Hatching an Industry: The Incubation and Growth of the Direct Air Capture Industry

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Abstract:

Studying the direct air capture (DAC) industry, this paper proposes a process model of how industries transition from the incubation period to the era of growth. Particularly, the model focuses on industries based on mission-oriented technologies, such as those that mitigate climate change. We posit that the transition was enabled not only by exogenous changes but also by internal efforts that redefined the commercial values of DAC-related products. It is shown that once DAC companies managed to reduce the commercial uncertainty that characterized the incubation period, inventive activities significantly increased. The transition from the period of incubation to that of growth has also been driven by the enrichment of the ecosystem and the convergence of business models.

Keywords: Industry emergence, Uncertainty, Nascent industries, Climate technology

Introduction

Recently, scholars of industry and technology evolution have started to examine the "incubation period" within an industry's evolutionary process, the period of time preceding the initial occurrence of commercialization. Contrasting the long-standing literature that looks at post-commercialization dynamics, this stream of research highlights the activities, investments, and capabilities of firms that culminate in initial commercialization attempts (Agarwal et al., 2017; Moeen et al., 2020). Despite advances in this literature, we propose that our understanding of the incubation period, as well as the emergence of industry, can be enriched by further studies on industries that emerge to address grand challenges. This type of industry has become increasingly common but remains under-studied. Agarwal et al. (2017) have discussed industries whose emergence is triggered by mission-oriented grand challenges, focusing on those championed by national agencies such as the Office of Scientific Research. Nevertheless, previous insights may not be entirely sufficient to help us understand the cases where the grand challenges are not identified by specific individuals, agencies, or organizations in a top-down manner. For example, climate technologies have given rise to industries such as carbon capture and long-duration battery storage. However, their emergence has had less to do with the direct and early intervention of powerful champions.

Furthermore, while we now know more about the characteristics of the incubation period and firms' activities during this time, we know less about how industries eventually graduate from this nascent stage and move on to the period that follows. In the tradition of Gort and Klepper (1982), the classic industry life cycle depicts an early period of quasi-monopoly that follows the first instance of commercialization, which is then superseded by a period of high net entry. These two periods in the early stages of industry evolution are characterized by intensive product innovation efforts and various technologies compete with one another until a dominant design eventually emerges. To bridge the research on the incubation period and the rich literature on post-commercialization industry evolution, this paper looks at the process and mechanisms that propel industries from the incubation period to the era of growth, characterized by technological diversification and high net entry rates.

The current discourse on the emergence of technology-based industries focuses on the nature and interaction between supply- and demand-side uncertainties. However, there is another form of uncertainty that transcend this dichotomy and originates from the mismatch between supply and demand forces. Labeled as commercial uncertainty, this concept is the starting point of this project, and we look at how it can be reduced and how its reduction influences the evolutionary trajectory of the technology and the industry. Fundamentally, commercial uncertainty arises from the lack of understanding of the products (technologies) and ambiguity of how economic value is created and captured. It is particularly relevant to industries whose emergence is triggered by grand challenges. For example, in the early stages of the emergence of the direct air capture (DAC) industry, potential customers were discouraged due to their inability to appreciate the value of the product even though they needed solutions for reducing carbon emissions.

We explore the origin of the technology underlying the industry of direct air capture (DAC) and analyze how the initial functional shift gave way to more radical innovation and propelled the growth of the industry. We look at how three intertwining elements of the industry—the underlying technology, the various business models, and the ecosystem—have evolved and interacted. Importantly, we recognize the important role of commercial uncertainty and how they have shaped the three elements throughout the process of industry emergence. Tracing the history of the DAC industry, we analyze changes in the external environment, behaviors of key actors, the composition of the ecosystem, and the degree of innovation, covering the years between 2007 and 2021. We rely on evidence from a broad range of sources, both primary and secondary, to create a process model linking exaptation, industry incubation, and industry growth.

Methodology

The research setting is the DAC industry from 2007 to 2022. When the severity of climate change became widely recognized in the late 1980s, the change in public perception of the risk associated with climate change galvanized R&D activities in search of solutions that can be deployed at scale. Mission-oriented organizations, both public and private, were created to mobilize more resources. Among the array of technological solutions to combat climate change that emerged during this era, direct air capture (DAC) was born in the labs of research academics who were working on highly innovative ways to reduce carbon emissions. DAC is a suite of technologies that capture carbon dioxide from the ambient air. Collecting carbon dioxide directly from the atmosphere as a way to reduce the risks of climate change was first introduced in 1999 (Lackner et al., 1999). In its early stage of development, the gas separation technologies in DAC extended the mature methods which were already widely adopted in point-source carbon capture. For example, solvents and sorbents had been used in polluting facilities such as coal-fired power plants or chemical manufacturers. Several pilot and demonstration projects provided evidence supporting the feasibility of capturing CO2 from ambient air. In the ensuing years, scientists and entrepreneurs have continued to create ever more novel solutions, with varying degrees of technological readiness. The evolution of technology has been tightly linked to that of the industry and the surrounding ecosystem.

Tracing the history of DAC, we identified two sequential phases of emergence. The identification is primarily based on the first instances of commercial-scale projects. This time can be conceptualized as the incubation period (Agarwal et al., 2017). With the founding of the first DAC companies, we mark 2007 as the start of the incubation period. At the time, there were only three companies active, and all of them were startups. During this period of time, these companies focused on demonstrating the viability of their technologies and at least two of them reached commercial scale around 2015. The first instance of commercialization marks the end of the incubation period and this first phase of industry emergence.

At the end of the first phase, the industry saw a drastic increase in entrepreneurial activities. With more than 20 new ventures active in the industry, this new phase was characterized by a high level of technological diversity. Deviating away from mature technologies repurposed from industrial CCS, innovative approaches were being developed and scaled up by a wider range of actors. Guided by our research question with its three-pronged focus on technologies, business models, and the ecosystem, we followed the temporal order to analyze our data to derive the process model.

Data: Sources, Collection, and Analysis

We draw on a wide range of data sources. In the initial stage of data collection, we focused on companies that had been developing DAC technologies in-house, gathering detailed information on their technological approaches, fundraising efforts, and commercialization attempts. Informed by our efforts in this stage, we moved on to collect data on the industry level, including information on ecosystem constituents, government policies, market conditions, and technological evolution.

Our database includes archival data and two rounds of semi-structured interviews. The table below details the sources of our data and how we use them in the analysis.

Insert Table 1 here

We analyzed the data through three stages. The process was iterative, and we focused on data sources, data analysis, and existing literature in an alternating manner. We first focused on developing a timeline of the industry and the evolution of air separation (capture) technologies. Reconstructing the history of the industry and the technology allowed us to identify key changes in the configuration of the industry, the evolutionary processes of multiple air separation technologies, and important events that affected market demand for direct air capture. Through these exercises, we delineated two phases in the emergence of the DAC industry, with 2015 marking the first example of commercialization. This cut-off year also saw a massive change in the industry entry rate. The number of active companies, mostly new ventures but also several diversifying entrants, increased significantly.

The second stage of data analysis involves open coding of the interview transcripts and archival data. At this stage, we focus on descriptive elements associated with technological development, policy changes, key players (including start-ups, universities, government agencies, and non-profit organizations), and various business models. We noticed the technologies used in direct air capture shared significant similarities with industrial carbon capture initially but novel technologies that are better aligned with the performance requirement of the DAC industry emerged in subsequent years. Following the evolution of the technology, we induced that the key factor that drove this process was the changes on the demand side. Consistent with research on industry incubation and nascent technology, demand uncertainty stemming from user preference and user adoption interact with supply-side uncertainty such as the focal technology and the business model (Kapoor & Klueter, 2021). Accordingly, we began to develop codes related to uncertainties that actors must tackle while operating in the nascent DAC industry. Delving into the drivers of technological innovation and key changes in the external environment, we began to theorize the importance of commercial uncertainty. While sharing similarities to user uncertainty on the demand side and business model uncertainty on the supply side, commercial uncertainty highlights the public good characteristics of DAC and suggests that the lack of clarity on the commercial or economic value of technology affects how it evolves and develops.

Applicable to other technology-based markets addressing grand challenges such as climate change, this type of uncertainty is less likely to be resolved by the actions of firms alone. Convincing others of the merits of the technology may not be sufficient to facilitate commercialization. Instead, the existing socio-technical regime needs to be disrupted to address the imperfections of the existing economic systems. Through this round of coding, we identified three key puzzles: (1) the convergence of business models without regulatory change, (2) the initial exaptation has given way to technological diversification, and (3) the presence of commercial uncertainty and how it affects the evolution of technology and industry.

With the three puzzles in mind, we commenced the third stage of analysis with directed coding. The preliminary theorizing in the previous stage allowed us to structure the subsequent data analysis more precisely by focusing on three distinct but interrelated aspects of the DAC industry: the underlying technologies, the ecosystem, and the external environment. We began by focusing on the technical aspect of the gas separation technologies that underpin the industry. Working with chemical engineers and geologists, we differentiated the various competing technologies and their respective evolutionary trajectories. While investigating how different technologies were developed, we simultaneously looked for themes in our data relating to the influences of the ecosystem and the external environment. For example, we noticed the increasing presence of specialized incubators and investors was a key change in the ecosystem. We then went back to the data to understand the role they played and what drove their emergence. To address the former, we looked at how companies reacted to their presence and activities, including the entrepreneurs in the space and other types of actors in the ecosystem. At the same time, we examined the identity of these actors and their motivations in creating such organizations to address the latter question. Similar iterative processes informed how we made sense of the data and induce the process model. Doing so led to our theorization of the main mechanism of commercial uncertainty reduction that pushed the industry forward. In turn, we investigated how commercial uncertainty had been gradually reduced through the interactions among technological innovation, ecosystem expansion, and institutional changes. To validate our model of the industry emergence process, we conducted additional interviews to see whether it fit well with our informants' own experience and observations.

Data Analysis

The first phase: the incubation period (2007-2015)

Entrepreneurs and scientists active in the first phase faced a highly ambiguous environment with uncertainties originating from the focal technology, the demand, and the ecosystem. The external environment during this period showed the first signs of support for DAC. The 2005 IPCC report explicitly recognized carbon capture as a crucial tool to mitigate risks associated with climate change. While the focus was mostly on industrial point source application, research and development in the DAC space picked up momentum; scientists based in research institutions made strides and some of them started to scale up their innovation by operating pilot and demonstration projects. Entrepreneurs entering the industry at this point did not place significant emphasis on downstream activities. While some new ventures did develop carbon utilization technologies, most efforts are dedicated to advancing the efficiency and efficacy of gas separation techniques. Table 3 below summarizes the different developmental stages and various events for company A and company B from 2005 to 2022, along with external influences taking place at the same time.

Insert Table 2 here

Technological development: exaptation and technological uncertainty

Repurposing existing technologies applied in industrial CCS required DAC companies to demonstrate their applicability in this new domain. The repurposing of existing technologies reflects the phenomenon of exaptation, the functional shift or expansion of objects (Andriani & Carignani, 2014; Cattani & Mastrogiorgio, 2021). While solutions such as liquid solvents were proposed as promising candidates, the applicability was severely limited because the existing technologies were adapted to environments where the concentration of CO2 is high. The laws of thermodynamics suggest that separating CO2 is more difficult when the concentration is low. Therefore, the technological uncertainty that defined this period stemmed from the lack of information on whether the exaptation would be successful and whether the technologies can be scaled up. Companies focused on piloting and demonstrating their gas separation technologies. It can be seen as modifying and refining technologies previously applied in industrial CCS to better suit the conditions specific to DAC. Nevertheless, the functional shift of the underlying gas separation technologies was sufficiently significant to trigger a change in their forms in some cases. This morphological change leads to the speciation of a new technological niche distinct from industrial carbon capture (Andriani and Cattani 2022).

Company A and technological uncertainty

Company A adopted the liquid solvent approach whereby the solvent reacts with CO2 chemically, trapping the gas in the form of a carbonate salt. Liquid solvent scrubbing is a widely used carbon capture technique with multiple off-the-shelf options available, ranging from monoethanolamine to hot potassium carbonate solvents. However, these existing offerings are not fully applicable in DAC due to the extremely low concentration of CO2 in the ambient air. Amine-based solvents, commonly used in industrial CO2 scrubbing, are mature and cost-competitive in the context of industrial carbon capture. However, their toxicity and volatility suggest that they are not compatible with DAC; one other technological bottleneck rooted in this technology is also the high energy intensity requirement to desorb CO2. The technological strategy pursued by company A was built on modifying air contactors, aqueous amine solvents, the workhorse of capturing CO2, and other existing concepts. In its early years from 2010 to 2014, its main activities were prototyping and improving its technological feasibility. The first full-scale facility became operational in 2015, and this is the first case of commercialization in the industry.

Company B and technological uncertainty

Company B adopted a solid sorbent approach, another technology whose application in industrial CCS is mature. Fundamentally, it is an adsorption-desorption process performed through a temperature-vacuum-swing (TVS) process. Temperature and pressure swing processes are used in the production of gases such as hydrogen. Industrial gas companies such as Air Liquide and Air Products both have capabilities in these techniques and have decades of experience. Incumbents in the oil and gas industry have also made progress in developing this class of technology. Even though the solid sorbent technology is generally less energy intensive compared to liquid solvent technology during the regeneration process, it still faces major challenges in application to DAC such as high capital investments in the early period. Company B achieved one of the earliest instances of commercialization in the industry through an industrial-scale plant in collaboration with an agricultural company that operates a greenhouse conveniently located next to a waste incineration plant that provides a suitable energy source.

The cases of Company A and B illustrate that, in the early years of DAC's evolution, relevant technologies are exploitative in the sense that the underlying techniques are co-opted from domains such as industrial carbon capture and industrial gas production. The likelihood of success of the technological exaptation was not immediately clear due to limited applicability. The main activities conducted by companies were modifying the technologies and demonstrating their feasibility under the conditions specific to DAC. Following the successful demonstration and commercial projects, the technological uncertainty was significantly reduced.

Ecosystem uncertainty: underdevelopment and primitive structure

In addition to technological uncertainty, the first phase of DAC's evolution was also characterized by a small and underdeveloped ecosystem. While entrepreneurs active during this period did not dedicate many resources to resolve ecosystem uncertainty, its primitive state, as well as the players involved, had a significant influence on the industry's development. Besides the entrepreneurs, actors that shaped the DAC industry include academic institutions, public organizations, philanthropists, as well as owners of certain complementary assets. The relatively simplistic composition of players in the industry can be attributed to the lack of clarity in the technological and demand aspects (Moeen et al., 2020; Teece, 1986). That is not to say that actors were ignorant, they were cognizant of what resources could be mobilized and which actors could be convinced to participate. However, as the DAC industry did not achieve legitimacy and the fundamental technological uncertainty hadn't been resolved, the breadth and depth of participation were significantly limited. For example, according to a project financing specialist interviewed, entrepreneurs had to rely on grants and individual philanthropists because the proposed projects were considered "unbankable". The magnitude and multitude of uncertainty were too high for traditional financing mechanisms.

The ecosystem uncertainty limited the options available to entrepreneurs. Both Company A and B relied primarily on unconventional sources of financing during the incubation period, particularly not-for-profit, mission-oriented investors, both individual and organizational. The long-term orientation of these investors, together with their pursuit of social returns, leads them to behave differently from traditional investors. They are less likely to use traditional valuation models and are more likely to select ventures based on the extent to which they can deliver social values instead of financial values. It leaves room for entrepreneurs to resolve technological uncertainty without diverting resources to reduce ecosystem or business model uncertainty (Scarlata & Alemany, 2010). These activities further strengthened the positioning of DAC as a climate technology whose value and purpose are environmentally oriented. Being identified as such affected how the industry evolved in the following years. This emerging value proposition enabled the identification of a set of actors whose activities contribute to its realization. For example, DAC entrepreneurs may subsequently look for support from government agencies whose mission relates to climate change mitigation, and they may form alliances with polluters looking for ways to reduce their environmental impact.

Business model uncertainty: experimentation and the lack of scalability

During this period, entrepreneurs took a cumulative, exploitative approach to technological development. In contrast, they were much more exploratory with their downstream activities, experimenting with various ways to commercialize the captured CO_2. While they had the intention to build profitable business models, it was not prioritized during this period. This is likely related to the limited resources these companies had and the amount of support they could mobilize externally. DAC companies did not have sufficient information on what products to sell even though they had the technological capability to capture CO_2 and transform it into various value-added products. The markets for transformed CO_2 were undeveloped and lacked infrastructures such as agreed-upon categories, pricing mechanisms, and norms of exchange (Lee et al., 2018). DAC companies experimented with different models as a result. Nevertheless, the business models adopted during this period were unprofitable, impeding the further development of the underlying technologies and the growth of the industry.

Company A and business model uncertainty

Company A explored producing synthetic fuels with the captured gas. Algae-based fuels have been publicized as an integral activity of the company since the early 2010s. However, the patent associated with the conversion technology was not filed until 2016 and it was not tested in the pilot plant at the pilot plant in 2017. The long time horizon suggests it has been a sustained effort, showing that market creation had been an ongoing process and technological, as well as demand, uncertainties remain high.

Another commercialization pathway discussed by the management of Company A was selling the CO_2 to perform enhanced oil recovery (EOR). EOR is a practice of injecting CO_2 into depleting oil fields to boost yields and it should be noted that EOR is a common downstream activity in industrial carbon capture. The practice of EOR allows the final fuel products to have a lower fossil carbon footprint than the regulated amount, enabling the producers to exploit a premium in certain markets. It should be noted that whether EOR can be a viable option depends on the price of oil and the cost of DAC-generated CO2. Company A's cost of capture was estimated to be around $200 per ton in 2016. This number suggests that the DAC-EOR pathway was unlikely to be viable without further incentives or a drastic decrease in costs.

Company B and business model uncertainty

In the early years of Company B, the business model was envisioned to be a set of integrated activities that starts with direct air capturing and end with converting the captured CO2 to synthetic liquid fuels such as gasoline, diesel, or jet fuel. In 2014, Company B collaborated with a major German automaker in a synthetic fuels project where a consortium of companies operated a pilot plant. While the automaker has continued its efforts in the development of synthetic fuels, it remained challenging to scale up its production of air-captured CO2 due to prohibitively high costs. During this period, Company B adopted a multiple-pronged strategy to commercialize its end products. First, as part of its first commercial-scale project, the CO2 is sent to the greenhouse owned by the pilot project's partner, which has the potential to boost vegetable yields by 20%. Second, in the company's announcement of the operation of its first facility, selling CO2 as raw materials for beverages, fuels, and other materials was described as their commercialization strategy. At the same time, underground storage, while not implemented, is proposed as a potential way to scale up the business.

Discussion

To summarize, the first few years of the DAC industry's emergence are characterized by diverse, exploratory business models. The pioneers experimented with various commercialization pathways and there was little sign of convergence. Company A and B both considered selling the captured CO2 as an input in the production of fuels, among other types of products. However, the cost of capture at the time was prohibitively high and this business model was therefore not economical. Similar concerns apply to the use of air-captured CO2 in EOR. While it is an established practice and the market was functioning well, operators did not have incentives to purchase from DAC companies.

The industry and its external environment, encompassing regulations, institutions, and public perception, were evolving rapidly and continuously at the time. Consequently, players active in this period had the flexibility to explore a wide range of business models. However, they had little information on which of them holds the most potential for value creation and capture (Kapoor & Klueter, 2021). This lack of clarity was further exacerbated by the ambiguity associated with the value chains since it was not clear how activities could be allocated among players and what kind of complementary products or services were needed. An interview with an industry expert based in a European incubator highlighted that the main problem during the incubation period is that actors were enthusiastic about the utility of the technology but had little idea about what can be purchased from DAC companies.

While this period of incubation ended with instances of successful commercialization, the market for DAC-generated CO2 was highly immature, suggesting that further scaling of both the supply and demand remained difficult. During this period, firms sought to commercialize captured CO2 through various methods, such as synthesizing fuels. However, the costs of producing these value-added products were prohibitively high, restricting the size of the demand. Without the means to generate economic value with DAC technologies, capital did not flow to the industry to support R&D efforts. We conceptualize this phenomenon as commercial uncertainty. The market for DAC-generated CO2 was underdeveloped because on one hand, sellers (operators of DAC projects) did not create products whose values were well-understood and economical and on the other hand, the offerings available at the time appealed only to a small number of buyers. Furthermore, buyers were unlikely to justify purchasing products without clear economic values. Even in such a mission-oriented industry, the identity of the buyers (individuals or organizations seeking to address climate change) and the utility of the DAC technology (mitigating climate change) were relatively clear-cut. The prevailing socio-economic forces prevented buyers from acting purely according to their environmental targets without economic considerations. The industry emergence, therefore, was impeded until such commercial uncertainty could be reduced.

The period of growth: the transition from incubation to growth (2015-2022 May)

Following the successful commercialization attempts by Companies A and B, the DAC industries saw an increase in entrepreneurial activities. This increase was preceded by intensified publicity efforts by the pioneers and heightened public awareness. At the same time, some critical changes in the external environment strongly influenced how the industry and the technologies evolved.

The commercialization of CO2 and commercial uncertainty

Coinciding with the end of the incubation period, the voluntary carbon market (VCM) boomed and reached mainstream around 2015. VCM is a marketplace in which "carbon offsets" are traded. Measured in tons of CO2-equivalent, one carbon offset represents one ton of CO2-equivalent reduced or removed. It is a product, in the form of credits, that allows organizations or individuals to compensate for emissions made elsewhere. In the DAC industry, companies adopting the capture-as-service business model capture CO_2 from the atmosphere, store it, and then generate offsets according to the amount captured to be sold to willing buyers. The growth of the VCM suggests the commercialization of CO_2, contributing to the reduction of commercial uncertainty surrounding the DAC industry. Commercializing directly captured CO_2 as carbon credits allow potential buyers to quickly understand the offerings of DAC companies as the mainstreaming of VCM markets raised the awareness and recognition of carbon credits.

Exogenous change—the development and growth of the VCM—were not sufficient to propel the emergence of the DAC industry *per se*. Reacting to this shift in the external environment, DAC companies started to adopt capture-as-service business models and commoditize the captured CO_2 as carbon credits (offsets). In the next section, we detail this development and analyze how it has affected the process of industry emergence.

Convergence of business models in response to the reduction of commercial uncertainty

During the incubation period, DAC companies struggled to come up with products with commercial appeal. The companies experimented widely without meaningful success in creating markets for these offerings. In contrast, during the second phase (the era of growth) we observed only some scattered efforts to create novel business models while the majority of companies converged in the way they create and capture value—by selling carbon credits.

Selling carbon credits as end-products marked a turning point in the emergence of the industry and the evolution of the underlying technology as it led to two important developments. First, pioneers that have successfully demonstrated their products' viability on the commercial scale were able to quickly deploy this model and connect with well-established, well-funded buyers. Second, carbon credits are a widely understood concept independent of the DAC technology and industry. The coupling between carbon credits and the DAC industry allows sellers to capitalize on the taken-for-granted nature of the new end products and therefore increase their legitimacy in the eyes of potential customers. From the buyers' perspective, DAC-generated carbon credits address their emission abatement needs without having to create new forms of collaboration with DAC companies. Early buyers generally have long-standing environmental strategies and capture-as-service allows them to integrate the products into their existing portfolios. Table 4 illustrates selected DAC companies' product types, technology, and fundraising results. The information shows the convergence of DAC companies' products to carbon credits. We have selected DAC companies from our database, depending on whether they were active during the at of our data collection period.

Insert Table 3 here

The collective adoption of a profitable business model also influenced the scale and diversity of the DAC industry's ecosystem. As the VCM continued to grow and develop, the outlook of the DAC industry became more sanguine. The increasingly positive prospect of the industry attracted actors like traditional venture capitalists, entrepreneurs, incubators, universities, and government agencies. The enrichment of the ecosystem injected capital and talent, pushing the technology and the industry further.

Ecosystem enrichment

As the period of growth superseded the period of incubation, we observe a sharp increase in the number and diversity of organizations active in the DAC industry. They coalesced into a more clearly defined value chain and form an enriched ecosystem. Beyond those directly involved in the creation and development of the underlying technology, a wide range of actors have appeared to further enable DAC's value creation (Kapoor, 2018). This was possible because once the commercial uncertainty of DAC is reduced, the technology's value proposition became understood, accepted, and credible. Actors both in the upstream and downstream value chain could better elaborate on how they can contribute to the realization of the value proposition for two reasons. First, the value proposition is commercially attractive and therefore actors are incentivized to invest necessary resources. Second, the value proposition is clearly defined and consequently, actors can work backward to see which actions are needed to achieve their respective goals. Being both willing and capable, we see more numerous and diverse organizations participate in both the upstream and the downstream of the DAC industry, pushing the process of emergence to an era of growth.

The enrichment of the ecosystem during this time was comprehensive. In the upstream**,** we observe a sharp increase in the diversity of actors and the intensity of their commitment, focusing on fostering and enabling innovation. These actors include traditional venture capitalists, incubators, universities, as well as corporate venture capitals (CVCs). At the same time, we see companies, primarily from the industrial CCS and the oil and gas industries, diversifying into DAC. Common entry strategies include forming partnerships or mergers and acquisitions (M&As) which allow rapid deployment of tested and demonstrated materials in larger-scale operations. In the downstream, focusing on scaling and commercialization of the innovation, organizations were being created to broker the supply and demand.

Compared to the funding landscape during the first phase of the emergence where investors are mostly mission-driven, we see second-phase investors seeking mostly strategic, and ultimately commercial, value from their investment in DAC ventures. Companies A and B, the pioneers in the industry, were both able to mobilize more resources from more traditional sources in this period.

They successfully raised capital from mainstream venture capitalists and received strong support from CVCs of large oil and gas players. The implications on industry emergence are two-fold. First, first-generation ventures (the pioneers) matured and gained legitimacy. Considered "bankable" by project financing providers is a hallmark of such achievements. To financiers, a project is only bankable if it can generate sufficient and stable cash flows to fulfill obligations created during capital outlay. Before resolving commercial uncertainty and adopting profitable business models, DAC projects were not backed by project financing apparatus. Instead, most startups relied on unconventional, mission-driven investors to provide them with capital. Second, the heightened interest in the technology and increased investments in its development have led to more inventive activities and have resulted in more innovative DAC methods. The case of Company C illustrates this.

Company C

Contrary to its peers established earlier, the team did not start the venture at a research lab. Instead, the founding team was affiliated with specialized incubators dedicated to the development of climate technologies. During the growth period of the DAC industry, a new breed of organizations has become increasingly important in supporting entrepreneurial activities dedicated to reducing carbon emissions and fighting climate change. These non-governmental organizations (NGOs) rely on mechanisms such as "founder in residence" programs to provide research, mentorship, and other resources for early-stage ventures. These NGOs have become a critical source of collective actions that shape the emergence of the DAC industry. They were, in many ways, replacing universities and research labs as the main hubs of DAC entrepreneurship. However, the roles played by universities and other public institutions did not diminish but evolved. We see more research centers being established across major universities and task forces being formed within public agencies to support more basic research that underpins inventive activities in this area.

In terms of commercialization, right at the start, Company C adopts the capture-as-service business model and sells carbon credits to large organizations. A notable observation is that many clients of Company C were also their investors. This relationship did not represent an attempt at vertical integration on the part of the buyers. The motives of these investments were not gaining more control over the production of carbon credits and lowering transaction costs, per the theories of transaction cost economists (Williamson, 2010). Rather, these investors appeared to be highly forward-looking and often have specific initiatives within their organizations to support this type of investment and purchasing. The emergence of this type of organization could be attributed to both exogenous and endogenous factors. Companies were facing increasing pressure to tackle their environmental impact from not only regulators but also their customers. The changes in public awareness of the importance of carbon emission reduction coincided with the growth of the DAC industry. Reducing technological and commercial uncertainty allowed the industry to be recognized as a legitimate "climate technology". The confluence of the two factors created a favorable environment for entrepreneurs to attract committed customers that are willing to actively participate in the creation of the market. The dual roles of these organizations created a "circular" ecosystem for DAC ventures.

Technological diversification: an intermediate outcome

The homogenization of the business models and the enrichment of the ecosystem both contributed to the advancement and diversification of DAC technologies. High levels of technological diversification are one of the defining features of this period. During the first phase of the industry's emergence (the incubation period), entrepreneurs repurposed technologies widely used in the domain of industry CCS and spent considerable resources in reducing technology uncertainty by demonstrating the applicability of these solutions in DAC. Showing that their technologies are fit-for-purpose did not resolve the uncertainties entirely, however, their successful pilot and demonstration projects showed that the technologies have the potential to be commercialized and it instilled confidence in the economic viability of the industry.

In the second phase, technological diversity increased, and the R&D efforts became more exploratory. To address obstacles such as energy efficiency, scalability, and engineering demand, new entrants not only sought to improve the available solutions but also created highly novel methods of carbon capture. Within the broad categories of solvents and sorbents, innovative solutions that emerged at this time including metal-organic frameworks, ion-exchange resins, and solid oxide sorbents. Moreover, novel gas separation technologies such as membranes and electrochemical systems were also developed. For example, Company D, a recent entrant, developed an electrochemical approach of direct air capture. Instead of using temperature or pressure common in chemical gas separation, scientists from Company D developed an Electro-Swing Adsorption (ESA) process. The ESA technology has the advantage of consuming 70% less energy than competing processes, addressing one of the key concerns of other, more conventional, approaches. Interestingly, instead of building on technologies used in industrial CCS, the flow of knowledge is reversed with the ESA process being applied in point-source carbon capture (Jin et al. 2022). Currently, the applicability of the electrochemical approach in industrial point-source carbon capture is limited since conventional methods such as amine scrubbing remain cost-competitive. However, as affordable renewable energy becomes increasingly available, its adoption is expected to spill over from DAC to industrial carbon capture.

The reversal of the technological flow is interesting. While exapted technologies such as solvents and sorbents were still widely used and improved upon in this period, the novel technologies developed specifically for DAC attracted the attention of players in industrial CCS. In addition to de novo entrants, diversifying entrants, from the adjacent industrial CCS sector, also joined the DAC industry. For example, Company E, founded in 2007, had been a provider of a carbon capture technology that is reportedly more efficient than traditional solvent-based systems. Specifically, its offering addresses the challenges associated with separating CO_2 from diluted flue gas characterized by low pressures and dilute concentrations of CO2. Recall that industrial CCS originates from industries whose waste streams have high pressures and high concentrations of CO2, resulting in heterogenous capture costs across polluting industries. To address this disparity, a large portion of the R&D activities has been directed to finding tailored carbon capture solutions for certain types of polluters. Company E was an important player in this adaptive process, driven by exploratory, radical innovations. It worked extensively with large industrial polluters to deploy its technology at an industrial scale. The diversification into the DAC industry commenced in 2020 when Company E signed a collaboration agreement with pioneering venture Company B. The joint project uses Company E's proprietary solid structure sorbent as the filter in Company B's machines. The partnership between the two companies indicates that the spillover of knowledge is two-way. Exploratory knowledge building stemmed not only from within the DAC industry but also from the adjacent industry (CCS and hydrogen production). It should be noted that Company E was not the only one diversifying from industrial CCS. During the same period, we observed three others that did the same.

The incubation period gave way to the era of growth and technological ferment, characterized by significant technological variation and competition that comes from a high degree of product innovation. The repurposing of the industrial CCS technologies opened a new process of adaptation as the criteria to evaluate the performance of DAC technologies are articulated and clarified. This is consistent with the view that transplanting a technology in a new user environment, defined as the set of socio-technical forces that select the relevant function of a technology, can lead to discontinuity in technological trajectories, increasing the diversity in the design of the artifact (Adner & Levinthal, 2001; Geels, 2004; Kaplan & Tripsas, 2008).

The process model of DAC Emergence

The emergence process of the DAC industry is driven by various mechanisms across different levels of analysis. Figure 1 illustrates. The figure is divided into three chronological sections vertically and four levels of analysis horizontally. As the DAC industry has continued to evolve, we offer only interim outcomes of the model. We take inspiration from Raffaelli (2019), who depicted the re-emergence of the Swiss mechanical watch industry with a similar graphical design. Before the presence of entrepreneurial or business activities, DAC existed as a concept in academic research. Researchers were explicitly addressing the need to mitigate climate change and proposed the direct capture of CO2 as a potential solution that deserves further research. This body of early research served as a fundamental inspiration for entrepreneurs that sought to realize this vision and set the tone for the mission-oriented nature of the industry.

Insert Figure 1 here

During the incubation stage, entrepreneurs built upon pre-existing solutions to create DAC technologies. Previously applied in different domains, gas separation technologies were refined and modified through intensive R&D, piloting, and demonstrating activities. One of the most critical goals was to demonstrate the feasibility of the technologies when applied in the new context (capturing CO2 from the atmosphere). While early industry participants made significant progress to reduce technological uncertainty, they faced formidable hurdles in finding and adopting profitable business models. They experimented widely with various downstream products, developing different methods to utilize the captured CO2. This exercise was highly challenging because markets for captured CO2, in its original or transformed form, were underdeveloped. There was a lack of market infrastructure, particularly, there did not exist agreed-upon categories, pricing mechanisms, and norms of exchange to guide and support transactions (Fligstein, 2001; Lee et al., 2018). While the utility and merit of DAC were not disputed, it was not clear what product or service offerings can be transacted to fulfill the goal of climate change mitigation. Put differently, DAC companies did not have sufficient information on what products to sell even though they had the technological capability to capture CO2 and transform it into various value-added products. This mismatch is conceptualized as commercial uncertainty in this paper and its presence is the most critical obstacle to industry emergence during DAC's early years of development.

Looking beyond organizational factors, the emergence of the DAC industry and the evolution of the underlying technologies were further delayed by the primitive ecosystem. In the early years, most industry participants operated in the public sector in some capacity. The founders of DAC companies themselves were commonly affiliated with universities. Many of the supporting organizations that provided capital and other resources were public institutions. One interesting exception was the intervention of wealthy individuals who supported the development of the technology because of their long-standing efforts in tackling grand challenges. The lack of scale and diversity limited the number of resources that went into DAC, impacting the rate and direction of innovation.

An important change in the larger external environment coincided temporally with the first successful commercial-scale DAC project—the expansion and refinement of the VCM. At that time, the scale and maturity of the carbon market reached a new height and became widely used by organizations and individuals alike. The commercialization of reduced, avoided, or removed CO2 proved to be pivotal to the DAC industry. As a better-understood and well-accepted product, carbon credits allowed DAC project operators to reinterpret their services and products. This change was quickly grasped by DAC companies and almost all of them abandoned their old business models and adopted the capture-as-service model. Newer entrants also rely on this model to sell their offerings more easily without having to experiment with more products and business models. This shows that exogenous change was not sufficient in itself to facilitate industry emergence. It was the concurrence of exogenous and endogenous changes that resolved the commercial uncertainty and drove the industry through the era of growth.

One direct implication of this development was the expansion of the ecosystem. The significant reduction of commercial uncertainty attracted not only more DAC entrants but also other types of industry participants. Upstream, we saw a sharp increase in venture capital investments and the rise of specialized incubators. Government agencies also took note of the technology and started to promote it through policies and subsidies. Downstream, the number of buyers similarly increased. Most interestingly, buyers of DAC-generated carbon offsets were often highly committed. Through mechanisms such as advanced market commitments, they not only purchased the credits issued by DAC operators but also did it before the products (credits) are created. In this way, their roles transcended that of a customer and took on the characteristics of an investor. Taking away uncertainties from the demand side, DAC companies were more incentivized to invest in R&D, creating innovations that addressed the shortcomings of the exapted, mature technologies. The level of innovation is further heightened by the increased intensity of competition as more players enter the DAC industry, resulting in a virtuous cycle that accelerated the period of growth.

Interim outcomes of DAC's emergence

On the supply side, the technological and business model uncertainties were reduced significantly. The incubation period gave way to the growth period as we noted the underlying technology has entered the era of ferment. A wider range of technologies competes with one another as new technologies that deviate from the mature sorbents and solvents continued to be developed. In contrast to this diversification, the business models have become highly homogenous with capture-as-service being the most prevalent. On the demand side, DAC-generated carbon credits were differentiated from others that were generated from renewable energy projects or afforestation. They tended to be more costly and less readily available. The buyers of DAC-generated carbon credits were more committed to the development of the technology. Through special arrangements such as advanced market commitments, they motivated DAC operators to innovate and scale by removing demand uncertainty. The timely change in the external environment has been successfully exploited by the DAC industry, transforming the business models and promoting innovation. External changes were met by corresponding internal efforts and therefore, the challenging commercial uncertainty was reduced, and in turn, the process of industry emergence transitioned from the incubation period to an era of growth.

Conclusion

This paper contributes to the literature on industry evolution and technological change by investigating the transition between the incubation period and the growth period. While scholars have started to pay attention to the incubation stage, we have only just begun to understand how this phase in the process of emergence impacts the stages that follow. We also focus on the relatively understudied mission-oriented industries that seek to address the grand challenges we face today. Certain characteristics of this type of industry set it apart from those that emerged from scientific discoveries or unmet user needs. Particularly, we find that the level of commercial uncertainty, an understudied phenomenon, tends to be very high in the early stages of emergence. We show that the reduction of commercial uncertainty, through efforts external and internal to the industry, was the linchpin for the development of the industry and the underlying technologies. The DAC industry illustrates that repurposed (exapted) technologies can serve as the basis of a new industry and achieve new technical heights. Eventually, technologies that are adapted to the purpose of DAC spilled back to the industrial CCS space, reversing the flow of knowledge.

As the urgency to address grand challenges continues to rise, more industries will emerge to enable us to mitigate problems relating to climate change and public health. The DAC companies' initial struggle with finding profitable business models has been and will be experienced by actors operating in environments with unfavorable socio-economic forces. Thus, the awareness of how external changes can be exploited to create and sustain markets is highly critical. Echoing the view that a systemic overhaul on the societal level is needed to ensure mankind's future, this paper underlines that systemic changes can be achieved through business activities and such changes are an important source of novelty.

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Tables and Figures

Table 1: Data sources and use

Source	Use
Firm Archive	
Company Websites	We gathered basic Information such as products, the management teams, current, and future projects from company websites.
Company seminars (Recorded and live)	We relied on web-based events to gain more in-depth information on the technologies, projects, partnerships, and industry outlook.
Scientific articles	Scientific articles allowed us to better understand the technologies, related policies, and key actors in the ecosystem.
Other archival sources	
Articles in specialized magazines	We collected data on industry participants, technological trends, business models, and policies through trade magazines.
Articles in newspapers	News articles informed us of changes in the external environment, such as new policies and government subsidies.
Recorded interviews with firm founders	Interviews conducted by third parties with DAC industry participants.
Fundraising record (Crunchbase, Marketline)	Specific fundraising status, rounds, size, and investors.
Governmental publications and announcements	Information on policies, regulations, subsidies, research, and government-sponsored projects.
Interviews	
16 interviews	The interviews covered a broad range of topics, focusing particularly on three key issues: (1) The status of the technology and the industry (2) The drivers of technological development (3) Changes in the external environment and how they relate to start-ups' technological and commercial strategies

Table 2: The evolution of DAC pioneers

Year	Company A			Company B			External	
	Stage	Events	Fund Raised	Stage	Events	Fund Raised	Range	Events
2005-2007	Academic Foundation	First DAC papers published		Academic Foundation	Acadamic foundation of founders		EU	EU Emissions Trading System is launched; The Kyoto Protocol enters into force.
								The IPCC and U.S. Vice-President Al Gore were jointly awarded the Nobel Peace Prize for climate change.
							IPCC	The Fourth Assessment Report focuses on limiting warming to 2°C.
							California	California's Low Carbon Fuel Standard adopted
2008	Conceceptual Design	Conceptual design was completed; Prototypes were constructed.					45Q	The tax credit under section 45Q was enacted.
2009				Conceptual Design and Prototyping	Foundation of Company B; The first system concepts and working prototypes were developed.			
	Prototyping	Foundation of Company A; First fundraising from individual philanthropist; Patent Filing; Prototype completed.	$3.5M		First grant and continuted fundraising from philanthropic organizations	$150K		
2010-2011					Fundraising of series-A round	$2M		
2012-2014		Fundraising of grants; Hire CEO	$3M		The first fully functional prototype; First patent filing; Fundraising of series-B round.	$3.3M		
2015-2016		Construction of the operational DAC pilot plant; Fundraising from government grants.	$3M					Paris Agreement is adopted; First media report about DAC
2017	Early Commericialization	First batch of initial products launched			Construction of first commercial-scale DAC plant and the first carbon dioxide removal plant.; Collaboration with one large carbon storage project.		US	President Trump announced his intent to withdraw the United States from the Paris Agreement; Extend and reform the 45Q tax credit
2018		Fundraising of seed round			Fundraising	$31M	IPCC	UN IPCC releases its 1.5 degress rise special report
2019		Venture arms of two giant energy companies jointly invested in A, supporting the first commercial plant; Fundraising of PE round and givernment grants	$93M		First B2C product Launched		EU	EU Green Deal Announced to achive climate neutral by 2050 in Europe.
2020	Commericalization Continued	Received investment from major clients		Commericalization Continued	Fundraising; Beginning of construction of new commercial plant.	$110M	US	US DoE announced financing specifically for DAC in March 2020 (USD 22 million) and March 2021 (USD 24 million).
2021		Carbon capture as service started			Launched the largest climate-positive DAC and storage plant		US	President Biden moves to rejoin the Paris agreement.
2022		New DAC plant plans announced			Fundraising of PE round	$600M		

Table 3: The convergence of DAC products

Company	Founding Time	Money Raised	Product Type	Carbon Credits as Main Product	Method
Company B	2009	>$100M	B2B/B2C	Yes	Sorbent
Company A	2009	>$100M	B2B		Solvent
1	2010	$10-100M	B2B		Sorbent
2	2014	$1-10M	B2B		Sorbent
3	2016	$1-10M	B2B/B2C		Sorbent
4	2018	$10-100M	B2B		Sorbent
5	2019	>$100M	B2B/B2C		Electrochemical
6	2019	$1-10M	B2B		Membrane
7	2019	<$1M	B2B		Sorbent
8	2019	>$100M	B2B	Yes	Electrochemical
9	2019	$10-100M		Yes	Sorbent
10	2020	$10-100M	B2B	Yes	Sorbent
11	2021	<$1M			Electrochemical
12	2020	$1-10M	B2B	Yes	Regenerative
13	2020	$1-10M	B2B/B2C	Yes	Electrochemical
14	2020	$1-10M	B2B	Yes	Sorbent
15	2021	$1-10M	B2B/B2C	Yes	Sorbent
16	2021	$10-100M	B2B	Yes	Sorbent

Figure 1: The process model