbon capture	$2.5 billion	Loans and grants
Carbon capture prize	$100 million	Loans and grants
New carbon management	$12 billion	Loans and grants (DoE)
CO2 Transportation	$2.1 billion	Loans and grants
Electricity Grid	$16.5 billion	Loans and grants (IIJA)

*All CCS must start construction by January 1, 2033, minimum capture: 18.8 KTPA for power plants and 12.5 KTPA for all other industries. ***CCS for electricity generation must capture at least 0.5 million tons/year; for industrial facilities must capture at least 0.1 million tons/year; for utilization of carbon, must capture at least 25,000 tons/year (IRA, 2022: 283).
Source: Authors' compilation of Aker Carbon Capture (2022); US DoE (2022b); Bistiline et al. (2023); Climate Home News (2023); Ladislaw and Larsen (2022).

Table 2
Estimated costs of CCUS "megaprojects" in Texas (2021–2023).

Cluster name	Total capture and transport costs using saline storage ($ billions)	Total capture and transport costs using depleted O&G wells ($ billions)
Corpus Christi	$3.3	$2.9
Freeport	$5.7	$5.3
La Porte / Baytown	$5.3	$4.9
Port Arthur	$7.7	$7.2
Lake Charles	$3.1	$2.6
Geismar / Ascension Parish	$8.3	$7.8
Point Comfort	$1.7	$1.3
Totals	$35.1	$32

Source: adapted from Waxman et al. (2021). Projects with costs over $1 billion.

4.2.3. Hub, clusters, and megaprojects (Hydrogen)

While the CCS and EOR clusters are already well established, and several megaprojects have been in operation for decades, blue and green hydrogen hubs and megaprojects are just taking off. In the domain of hydrogen technologies and infrastructure we identify, consistent with (Geels, 2014: 274), a significant "reorientation of regime elements, based on technological search activities and cognitive adjustments in core beliefs and mission" (Geels, 2014: 274). Unlike CCUS and EOR—-which are largely built using modular substitutions—hydrogen production, transport, usage, and storage demands significant architectural reorientation (Markard et al., 2020; Andersen et al., 2023).

The future of hydrogen in Texas, on the other hand, looks promising. Indeed, there is great potential for industrial reorientation based on hydrogen, as explained by Bender and Maxwell (2023: 21): "Texas and the broader Gulf Coast region have a well-established history in hydrogen production. More than a quarter of today's total U.S. hydrogen demand, roughly 3 megatons H2 per year, is currently used for ammonia, methanol, and petrochemical refineries on the Gulf Coast. The region also hosts roughly 50 percent of the country's existing hydrogen production capacity and almost the entirety of the nation's dedicated hydrogen pipeline infrastructure, approximately 1,600 miles long."

Consistent with other studies that use the TEF, we find that incumbent firms within the industry regime can and do reorient, especially in the case of hydrogen—furthermore, that "architectural change can also take place without major disruptions to incumbent actors" (Andersen et al., 2023: 2). This can be observed in the fervent activity that surrounds industrial hydrogen production and usage, and to a lesser degree in the extensive CO2 pipeline infrastructure. Below we list the core hubs and megaprojects for hydrogen, followed by a discussion of the LTS within the fourth and fifth TEF phases (see projects 41–48 in Appendix Table 6.3).

4.2.4. Industry regime core and peripheral actors

We observe that several firms participate in multiple hubs and megaprojects, which can be considered first-movers in the current phase. These are mainly firms with previous experience in carbon capture and chemicals (Air Liquide, Air Products, MMEX resources). Air Products, indeed, was an early mover in the CCS and blue hydrogen space, having installed a facility in 2017 in Port Aurthur Texas (Bender and Maxwell, 2023).

As depicted in Table 3, there are a mix of industry regime and new actors coming online in the green hydrogen space (GTI Energy, Green Hydrogen International, Mitsubishi Corporation, Repsol Hydrogen, and Sempra Infrastructure). Again, Air Products emerges in a dominant position, owning six hundred miles of hydrogen pipelines that connect the Houston Ship Channel with New Orleans, and also 20 hydrogen plants in the area (Bender and Maxwell, 2023). A relative newcomer, or

Table 3
Industry regime and peripheral actors.

Regime actors	Industry type	Peripheral actors	Industry type
Air Liquide	*Chemicals, hydrogen, and CCS*	1PointFive*	*Carbon capture*
Air Products	*Chemicals, hydrogen, and CCS*	8Rivers	*Finance*
Bechtel	*Chemicals, hydrogen, and CCS*	AES Corp.	*Low-carbon Energy*
BP	*O&G*	Arkalon Energy	*Carbon capture*
Chevron	*O&G*	Apex Clean Energy	*Low-carbon Energy*
Citgo	*Chemicals and O&G*	Barrel Energy Inc.	*EVs and CCS*
Equinor	*O&G and CCS*	Chevron New Energies	*Low-carbon Energy*
ExxonMobil	*O&G*	Carbon Engineering*	*Carbon capture*
GTI Energy	*Energy*	Chaparral Energy LLC	*Energy*
INEOS	*Chemicals and O&G*	Charm Industrial	*Industrial processes*
Kinder Morgan	*Pipelines*	EDF	*Energy*
Linde	*Chemicals, hydrogen, and CCS*	Enbridge	*LNG*
LyondellBasell	*Chemicals, hydrogen, and CCS*	Enid Fertilizer	*Fertilizers*
Mitsubishi Power Americas	*Power*	FuelCell Energy	*Energy*
MMEX Resources	*Carbon capture*	Gulf Coast Sequestration	*Energy*
Net Power LLC	*LNG energy and CCS*	Harnyss	*Energy*
NRG Energy	*Energy and CCS*	HbZRO	*Carbon sequestration*
Occidental Petroleum	*Fossil fuel extraction*	HIF Global	*Hydrogen*
Sempra Infrastructure	*Pipelines*	HyAxiom Inc.	*Hydrogen*
Shell	*O&G*	Marathon Petroleum Corporation (MPC)	*O&G*
Valero	*Energy production and carbon capture*	MPLX (subsidiary of MPC)	*O&G*
Valverde	*Pipelines*	COI N.V.	*Blue Hydrogen*
		Orsted	*Low-carbon Energy*
		Ozona Carbon Capture	*CCS*
		Next Hydrogen USA	*Hydrogen*
		Oxy Low Carbon Ventures	*DACCs and CCS*
		Panda Energy Fund	*Carbon capture*
		Plug Power	*Low-carbon Energy*
		Repsol	*O&G*
		Siemens Energy	*Hydrogen*
		SpaceX	*Rockets*
		Talos Energy	*Energy*
		Technip Energies	*Rockets*
		White Energy	*Energy*
		Wood	*Engineering*
		Worley	*Engineering*

peripheral actor, is Green Hydrogen International (GHI), which is a start-up company hoping to supply Elon Musk's SpaceX by "combining hydrogen with CO2 at the Port of Brownsville to create a green methane rocket fuel for launch operations in South Texas" (Hydrogen Central 2021). This megaproject might also connect to the Integrated Regional Clean Hydrogen Hub in Corpus Christi. This observation falls in line with the expectation that "peripheral actors find it easier to deviate from institutional logics, while central actors can use power to shape institutions to their advantage" (Geels, 2014: 265).

4.3. System integration and restructuring of the industry regime

In general, consistent with prior industrial decarbonization megaproject literature (Sovacool et al., 2024a,b), we observe that hubs are indeed facilitating system integration, and that the technologies being used are predominantly favored by incumbent industry. CCUS and DACCs hubs have already entered the fifth stage of the TEF. Most hydrogen hubs and megaprojects, on the other hand, remain in the fourth phase, with only the HyVelocity Hub successful in the US DoE Hydrogen Hub application process. We contend that EOR remains in the third phase, however, since it is tethered to fossil fuels (and therefore does not require any significant firms-in-industry reorientation). As is expected, O&G industry-regime actors are heavily involved in both CCS/EOR and DACCs (BP, Citgo, ExxonMobil, Shell, and Valero)—though the DACCs technological domain is dominated by Occidental Petroleum and its various subsidiaries (1PointFive, Carbon Engineering, Oxy, Oxy Low Carbon Ventures).

As Geels (2014) and Kungl and Geels (2018) propose, despite the existence of an industry regime, firms-in-industries might develop different behaviors in response to regulatory stringency. The emergence of a new constellation of actors, moreover, might serve to stimulate transitions (Kivimaa et al., 2021). This can lead to distinct responses by firms within the industry-regime (Kungl and Geels, 2018). We observe this in, for instance, chemicals companies that are quickly filling in the space to provide CCS and hydrogen capabilities (e.g., Air Liquide, Air Products, Linde), while incumbent O&G firms are forming partnerships with these players for CCS, EOR, and blue hydrogen (see projects 32, 33, 37, 39, 47 in Appendix Table 6.3).

4.4. Discussion

While in the first three TEF phases relatively little industrial decarbonization megaprojects were initiated—and, in general, the industry regime evidently resisted the decarbonization transition—we did identify earlier explorations into more fundamental technological innovations, such as EOR and CCS that were, indeed, new to the world. In the first three stages of the TEF, furthermore, we also identified new partnerships and collaborations, especially for carbon and hydrogen pipeline infrastructure (Ruggiero et al., 2021). These findings are largely consistent with prior literature that uses the TEF to explore the industry regime across different sectoral foci (Geels, 2014; Steen and Weaver, 2017; Turnheim and Koretsky, 2023).

There were also instances of substantial system reconfigurations involving the combination of incremental improvements in system components. New technological moons are emerging in this domain. These can potentially lead to, in addition, incremental improvements in system components and changes in the "system architecture"—which can be observed by new linkages between system components (Geels and Turnheim, 2022). Future research might take a whole systems approach to include analysis of the reconfigurations of system architectures (McMeekin et al., 2019; Markard et al., 2020; Andersen et al., 2023).

In line with Geels and Gregory (2023), we observed volatility in the transition from the third to the fourth TEF phase, characterized by the emergence of new peripheral firms. Their findings, in an exploration of the UK's industrial decarbonization transition, are largely consistent with ours: a "strategic orientation (from defending the existing regime to shifting to a new regime)" occurs from the third to the fourth phases, corresponding to a doubling down of "capital expenditures in deploying low-carbon technologies" (Geels and Gregory, 2023: 3).

In the fourth phase of the TEF, consistent with Geels (2014: 274), we observed that the industry regime has changed its "core beliefs, identity and mission." This is particularly evident in the recent experimentation and engagement in the hydrogen space, supported by a handful of peripheral actors and new firms entering the industry regime. In our context this also meant that the traditionally extractive O&G industry began, in earnest, to experiment with decarbonization technologies, and new ways to produce energy (e.g., blue hydrogen and natural gas with CCS).

While the fourth stage is winding down now, the fifth stage is largely prospective in nature—owing to hubs and projects awaiting government funding—and therefore we are not able to provide concrete conclusions here. Nevertheless, consistent with related literature Turnheim and Geels (2013, 2012), we did observe that the industry regime is beginning to exploit emerging decarbonization technologies, revamping business models, and reorientating strategies to align with new financial arrangements.

The elephant in the room, even for the industry in Texas, are permits for Class VI wells, required for the industry regime to store CO2. In similar fashion, blue hydrogen might, indeed, keep the industry regime from moving from the fourth to the fifth TEF, since it also remains tethered to the planetary system of fossil fuel technologies and firms. On the other hand, green hydrogen is beginning to instantiate a new constellation of technologies and firms—a new industry regime galaxy within the LTS universe so to speak—which might soon exert strong gravitational pull in a lower-carbon direction and catalyze an entirely new industry regime if significant technological advances can be garnered.

5. Conclusion

This article focused on the industry regime and the industrial decarbonization transition in Texas, which is a global leader in energy production, fossil fuel extraction, chemicals, and other related industrial processes. Should industrial decarbonization eventually succeed in Texas, the technologies and know-how can be brought to industrial hubs elsewhere around the country and the world. Given this potential, we used Texas as an exemplary case study to explore the industry regime for the industrial decarbonization transition using the Triple-Embeddedness Framework (TEF).

We conclude by drawing attention to certain technologies that might be precluding the transition to the fourth and fifth phases of the TEF such as EOR. We find that EOR, indeed, is a "technological moon" pulling the constellation of industry-regime planets back to the third phase (as it exclusively relies on oil and gas production). A yet to be resolved issue for the industry regime concerns blue and green hydrogen megaprojects and hubs which, apart from the HyVelocity Hub, have yet to move forward. Thus, while we observe that the industry regime with respect to hydrogen technologies remains in phase 4 of the TEF, in the absence of significant financial incentives (e.g., direct subsidies and tax rebates hitting corporate books), we do not yet expect a significant reorientation in a low-carbon, hydrogen direction. Until then, technological diversification and distant searching can be expected to continue (Geels and Turnheim, 2022). Blue hydrogen is moreover confronted with the major bottleneck surrounding permitting for CO2 storage. In addition, the jury is still out on the performance and efficiencies for both blue and green hydrogen. Should industrial hydrogen megaprojects and technologies not perform as well as expected (McLaughlin et al., 2023), there is risk that hype-cycles in this technology domain will ensue (Borup et al., 2006; Torvanger and Meadowcroft, 2011). Promise-disappointment cycles have already featured extensively in hydrogen technology projects in the past (McDowall and Eames, 2006; Ruef and Markard, 2010). It is therefore unclear whether industrial decarbonization in Texas will be short-lived or long-lived, and incremental or transformative, from a technological standpoint, even though the industry regime has begun to reorient in this direction.

CRediT authorship contribution statement

Kyle S. Herman: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Benjamin K. Sovacool:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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Appendices

Table 6.1
Longitudinal overview of industrial decarbonization megaprojects.

Project Name	Leader/developers	Technology	Cost	Status**	Phase
Sharon Ridge		EOR	unknown	1972	1
Terrell gas	Val Verde; Occidental	EOR natural gas processing (0.5 million tons/year)	$10 million; $27.6 million	1998	1
Petra Nova	NRG Energy JX Nippon	CCS-Coal, post combustion, scrubbing, EOR (expected 1.4 m/ton year)	Total: $1 billion; $167 DoE	2017–2020 (On pause)	2
Texas Clean Energy Project	Summit Power Group Inc.; Siemens, Fluor, Linde	CCS-Coal; IGCC, EOR (1.5–2 million tons/year), chemical production?	Total: $4 billion ($811 DoE)	2011–2016	2
Century Natural Gas	Oxy (subsidiary of Occidental), Oxy Low Carbon Ventures	Natural gas CCS (5 million tons/year) (expected 8.4 m/ton)	$1.1 billion	2010–2012	2
Port Arthur	Valero Refinery; Air Products	Steam methane, EOR (1 million tons/year)	$652 million (est.)- $284 DoE grant	2013 began operations	3
La Porte CCS	Net Power LLC, Oxy, 8 Rivers, CB&I	Natural gas CCS (Allam-Fetvedt cycle) (match with other??)	$1 billion	2018–2021 (began)	3
Gulf of Mexico Hub	OGCI (SECARB), Occidental, Shell, ExxonMobil, bp, Chevron, Repsol, Total	CCS (20 million tons/year)		2019 announced (2024 est.)	3
Ector County	Occidental, 1PointFive	DACs (1 million tons/carbon year)		2022	4
West Texas Occidental	Occidental and 1PointFive	CCS (1.2 t/year)		2024 (est.)	4
Odessa Net Power	Net Power LLC (Occidental)	Net Zero Gas (860k metric tons/year capture)		Start 2024–2026	4
Houston Ship Canal	ExxonMobil	CCS Hub		2025	5
Blue Bonnet Hub	1PointFive (subsidiary of Occidental)	CCS for industry	DoE funded $16.48 million)	Operational 2026	5

(*continued on next page*)

Table 6.1 (*continued*)

Project Name	Leader/developers	Technology	Cost	Status**	Phase
Baytown Texas	ExxonMobil			2027	5
Kleberg County	1PointFive, Carbon Engineering, Worley	30 DACs (3 billion tons/carbon per year)	(half $1.2 billion awarded by DoE, Aug. 2023)	2027 (est.)	5
Charm Industrial	Charm Industrial	Biochar CCS, pyrolysis oil into geological formations		2028 (researcher est.)	5
Beaumont Hydrogen	OCI N.V.	Blue hydrogen and CCS?	$1 billion	2022–2025 construction	3
Wilbarger County	Air Products, AES Corp.	Green Hydrogen (220 tons/day, 1.4 GW wind/solar)	$4 billion	2024	3
HyVelocity	GTI Energy, CHF; Air Liquide, U Texas, Chevron, Sempra Infrastructure	Green and blue hydrogen		2025	3
Gulf Coast CCS	BP and Linde	Blue hydrogen and CCS (15 million metric/ tons year capture)	$1.8 billion	Start 2025	3
Bay City	HIF Global, Bechtel	Green Hydrogen	$6 billion	2025	3
Pecos County	MMEX Resources, Siemens	Blue hydrogen, ATR		2026 (est.)	4
Horizons & Trans Permian Clean H2 Hub	Port of Corpus Christi Authority (many partners)	Clean Hydrogen Hub		2026 (est.)	4
Hydrogen City		Green hydrogen (3 billion kg; 60 GW solar/ wind); green ammonia and aviation fuel		2026	4
Port Corpus Christi (HCH2)	Many	Hydrogen Hub: Submitted to Regional Clean Hydrogen Hubs Program.		2026 (est.)	4
HIF Matagorda	HIF Global	eFuels CCS (2 million tons/year)	$6 billion (est.)	Starts operation 2027	4
LIGH2T	INEOS, Linde, MPLX, U Houston, NREL, SSEB (13 other partners)			2028 (researcher's est.)	5
Trans Permian Hydrogen Hub	MMEX Resources, Siemens Energy			2028 (researcher est.)	5
Gulf Coast Hydrogen	Air Liquide, Chevron, LyondellBasell, Uniper	Study for hydrogen ammonia production		2028 (researcher's est.)	5
Brownsville Horizons Clean H2 Hub	Port of Corpus Christi Authority (and many firms)	CO2 for green methane rocket fuel; 10 million metric/tons per year		2030 (est.)	5

Sources: the authors collected data from numerous corporate websites and corporate announcements to compile this table (PointFive, 2022; Products, 2023; Ammonia Energy Association, 2022; Wire, 2022; Wire, 2022; Mobile, 2023; Global CCS Institute, 2022, Global CCS Institute, 2023; Houston, 2023; Oxy, 2023; Newswire, 2022; Resources for the Future (2023). Hydrogen hubs: Get to know the encouraged applicants. URL: https://www.resources.org/common-resources/hydrogen-hubs-get-to-know-the-encouraged-applicants/. Last accessed: October 5, 2023.; Upstream Energy Explore, 2023).

*megaprojects are those with estimated costs in excess of $1 billion or with above 1 million tons of estimated carbon capture.

** Status: if unknown, researcher's estimate 2028.

Table 6.2
Summary of TEF pressures, responses, and phases.

Time period and phase	External pressures	Response strategies	Reorientation phase
Phase 1: prior to 2000	EOR provides viable path to lowering emissions and extracting more fossil fuels	Several firms build out EOR and initial CCS projects	Proof of concept
Phase 2: 2000–2010	Hydrogen and coal subsidies under Bush. Energy Policy Act (2005)	Hydrogen infrastructure expansion: CCS for energy rollout (coal)	Planning and initial policy development
Phase 3: 2010–2015	Subsidies under Bush and Obama (Recovery Act)	Hydrogen experimentation; CCS for energy (gas)	Infrastructure and first-movers
Phase 4: 2015–2022	IIJA provides initial rewards for EOR, CCS, H2	Widespread EOR pipeline buildout; expansion of CCS for energy (gas / other); expansion of renewable energy	Widespread project and hub development, local and distant technological searches
Phase 5: 2022–2032	IJA rewards	Ten CCS / Hydrogen hubs announced. E-fuels and green hydrogen.	Significant industry-regime re-orientation (expected)

Source: Authors.

Table 6.3
Industrial decarbonization megaprojects and hubs in Texas (1972–2023).

1. Val Verde and Occidental were the first-movers for Enhanced Oil Recovery (EOR), not only in Texas but in the world (1972)
2. Canyon Reef Carriers Pipeline dedicated to CO2 constructed (1972)
3. The Enid Fertilizer plant became the first of its kind in the world to use CCS (1982)
4. Central basin CO2 pipeline constructed (1982)
5. Cortez CO2 pipeline, connecting from Texas through New Mexico and into Colorado, is constructed by Shell (1982)
6. Air Liquide converts two crude oil pipelines to hydrogen (1990) (US DoE, 2022)
7. Valverde CO2 pipeline completed, connecting to Canyon Reef pipeline (1998)
8. From 1994 to 2004, $980 million was claimed in tax credits to develop EOR for CCS (IRS, 2004)
9. Over 2000 miles of CO2 pipelines were constructed from 1980 to 1990 (Dooley et al., 2009)
10. Centreline CO2 pipeline is completed (2003)

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Table 6.3 (*continued*)

11. NRG Energy and JX Nippon were awarded $167 million from the US DoE to affix carbon capture to Petra Nova's gas-fired powerplant. It uses post combustion scrubbing, and EOR, with an expected capture rate of 1.4 m/tons per year. Petra Nova was put on pause in 2020 to August 2023 due to cost concerns.
12. Corpus Christi hydrogen pipeline was built (**need citation)
13. Kinder Morgan expands SACROC CO2 pipeline (2002)
14. Air Products and Chemicals and Valero: Port Arthur CCS, receive $254 million from the DoE (construction from 2009 to 2013)
15. Texas Clean Energy Project (TCEP): $450 from DoE, begins construction in 2010, cancelled in 2016 (total DoE grants: $811 million; total project costs: $3.98 billion) (http://sequestration.mit.edu/tools/projects/tcep.html)
16. Century plant EOR/CCS, Pecos County: 8 Mt/Year. Occidental Petroleum estimated to invested $1 billion in construction, operations began in 2010 (http://sequestration.mit.edu/tools/projects/century_plant.html)
17. Denbury green pipeline, 300 miles connecting Louisiana to south of Houston—goes through Texas Supreme court for approval (construction 2010–2013) (https://www.jonesday.com/en/insights/2017/01/texas-supreme-court-clarifies-common-carrier-test-for-pipeline-companies)
18. NET Power la Porte became the world's largest gas CCS plant
19. Air Products Port Arthur, 12 mile CO2 pipeline constructed. For CCS/EOR. DoE funded $284 million (began 2013)
- Two SMRs in Valero refinery, average 1 Mt/CO2 year (https://sequestration.mit.edu/tools/projects/port_arthur.html)
- Air products, world's largest hydrogen pipeline network, 1 billion cubic feet per day. DoE funded $400 million (completed 2012) https://microsites.airproducts.com/h2-pipeline/pdf/air-products-us-gulf-coast-hydrogen-network-datasheet.pdf

20. The Gulf Coast hydrogen pipeline, 180 miles (completed October 2012)
21. Sargas EOR/CCS pipeline, 50 miles (construction began 2017)
22. Petra Nova EOR/CCS pipeline, 82 miles (construction began 2016)
23. Texas Clean Energy Project (TCEP) EOR/CCS pipeline, 1 mile (construction began in 2019 but was halted)
24. Oxy and 1PointFive announced a plan for DACCs in Ector county, to capture 1 million tons of carbon per year (2022 targeted start date)
25. Occidental Petroleum Denver Unit CO2 Recovery Plant, Denver City, West Texas: (2016–2026, 1 Mt/year)
26. NET power and Occidental announced a new net zero gas plant called Odessa net power (to start between 2024 and 2026)
27. A Dutch company, OCI N.V., breaks ground for an ammonia blue hydrogen facility suing CCS, called Beaumont Hydrogen (2022)
28. Enbridge and Oxy Low Carbon Ventures plan a CO2 hub in Corpus Christi (announced 2022)
29. Oxy, Occidental, and 1PointFive DACCs plant Permian Basin (construction began 2022, expected 2024 operational) (https://www.globenewswire.com/news-release/2022/08/25/2504560/0/en/Occidental-1PointFive-to-Begin-Construction-of-World-s-Largest-Direct-Air-Capture-Plant-in-the-Texas-Permian-Basin.html)
30. BP and Linde plan CCS project in Texas Gulf Coast (announced 2022, operational 2026) (https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-and-linde-plan-major-ccs-project-to-advance-decarbonization-efforts-across-texas-gulf-coast.html)
31. The Houston Ship Canal, a CCS Hub spearheaded by ExxonMobil (targets 2025 to begin operations)
32. 1PointFive announced the Blue Bonnet Hub, building out CCS for industry (to begin operating in 2026)
33. 1PointFive, Carbon Engineering, and Worley announced a DACCs hub, with over 30 individual DACCs projects planned in Kleberg County West Texas DACCs Hub, to be operational by 2025
34. HIF Global planned an e-Fuels CCS project to begin construction in 2024, and start in Matagorda in 2027
35. Occidental and 1PointFive announced a CCS project in West Teas to start in 2024
36. DOE announced funding to advance the development of two commercial-scale DAC facilities in Texas and Louisiana. The two projects, representing the initial selections from the BIL-funded Regional DAC Hubs Program, will help further demonstrate the ability to capture and store atmospheric CO2
37. Project Cypress (Calcasieu Parish, Louisiana) seeks to capture >1 million metric tons of CO2 from the atmosphere annually and store it underground. The South Texas DAC Hub (Kleberg County, Texas) seeks to develop and demonstrate a DAC facility designed to remove up to 1 million metric tons of CO2 annually and store it in an associated saline geologic CO2 storage site. From energy.gov. August 2023
38. Gulf Coast Storage Network Announced Barrell Energy Inc. announced it is developing the Gulf Coast Storage Network consisting of four carbon storage sites along the Gulf Coast in Louisiana and Texas. The energy company has performed an extensive evaluation of multiple carbon storage sites targeting the Miocene, Frio, Wilcox, and Cretaceous reservoirs in Louisiana and Texas. From Business Wire. August 2023.
39. Equinor Joins CCS Project Equinor acquired a 25 % interest in the Bayou Bend CCS project along the Gulf Coast in southeastern Texas. The Bayou Bend CCS project has nearly 140,000 gross acres of pore space for CO2 storage, including approximately 40,000 gross acres offshore near Beaumont and Port Arthur, Texas. Bayou Bend is a joint venture among Chevron, through its Chevron New Energies division; Talos Energy, through its Talos Low Carbon Solutions division; and Equinor. From Offshore Magazine. August 2023.
40. Zero emissions gas Plant, Net Power Texas
41. HyVelocity Hub: it envisions a to reduce 2 kgs of carbon for each 1 kilogram of hydrogen produced, and to reduce hydrogen production by 80 %. Core industry partners: AES Corporation, Air Liquide, Chevron, ExxonMobil, Mitsubishi Power Americas, Ørsted, and Sempra Infrastructure. Peripheral partners: GTI Energy, the Center for Houston's Future, and the University of Texas, Houston Advanced Research Center (won public funding in October 2023).
42. Port of Corpus Christi Horizons Clean Hydrogen Hub merged with the Trans Permian H2 Hub for the DoE proposal, Integrated Regional Clean Hydrogen Hub Proposal (unsuccessful). Core industry partners: Apex Clean Energy, Ares Management Infrastructure Opportunities funds, Epic Midstream, Mitsubishi Corporation, Plug Power, Repsol Hydrogen, Sempra Infrastructure. Peripheral partners: Ambient Fuels, AMMPower, Avangrid, Avina Clean Hydrogen, Big Hill, Buckeye Partners, Green Hydrogen Energy Partners, Green Hydrogen International, Howard Midstream Energy Partners, Hydrogen Optimized, Magellan Midstream Partners, Monarch Energy, Motus Energy, Pattern Energy, Trafigura, Teal Chemistry and Energy
43. Hydrogen City: A 60 GW 2.5 billion kilograms of green hydrogen megaproject to make clean rocket fuel for Elon Musk's SpaceX. Core industry partners: SpaceX, Green Hydrogen International. To begin operations in 2026
44. Leading in Gulf Coast Hydrogen Transition (LIGH2T): To produce clean hydrogen and help decarbonize chemical manufacturing, refining, transport, and power generation. Core industry partners: INEOS, Linde, MPLX. Peripheral partners: NETL and the University of Houston. Unsuccessful in hydrogen hub application

(*continued on next page*)

Table 6.3 (*continued*)

45. Kleberg county hub: Air Product and AES corp. are planning a green hydrogen facility to begin in 2024.
46. HIF Global and Bechtel are planning a green hydrogen facility to start in 2025
47. MMEX Resources and Siemens are planning a blue hydrogen plant in Pecos county, estimated to start in 2026
48. AES Corp Announce a Green H2 plant in Wilbarger County to begin operations in 2027

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