Industrial process heat decarbonization: A user-centric perspective

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Abstract

Eliminating greenhouse gas emissions from industrial process heat (IPH) is considered a key element of decarbonizing the overall industrial sector. However, industrial users and the processes by which they may adopt and implement technologies for decarbonization have largely been overlooked in the United States by an emphasis on developing and commercializing new technologies. While recent deployment and demonstration programs are an indication that decarbonization policy is beginning to acknowledge industrial users, little research has been conducted to understand how users mediate technical and nontechnical requirements to decarbonize IPH. Our exploratory analysis uses interviews with industry representatives and document analysis to begin developing a user-centric perspective. We find that successful adoption and implementation of decarbonized IPH technologies may require adaptation to diverse and potentially unique combinations of user requirements and local contexts. Instead of pursuing "crosscutting" IPH technologies, a more effective and expeditious approach may be to develop crosscutting decision-making that spans multiple technologies. This approach may offer unexplored opportunities to improve demonstration and deployment programs, but more user-centric research is needed.

Keywords: industrial process heat, decarbonization, users, adoption, implementation, socio-technical analysis

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1 Introduction

The framing of industrial decarbonization is missing the consequential perspective of industrial users[1], particularly in the United States. These users and the processes by which they may adopt and implement technologies for decarbonization have largely been overlooked by a focus on developing and commercializing new technologies. Similarly, adoption[2] is treated simply as an outcome and not as part of a process that may lead to successful implementation[3] and routinization [4], involving industrial user contributions to innovation (e.g, [1,5]). Adoption is seen as being determined not by users, but by the various characteristics of a technology, such as its price, performance, ability to be produced at scale, and regulatory environment [6]. Even when industrial users are acknowledged, they are often discussed in terms of static techno-economic characteristics, such as the physical layout and locations of facilities and their maintenance schedules, as well as high capital and operating expenses of technologies [7,8]. This is especially true for industrial process heat (IPH) [7–9], a key component of decarbonizing industry due to its continued, significant use of fossil fuels [10,11].

However, the policy landscape in the United States has started to shift. Recently created incentives for demonstration projects and deployment are an implicit recognition of the importance of industrial users. The Infrastructure Investment and Jobs act, more commonly referred to as the Bipartisan Infrastructure Law (BIL), provides funding for the Industrial Emission Demonstration Projects program and created the U.S. DOE's Office of Clean Energy Demonstrations to accelerate deployment and adoption [12]. Following the BIL, the Inflation Reduction Act (IRA) includes grants, investment tax credits, and loan guarantees for innovative clean energy projects for industry[13].

Nonetheless, the current U.S. emphasis of industrial decarbonization on technologies and their developers persists. This can be seen as the continuation of energy policy that has historically omitted the social dynamics and contexts of energy use [i.e., 14,15]. There are few indications that U.S. industrial decarbonization strategy has incorporated the concept that individual technologies and industrial organizations, as well as technological systems and society at large, can shape and be shaped by each other [e.g., 16–20]. This includes the recognition that industrial users, like consumers [21], can play active roles in decarbonization. Groups of industrial users may represent lead markets, which can spur

[1] Lundvall distinguishes between consumers and professional users, with professional users identified as acting within the formal economy and under a more restricted goal than consumers [1]. We use the term industrial users because it is consistent with the term industrial decarbonization. As an additional point of clarification, we are referring to manufacturing industries. In the United States these industries fall under the North American Industrial Classification System (NAICS) codes 31-33.

[2] We consider adoption to be the stage in a sequence of decisions at which point industrial users decide "to make full use of an innovation as the best course of action available" [2: 21].

[3] We distinguish implementation from adoption and define it as "a dynamic process of mutual adaptation between the technology and its environment" [4: 252].

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market forces to upscale demonstration projects [22]. Conversely, industrial users may impede development and deployment of decarbonization technologies, as they have when acting through industry trade associations [23] and by exerting pressures through a global regime [24].

The industrial sector is a growing focus of socio-technical analysis, as shown by recent reviews of industrial technologies [24] and fuels [25,26], analysis of energy-intensive basic materials industries [27], and reviews of specific industries [23,28–32]. Many of the reviews for fuels and industries are far-reaching; however, several uncovered only limited existing research on the interactions between industrial user requirements and decarbonized IPH technologies. For instance, a review of the chemicals industry [29] related greenhouse gas mitigation strategies to farmers' decision-making are, but not to ammonia producers themselves. As another example, the authors [28] review structural aspects of the food and beverages industry and firms' typical management priorities, but not how these nontechnical aspects are mediated for IPH technologies.

Similarly, although there are studies that more closely examine the roles of users in supporting decarbonization, these have been focused on consumers and residential building technologies, not industrial firms and process technologies. This includes literature on domestic heating socio-technical transitions [33–35], consumer roles in evaluating renewable gases [36], residential heat pumps [37,38], and heating, ventilation, and cooling systems [39].

We contend that there is a lack of systematic understanding of how industrial users mediate the adoption and implementation of decarbonization technologies. The growing literature on decarbonizing residential heat technologies and individuals as technology users (and non-users) has limited relevance to industrial firms given their nature as complex organizations comprised of many individual actors with interdependent behavior. As organizations, firms may be materially different from individuals in terms of technology adoption and other decision-making processes [16,40,41], general routines[42], behavior related to energy use[43,44] and ability to bring about technological change [45].

Our work builds off Wesche et al. [46], who argue that the slow pace of decarbonizing building heating relative to the electric grid in Germany can be related to the configurational nature of the building heat. Using concepts of configurational and generic technology systems defined by Fleck [47], the authors find that building heat is configurational based on the diversity of heat generation technologies, which include both single-building and multi-building network solutions; the need to adapt heat technologies at the point of installation to the local physical and social contexts; and the diversity and multidirectional nature of information flows between many local installers, component manufacturers, and energy agencies. They then point to challenges for accelerating heat decarbonization that are a function of the critical need to align heat technologies with the requirements and local contexts of their users.

To begin filling knowledge gaps about industrial decarbonization from a user perspective, we explore the roles that technical and nontechnical user requirements and contexts play in adoption and implementation processes for alternative IPH technologies. This approach and its supporting theories go beyond the typical framing of user requirements and

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contexts, particularly nontechnical ones, as barriers to overcome or opportunities to exploit [e.g., 8]. More specifically, we explore the following three research questions:

1. What are technical *and* nontechnical user requirements and contexts for industrial IPH?
2. How do characteristics of IPH technologies align with the three features of configurational technologies (i.e., lack of identity, lack of systematicity, and uncertain system dynamics)?
3. What technological and organizational co-adaptations occur during implementation of alternative IPH technologies?

This paper is part of our ongoing attempts to promote cross-disciplinary approaches to industrial decarbonization, as suggested by Sovacool et al. [48]. We build off previous work that has complemented improved technical analysis of IPH [49,50] with calls for socio-technical analysis [51] and IPH user engagement [52]. In Section 2 we outline our conceptual approach by identifying the importance of IPH, providing a detailed overview of configurational and generic technologies, and summarizing the technical aspects of IPH configurations. Section 3 summarizes our material and methods, which consist of semi-structured interviews conducted with industry representatives and analysis of documents related to local regulation of air pollution from IPH. We present the results of our analysis in Section 4, organized by the three features of configurational technologies. Section 5 discusses reframing industrial decarbonization from a user perspective. We end with conclusions and potential avenues for future research in Section 6.

2 Conceptual approach

2.1 IPH in the United States

The focal point of our analysis is the use and decarbonization of IPH in the United States. We define IPH as thermal energy used in production processes, which includes energy used in industrial furnaces and kilns, for example, as well as in process steam produced in boilers and combined heat and power units. We focus on IPH for two reasons. First, decarbonizing IPH in the United States is proceeding very slowly. Although direct combustion energy-related CO_2 emissions from industry began to decline in 1997, they have largely flattened since recovering from the Great Recession of 2008-2009. Compared to 2005—base year of the U.S. goal to achieve net zero greenhouse gas emissions by 2050 [53]—industrial energy-related CO_2 emissions from direct combustion were just 6% lower in 2022 [54]. Implementing either zero-carbon sources of IPH or processes that negate the need for heat is central to industrial decarbonization [8,11]. IPH in the United States is derived overwhelmingly from fossil fuels, particularly natural gas. In 2018 natural gas constituted 88% of reported U.S. IPH energy [55], up from in 74% in 1998 [56].

The second reason we focus on IPH is that it is central to the operation and character of many types of industries. IPH can be considered a core process, which is closely associated with competitiveness and core competencies of firms [57] and that firms are highly

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sensitive to risks of disruption or ceding control over its operation [58,59]. As a result, we anticipate technology adoption and implementation for IPH decarbonization will require the mediation of many nontechnical user requirements, in addition to conventional requirements for cost and technical performance.

2.2 Generic and configurational technologies

Over time, the field of science and technology studies has developed different approaches for studying interactions and other connections between users (and non-users) and technologies [e.g., 46]. Although consumers have typically been the focus of these approaches, users of either type undergo the potentially fraught process of mutually aligning their requirements with the characteristics of technologies. As evidence of some ties between industrial users and consumers, we note that the theories we discuss in this section were developed based on industrial users and have been used to inform analyses of consumers and producers of consumer products [61]. Similarly, analyses of industrial users are related in some ways to approaches developed with the consumer in mind, such as focusing on the point at which a technology is selected from a menu of options and how relevant social groups may influence selection [62].

Because a goal of our work is to bring users to the forefront of analyzing industrial decarbonization, we highlight Fleck's [47] original emphasis on users, which was subsumed to a degree by Wesche et. al's [46] broader interest in structural-functional analysis of the building heat technology innovation system. Fleck [47] distinguishes configurations from generic systems based on three features: identity, systematicity, and system dynamics. Fleck uses the bicycle as an example of a generic system, which we borrow and expand on here. For a configurational system, we use the example of building heating developed by Wesche et al. [46].

Generic systems have a clear identity, with standards that explicitly define functions and performance. Markets exist not only for the integrated system, but also for its standard components. Conversely, configurations form ad-hoc identities based on their specific instances. Bicycles, regardless of where they are ridden, can be clearly identified by their function and their components (two wheels, frame, handlebars, pedals, brakes, etc.). On the other hand, buildings vary by age, design, and function. They may use heating systems that are designed for single units or buildings, or are designed for multiple connected buildings. These characteristics, along with location, create unique instances for heating.

Generic systems also have systematicity, or standardized plans for component integration using standardized parts. Configurations, however, do not have a governing coherence of how components are integrated and how they relate. As Fleck [47] explains, "[c]onfigurations develop by incorporating the structured complexity of user activities in a process which goes far beyond that of fine-tuning or customizing an existing standardly available system". Bicycles can be purchased pre-assembled, or they can be built up by purchasing standard components individually. In both cases, the bicycle is standardized in terms of how its individual components relate and are assembled to provide transport for its user. Conversely, although building heating relies on standard components, such as

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piping and heat exchangers, how these are combined in a final heating system "varies depending on the local physical conditions and social preferences" [28: 104].

The third feature, system dynamics, is a function of identity and systematicity. This feature has important implications for further development of a technology system. Because generic systems have a consistent identity across their instances and have systematicity, it is possible to make component-level innovations that improve overall performance. These innovations are not dependent on user context and can be pursued independently by technology developers, who are guided by stably defined design and performance parameters. Bicycles have been incrementally improved through developments that include lighter-weight materials and, most recently, battery electric motors. Although these developments may have been focused on specific types of bicycles, they are not dependent on user contexts (e.g., electric motors are now used on road, mountain, and city bicycles, for example).

By having neither a clear identity nor systematicity, the system dynamics of configurations are characterized by highly uncertain development. The variety and specific contexts of user requirements mean that it is not possible to completely define a successful configuration before implementation. Fleck [47: 27] explains that "[t]he creation of working configurations is consequently a highly creative process, which requires extensive *local* input and effort (including end-user involvement)." Nontechnical requirements may take physical form in the configuration, an effect called crystallization. The need for continuous adaptation of building heating systems to meet specific user requirements and local contexts has also been linked to labor costs persisting as a large part of total installed costs [46].

Innovations occur at each instance of a configuration as a response to the user requirements and local contexts. These innovations are then passed down to future instances by either direct replication or by incorporating or removing components as new configurations. Fleck [47] coined the term "innofusion"—the melding of innovation and diffusion processes—to describe this development pattern.

Over time, configurations can develop into generic systems if a standardized body of knowledge is created regarding the range of possible instances, and a market demand develops for instances where technology identity and systematicity have been established. The transition from configuration to generic system is not guaranteed, however, and crystallization and standardization of technical and nontechnical requirements may be resisted by many factors. These factors include a lack of perceived market opportunities, social groups that would be negatively affected by standardization, and an excessively wide range of user requirements and local contexts.

2.3 Technical aspects of IPH configurations

This section discusses examples of the technical user requirements that are incorporated into an IPH configuration. However, user information needed to build up a configuration extends far beyond technical requirements and includes local practices and procedures, as well as employee knowledge [47]. These nontechnical aspects are identified and discussed in our results (Section 3).

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The range of technical aspects of IPH configurations becomes clear after only a brief comparison with space and water heating for buildings. Like heat for buildings, IPH technologies also supply thermal energy. However, the user requirements for IPH are much broader and context dependent, such as the far wider range of temperature requirements and the ultimate use of thermal energy (e.g., driving chemical reactions or shaping materials, versus heating air or water). These user requirements translate into a greater diversity of technological options to supply IPH.

At a fundamental physical level, thermal energy can be transferred to a working material via conduction, convection, and radiation. This thermal energy can be the result of fuel combustion, an electric current, or electromagnetic waves, such as microwaves. IPH equipment can be classified based on whether heat is applied in a batch or continuous process, applied directly or indirectly to the working material, and how the working material is moved through the equipment [63].

In the case of a single chemical facility, for instance, process heating requirements may involve gas-fired heaters, electricity, steam, specialized heat transfer fluids, as well as multiple cooling systems. Process materials may respond differently with methods of heating (e.g., direct, or indirect) and with varying residence times. The facility's engineering plan specifies how these components apply or remove heat from processes via heat exchanger networks, which in many cases are determined with extensive thermodynamic analysis during facility design. The heating system infrastructure within the facility is also closely tied to the spatial footprint of the plant. Therefore, the identity of a heating system for a chemical facility is not uniform, but rather ad hoc.

Likewise, a heating system could not simply be transferred directly to another plant, so it inherently lacks systematicity. In terms of system dynamics, although components of the facility's process heating system can be improved, the improvement may not result in the same overall effect if translated to a similar facility (see the ranges in operating parameters for ethylene production [64]), let alone to facilities in different industries.

The process for selecting and building an IPH configuration therefore involves more technical and organizational considerations than buildings' heat. Not only is this true in terms of the existing or potential system design, some of the technology options also vary in their effectiveness, footprint, and how they should be integrated based on climatic considerations. For example, evaluating the applicability of an alternative IPH technology like solar IPH involves detailed facility-specific analysis of operating conditions and performance criteria and may require separate adoption of energy efficiency measures for appropriate system sizing [51]. Furthermore, solar IPH technologies, which include several types of concentrating and non-concentrating collectors that are selected based requirements of the particular IPH demand, may be integrated either at the supply/utility level or process level, which has implications for the types of heat transfer media, heat exchangers, and thermal energy storage [65,66]. High temperature heat pumps can also be integrated at the supply/utility or process level and require a similarly extensive thermodynamic analysis to determine the integration point that maximizes their performance [67]. Although it may be possible for high temperature heat pumps to

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generalize some processes for integration analysis, others require case-by-case analysis [68].

While low carbon fuels are not widely available at this time in the United States, potential availability is a key consideration that may also depend on location, for example if hydrogen hubs or pipelines are built. Electrification of IPH turns out to have similar locational dependency, which we explore in the results.

2.4 Technology implementation

Fleck is concerned with user implementation of configurational technologies, particularly the reliance on users' knowledge and their local contexts: "[i]n the process of building configurations and crystallizing contingency, the boundary between the technological and the nontechnological breaks down: new technological artefacts are shaped by and emerge from social and organizational exigencies" [47: 27]. He uses the "fundamental implementation equation" [47: 30] as a central representation of configurations: successful implementation is equal to the sum of technology supplier knowledge and technology user knowledge of their local functional requirements and practices.

We identify Leonard-Barton's [3] concept of technology-organization co-adaptation as a relevant framework for studying how configurational technologies are implemented. Fleck's subsequent work also made connections between the two perspectives and referred to Leonard-Barton as providing detailed analysis of the "micro-processes of implementation" [69: 638]. Leonard-Barton's framework is also relevant for us because it was developed using case studies of production technologies in very large firms, matching our focus on IPH and the firms represented in our interviews.

Implementation occurs when there are technology-organization misalignments at the time of initial use that are corrected by changing the technology, the user environment, or both. These misalignments can be generalized into three types: technical, delivery system, and value [3]. Technical misalignments occur when the technology fails to meet its original specifications, or when there is a mismatch between production knowledge and the technology. Misalignments of the delivery system (i.e., the system through which a technology is delivered to its users) occur when there is a mismatch between the technology and its supporting software, hardware, or educational programs. Value misalignments occur with a mismatch between the technology and the organization's job performance criteria.

The learning process of building a successful configuration goes beyond the marginal improvements behind learning by doing (i.e., decreasing production costs as a function cumulative production) or learning by using (i.e., improvements identified from using an already functioning system) [69]. Instead, configurational systems are characterized by learning by trying, which is defined by the significant amount of learning that occurs during implementation itself before a new configuration can be successful [69].

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3 Material and Methods

3.1 Semi-structured interviews with industry representatives

We conducted 12 semi-structured interviews (i.e., working from a set of standard questions, but allowing discussion to flow organically) via video conference from September through November 2022. In all but one, we interviewed a single firm representative at a time; in interview 9, we interviewed two representatives from the same firm. Appendix A, Table A1 summarizes the industries and general job descriptions of the interviewees[4]. Transcripts were checked against their video recordings and coded using Taguette [70].

We identified firms that had shown interest or had direct experience adopting alternative IPH technologies through our professional networks and by snowballing (i.e., identifying individuals to interview based on recommendations from previous interviewees). Interviewing representatives from a range of industries is important for understanding the socio-technical variations in IPH in the United States and beginning to understand their implications for adoption and implementation of alternative technologies. Several firms are in the chemical industry, but overall there is a wide range of industries and IPH applications represented.

Our interviewees were almost all sustainability professionals whose roles are generally concerned with achieving energy, emissions, and other sustainability goals developed by their firms. They also tended to be part of corporate organizations that provide services across business units. This contrasts with an organization within a business unit that is concerned primarily with performing job functions for that unit. As we discuss in Section 4, many of these interviewees serve key functions in their organization for evaluating IPH decarbonization and provide a mediating role for the firm overall. Given that at the time of writing the United States lacks any national targets for non-fossil fuel IPH [51], these firms could be considered lead users [71] based on their anticipation of needing to reduce onsite combustion emissions and thus may provide valuable information for IPH decarbonization. Statements from several interviewees indicated that they were indeed anticipating the need to reduce or eliminate emissions from IPH operations (i.e., scope 1 emissions [72]) and have already adopted and implemented IPH decarbonization technologies.

Our interview questions focused on three primary areas: (1) identifying and characterizing process heating demands, including fuels, temperature requirements, heating processes; (2) describing the organizations, drivers, barriers, and metrics of alternative IPH

[4] Because we are also exploring the possible misalignments between different organizations in the same company, we asked interviewees for additional contacts in other corporate or business unit organizations. This was not as fruitful as had hoped and there was a general reluctance on the part of interviewees to connect us with colleagues that were outside of their own organizations, especially for individuals that are directly responsible for production activities. We were, however, able to interview multiple people from three companies, as indicated in Table A1.

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technology adoption; and (3) describing the process of implementing an alternative process heating technology, including evaluation metrics, barriers, benefits, and organizations involved. We specifically devised interview questions (included as Appendix B) with the theories of configurational technologies [46,47] and organizational-technology mutual adaptation [3] in mind, which we describe in Section 2.2 and Section 2.4, respectively. As a result, we were purposeful about collecting information on how organizations within firms approached the adoption and implementation of alternative IPH technologies, including the exchange of information between the companies as users and their equipment and services suppliers.

3.2 Document analysis of local IPH regulations

We complement our industry interviews with an analysis of public documents related to California's South Coast Air Quality Management District's (South Coast AQMD) recent amendments to Rule 1153.1 [73]. In November 2014, Rule 1153.1 was first adopted to establish limits of nitrogen oxides (NOx) and carbon monoxide (CO) emissions from commercial food ovens, roasters, and smokehouses [74]. In 2021, South Coast AQMD staff began developing proposed amendments to the Rule that would require transitioning to zero-emission technologies (i.e., electric ovens) where feasible. Although the Rule amendments address emissions of local air pollutants and not greenhouse gases, the general approach to meeting proposed zero-emission limits is similar to some decarbonization pathways as it would involve either retrofitting or replacing natural gas IPH technologies with electric technologies. The South Coast AQMD ultimately abandoned the zero-emission limits for several commercial oven categories, due in part to what we identify as configurational features of IPH technologies. In Appendix C we include a list and brief summary of the documents we coded and analyzed using Taguette [70].

4 Results

Although the interviews reflected the fact that most of the individuals had identified various user requirements and contexts for an alternative IPH technology, they were not yet in a formal adoption process, let alone engaged in implementing an alternative. These interviews are bolstered by our analysis of documents related to proposed amendments to South Coast AQMD Rule 1153.1, which provides additional insights into the configurational nature of IPH technologies, as well as potential implications for decarbonization policy.

We have synthesized results of our interviews and document analysis and organized this section according to the features of configurations that distinguish them from generic technologies (i.e., lack of identity, lack of systematicity, and uncertain system dynamics) and the implementation of alternative IPH technologies. Table B1 in Appendix B shows which features of configurational technologies were reflected in each interview.

4.1 Lack of clear identity

> …the company as a whole has embraced the understanding that, like, we're moving away from traditional fossil fuel generated heat, right, and understanding [what] is

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> the best way to do that and it's a very local and a very site specific answer to that question based on local resources and local things…(Interviewee A8).

The most apparent configurational feature of IPH technologies is their lack of clear identity, which is a function of fundamental technical and organizational characteristics. From a technical perspective, the lack of a clear identity begins at levels as basic as an energy carrier, required temperature, and heat transfer mechanism, as we discuss in theory in Section 2.3. Although it is true, as shown in Figure 1, that the use of natural gas was nearly universal for the represented companies, this energy carrier is used for many different functions, each of which comes with its own set of technical performance requirements, such as temperature.

When considering alternative IPH technologies, however, this sole identifying characteristic disappeared. Nearly every interviewee indicated their organizations were aware of, or actively evaluating, multiple energy carriers or end-of-pipe options for decarbonization. These included solar thermal, geothermal, electrification, green hydrogen, renewable natural gas, biomass, small modular nuclear reactors, thermal energy storage, carbon capture and sequestration, and heat as a service.

The number of potential decarbonized IPH technologies leads to a combinatorial effect for user requirements. Even when an alternative IPH technology involves only a fuel switch (e.g., from natural gas to renewable methane) and no equipment changes, firms may require the new fuel be available with long-term delivery contracts and be certified zero-carbon under a trusted verification process. Similarly, a firm that seeks to become solely a purchaser of heat without any responsibility for capital equipment (i.e., heat as a service) may require additional assurances for their production and finance organizations regarding the technical characteristics of the heat and the elements of the leasing agreement, respectively. As A6 indicated,

> If they start offering [heat as a service], the next challenge is going to be to get our industrial team and our financial team to actually approve of that model because it's very intimidating from an industrial perspective to leave this, like extreme—this absolutely fundamental part of your business to somebody else and just trust them to do it right.

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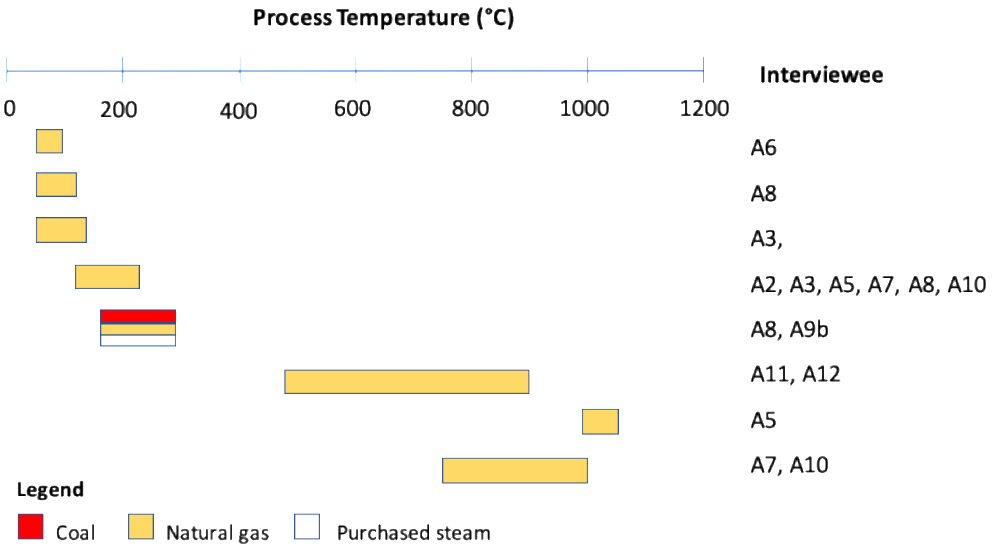

Figure 1 Summary of typical process temperatures and associated combustion fuels mentioned by interviewees for IPH demands. Figure adapted from [75]. Typical process temperatures from [75] and interviewees.

As one engineer put it in response to the South Coast AQMD's proposed rule amendments, "there is more to baking than just the baking temperature" [72: 4]. The importance of user requirements was recognized over time by the regulatory staff themselves, who identified that each baked product required a unique set of qualities (e.g., appearance, texture, and taste) that was created by a specific combination of oven and burner types [73]. As an extreme example of unique user requirements, one firm commented that producing a specific brand of English muffins required them to use a proprietary oven design that cannot be replicated by competitors [76].

User requirements for IPH technologies are defined by a large number and variety of internal organizations. Adoption decisions may incorporate requirements from that span production, site maintenance, safety, sustainability, compliance, and corporate management functions, as identified in Table 1. However, requirements from different organizations may carry different weights. The sustainability organization may not have a formal role in the IPH adoption processes and can act only as an "influencer" of other organizations. On the other hand, sustainability requirements may come directly from a firm's corporate leadership. In this case, there may be additional support and motivation to adopt decarbonized IPH technologies.

The lack of identity for IPH technologies is also the result of external groups directly or indirectly influencing user requirements and shaping local contexts. One of the clearest examples we encountered in our interviews was the influence of grants and taxes created by national and sub-national governments in shaping the relevant IPH technologies for a facility. Interviewee A7 was frank about this influence on switching from natural gas to zero-carbon electricity at one of their facilities, saying that "… we are getting an incentive to help balance out the OpEx and we're avoiding paying a carbon tax…[i]n areas where we can

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do it, because we have lower electricity prices, we are avoiding carbon tax, and we can balance the economics—then it makes sense. Currently that does not exist in the United States."

Table 1 Summary of interview observations related to organizations and user requirements associated with adoption and implementation of IPH technologies.

Organization or User Requirements		**Observation**
Organizations	Internal	Corporate sustainability, site sustainability, corporate engineering, site engineering, site safety, site maintenance, site production, product quality, purchasing/procurement, site facilities, corporate leadership, contracting
	External	State and federal governments, competing peer firms, non-competing peer firms, maintenance contractors, insurance providers, equipment suppliers, engineering consultants, customers, local utilities, industry trade groups, non-governmental organizations (e.g., Renewable Thermal Collaborative, Science Based Targets), site tenant companies, national laboratories, Better Plants®
User Requirements: Non-technical		Site and corporate sustainability goals, minimum capital expenditure requirements, safety requirements, operational continuity, financial metrics (e.g., minimum simple payback period), air permitting regulations, emissions trading regulations, green fuel certifications, customer interest in zero-carbon products, government subsidies, utility rebates, energy carrier prices, long-term energy supply contracts, likelihood of extreme weather events, community acceptance, familiarity with technology, backup/redundancy
User Requirements Technical		Temperature, humidity, reliability, controllability, burner design, availability of renewable resources/energy carrier, space constraints, emissions intensity of energy carrier.

Several interviewees discussed user requirements for electric IPH technologies. These included requirements for their local utilities, such as a zero-carbon generation mix or generation that can be secured by a physical power purchase agreement. Several interviewees also mentioned that the utility at certain sites was unable to service the expected load from IPH electrification, representing both generation capacity and transmission and distribution constraints. Servicing a large increase in load could require costly infrastructure buildout, which could result in the technology not meeting the firm's financial requirements. As a case in point, Interviewee A5 mentioned that costs to build new infrastructure contributed to ruling out adopting an electric boiler. Additionally, some form of onsite energy storage may be identified as a critical user requirement depending on the intermittency of the generation source, the firm's tolerance for potential disruptions to operations, and the facility's typical operating schedule.

In the context of commercial bakeries in the South Coast AQMD, the finding of increased loads leading to additional concerns was echoed by industry representatives, as well as the South Coast AQMD staff. A substantially increased facility load could result in requirements for new safety training and personnel, electricity service upgrades for facilities, and additional utility transmission and distribution infrastructure [76–79]. South Coast AQMD staff disagreed with the position of several industry representatives that the utilities serving commercial bakeries would not be able to meet increased demand from newly-electrified baking ovens, but agreed that increased electricity use was a challenge for the proposed Rule amendments [73].

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Adopting and implementing hydrogen as an IPH alternative could be seen as an even more explicit example of how technical and nontechnical requirements contribute to a lack of clear identity. According to Interviewee A5, hydrogen could be blended up to 40%[5] with natural gas in their operations before triggering additional requirements. Past this point, internal and external organizations responsible for air permitting would require re-evaluating and potentially changing air permits for increased NOx emissions; engineering organizations would require installing all new piping to distribute hydrogen without leaking; safety organizations would require new safety procedures given the different properties of hydrogen; and other engineering organizations would require evaluating the switch from natural gas burners to hydrogen burners.

Technical and organizational requirements can interact in other ways, as we observed in case of the requirement to avoid disrupting production. This was not a universal requirement across users and instead appeared to be the outcome of a co-construction of organizational and technical features that reflected, for example, the type of production processes, standard practices, and existing pilot production equipment.

At one end of the spectrum, we found firms like those of Interviewees A6 and A9b who, according to the interviewees, required that an alternative IPH technology be implemented with little, if any, disruption to production. Interviewee A6 indicated the organizational requirement to avoid any production disruption was significant: “we’re under so much pressure when it comes to production that if you give me a solution that requires the factory to shut down for a week, you have not given me a solution.”

At the other end of the spectrum, firms may be familiar with the regular practice of temporarily shutting down operations if a product cannot be produced at a profit. There may also be organizational support that permits stopping production for a commissioning period to identify and fix any problems with a new technology before resuming regular production (i.e., fix it before living with it). A firm may also have technical capabilities to preemptively identify production issues, such as of laboratory facilities and pilot production lines, where a new technology can be tested and have its kinks worked out at smaller scales before being scaled up for production.

Much of our discussion of user requirements and site-specific contexts of IPH has assumed that an alternative technology would be adopted to retrofit an existing operational facility. This lends a degree of path-dependence to the adoption process, not only in terms of the physical infrastructure inside and outside of the facility, but also the established practices and other organizational features of the facility. There may be a general discomfort with alternative IPH technologies on the part of facility maintenance and utility organizations. These groups have knowledge and established procedures for traditional fossil fuel technologies and may either become redundant, or may be retrained to develop new knowledge and procedures for alternative technologies.

[5] Interviewee A5 did not say if this was on an energy or volume basis.

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Adopting an alternative IPH technology to decarbonize a greenfield facility may avoid some of these path-dependencies. While discussing the challenges that come with the age of their facility, Interviewee A6 explained how contexts of decarbonizing IPH with an electric boiler differ between a greenfield facility and their own existing facility:

> So, for example, companies that put in electric boilers, they're normally building a new factory. They attach the factory to a really big power purchase agreement [PPA] and the PPA then offsets the electricity that they use in those boilers. So, all of a sudden they're raising all of their heat, basically without carbon. That would be an extremely difficult transition for us.

4.2 Lack of systematicity

> I mean, every plant is different because it makes different products. It has different configurations and it might have different technologies. You might have different ages and so you have to look at it a plant at a time in order to determine what's the best transformation or change that you need to make (Interviewee A12).

The lack of a clear identify for an alternative IPH technology feeds into the lack of systematicity, an underlying standard plan of how the system components relate and integrate. As established in our discussion about the wide range of user requirements and contexts, a firm cannot formulate an alternative IPH technology prior to having this information (i.e., it is not possible to flick a switch to a decarbonized alternative). Interviewee A7 discovered it was not possible to retrofit its existing natural gas process with electric heating because the electric alternative could not meet process temperature requirements. Instead, the electrified alternative for the facility took the form of a new process.

The technology-forcing aspect of South Coast AQMD's proposed Rule amendments aimed to standardize electricity as the zero-emission technology for bakery ovens. However, the other components of these configurations remained unclear. This lack of systematicity was tied to existing electrical load at the facility, types of products produced, production rates, and even the knowledge embodied in product recipes. Given that these recipes had been tailored over time to the specific characteristics of existing ovens that are largely heated by natural gas combustion, it could be challenging to replicate the same product qualities with an electric oven [76]. In this case, firms would need to test new recipes and generate new knowledge for all-electric baking, which would then be integrated into the new IPH configuration.

Additionally, due to the high price of electricity relative to the price of natural gas, the costs of nearly half the equipment categories of electric baking ovens estimated by South Coast AQMD staff exceeded their cost-effectiveness threshold [73]. To potentially reduce these costs, the staff evaluated adding components of solar photovoltaics or fuel cells to the baking oven configuration, but costs remained above the threshold. These oven categories were ultimately excluded from the zero-emission requirement.

The firms we interviewed varied in their efforts to address the lack of systematicity and we heard a range of motivation and abilities among sustainability organizations in their search

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for alternative IPH technologies. In some cases, sustainability organizations and their firms were beginning to formalize the set of information and the mediation process after adopting and successfully implementing an alternative IPH technology. However, even with this formalization, the resulting IPH configurations still required information on the various technical and organizational requirements and local contexts.

Overall, our interviews reveal that sustainability organizations are challenged by the lack of systematicity of IPH technologies. Several interviewees explicitly acknowledged that there was no obvious alternative and even if there was, it might not be applicable across all the firm's facilities. This meant that multi-faceted approaches would be needed based on facility-by-facility evaluations. The time and effort required for these evaluations can be a source of frustration, which Interviewee A6 expressed as

> Can't you [the DOE's national laboratories] just give us the answer? Guys like me, do each of us need to discover this for ourselves? Can't you just put out a paper that says, hey, if you've got a natural gas boiler that's giving you, like, this temperature steam, the best way to decarbonize is by following these five steps, and it's obviously more difficult than that, but that would be the hope.

4.3 Uncertain system dynamics

> I'll say there's a bias to looking for partnerships and sort of buying decarbonized energy in the future as opposed to buying the equipment that does it ourselves (Interviewee A9b).

> So, we actually, you know, one of the challenges again with the heat pump for us is the temperature requirements, so ours is a high temperature process and high temperature heat pumps do not exist at the values we need so we are working with suppliers to design them (Interviewee A7).

Given the current lack of clear identity and systematicity, it is not surprising that development of alternative IPH technologies was uncertain for the interviewees. Our discussions indicated that firms were focused on different development paths, as reflected in the two quotes above. This leads to an overall impression of uncertain system dynamics (i.e., "an inherent logic which strongly structures development over time"[47: 17]).

The first quote describes one firm's passive approach to development, based on the interviewee's opinion that decarbonizing IPH was not a problem for an individual facility or firm to solve, but for the broader chemical industry to address, given the shared nature of the challenge. This sentiment also reflects the preference for an incremental approach to IPH decarbonization that focuses on energy efficiency and heat recovery measures that meet aggressive financial requirements, as opposed to transformational changes to IPH systems themselves.

The second quote reflects a more proactive approach to engaging with technology developers. It is worth highlighting because the firm is taking their user requirements directly to suppliers to have them integrated with suppliers' technical knowledge. A firm's trust that a technology developer understands their requirements may be necessary for

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Fleck's [47] fundamental implementation equation (i.e., successful implementation is equal to the sum of generic technology knowledge and local practical knowledge) to hold. When asked about their most- and least-trusted sources of information about IPH technologies, Interviewee A7 responded,

> So, the most trusted source is usually suppliers we've worked with, so, and it's really our central engineering teams and making sure that they have—they believe in what's being proposed to us. … So, it really is building the confidence of our internal teams, and by that we work and partner with, you know, these external companies, work with their engineers to get—to get that knowledge.

Relationships with technology developers were also discussed in the context of South Coast AQMD rule amendment, particularly because certain types of electric ovens were not commercially available [76,77]. Developer-owned test kitchens, where bakeries would attempt to replicate existing product characteristics using developers' novel technologies, were identified as one approach for technology development [73].

South Coast AQMD staff also preferred a more fundamental change for commercial oven development than at least one industry representative. The American Bakers Association argued for a stepwise approach, where natural gas ovens would transition to natural gas-electric hybrid ovens before implementing all-electric versions [80]. However, this development pathway did not align with the regulator's requirements. South Coast AQMD staff ultimately rejected using incremental technologies, such as gas-electric hybrid ovens, because they viewed these interim technologies as potentially delaying development and commercialization of zero-emission ovens [73].

4.4 Alternative IPH implementation

Interviewees from two firms (A7 and A10, and A8) had adopted and implemented an alternative IPH technology for decarbonization. Although discussions of technology implementation were much more infrequent than those for user requirements, we noted some evidence of implementation shaping organizations (i.e., the mutual adaptation of technology and its user environment [3]).

With Interviewee A7 we identified one example of a delivery system alignment and learning by trying. Knowledge gained during their first IPH electrification project enabled engineers to make an improvement to the subsequent configuration. Note that this improvement—the removal of natural gas backup—could be considered a large cycle adaptation. It is also consistent with the concept of technology development via innofusion, where learning during implementation is directly transferred to a subsequent configuration (i.e., by removing a component):

> I know to electrify our plants, it was, you know—our engineers took almost two years of, "okay, is this gonna work for us?" … and once they've vetted something, you know, it gives us the confidence. In the first electrification project, you know, it's not just straight electric. They actually install[ed] the capability of both electrical heating and natural gas heating as a backup, but the subsequent electrification

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project they realized, “OK, we're confident with the electric heating elements. We no longer need the backup”.

We identified two examples of delivery system misalignments and subsequent small adaptation cycles based on our discussion with Interviewee A8. The firm realized that their existing practices for water treatment for operating fossil fuel boilers did not meet the more stringent requirements for electric boilers to avoid scaling and corrosion. The firm then worked with the boiler supplier and a water treatment vendor to provide support for chemical and physical treatment of boiler feedwater. Similarly, maintenance personnel at the facility were not trained to work on high voltage equipment and the company decided to outsource boiler maintenance as a result.

Learning by trying is not limited to overcoming organizational and technical challenges. It may be the case that unanticipated benefits of a technology are discovered during implementation, which uncovers new pathways for innovation. In the case of implementing electric boilers, Interviewee A8 indicated that facility staff discovered that the boilers can be operated more flexibly and efficiently to match production cycles than the traditional natural gas boilers. It may also be the case that implementation reveals that a new technology is more aligned with an organization’s performance criteria. This also occurred for electric boilers, whereby maintenance staff found out that they were simpler and quieter to operate than traditional boilers.

5 Discussion: reframing decarbonizing industry

Our analysis reveals the insights of individuals who, along with others in their sustainability groups, are at the junction of building IPH configurations. This research is an initial indication that firms mediate a multitude of nontechnical and technical requirements within potentially unique local contexts to adopt and implement alternative IPH technologies. Incorporating these user requirements and contexts can be critical for the success of decarbonized IPH technologies. Yet, they may be difficult to standardize and may lead to uncertainty in developing new IPH configurations. How firms and policies identify and address the configurational features of IPH technologies has implications for decarbonizing IPH and thus decarbonizing industry.

5.1 Moving to a user perspective: industrial heterogeneity

U.S. industrial decarbonization strategies often identify the heterogeneity of industrial processes, especially related to IPH, as a challenge for decarbonization [7,8,53]. This heterogeneity is described in terms of the technical aspects of how different subsectors use heat, as well as where facilities are located and their physical layouts. Our interviews and document analysis confirm the variety of technical requirements and contexts for industrial users. However, as summarized in Table 1, there are also numerous non-technical requirements and internal and external organizations that can be involved with adopting and implementing IPH technologies. Organizational and technical features can also interact to create unique user contexts, as in the case of firms’ different capabilities for avoiding disruptions to production from implementing new IPH technologies.

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One typical approach to addressing the challenges posed by technical heterogeneity is to develop "crosscutting" technologies. Crosscutting can be defined as "[t]echnologies, approaches, knowledge management, and infrastructure that are developed or deeply used in one energy production or demand sector could benefit others, resulting in synergies that amplify benefits, leverage resources, reduce costs, speed adoption, improve system efficiency, and conserve resources" [8: 10]. The crosscutting framing of technology is a prominent feature in not only national decarbonization strategy [7,8], but also in scientific literature [28–30].

The crosscutting framing of IPH technologies reflects features more closely associated with a generic technology (e.g., a common, identifiable use; requiring only incremental adjustments to fit a new application) than a configurational technology. Although process heat may be a common energy service that cuts across many different industries, IPH technologies are adopted and implemented under organizational and technical contexts that can be unique to individual facilities. By focusing on technical heterogeneity and not industrial users, current industrial decarbonization strategies may also miss opportunities to accelerate decarbonization. IPH users must not only mediate their unique requirements and contexts in the adoption process, but also work with technology developers for successful implementation. Although the South Coast AQMD Rule amendments reduced technical heterogeneity by forcing electric baking technology, for some users successfully implementing this technology may require close collaboration with technology developers.

A user perspective could help accelerate industrial decarbonization by decoding and standardizing the processes for successful adoption and implementation of alternative IPH technologies. Essentially, this user perspective could develop crosscutting decision-making for IPH across multiple technologies, as opposed to a focus on developing crosscutting technologies. This could be pursued by developing decarbonization strategies that address such questions as

- how to assist firms with navigating the organizational and technical requirements in their unique user contexts?
- how to standardize the processes by which these user contingencies are successfully mediated as an alternative IPH configuration?
- how to share knowledge of the innovations that emerge during implementation (i.e., learning by trying)?

We identified in our interviews that one firm had standardized their process for systematically evaluating alternative IPH technologies for their individual facilities. The success that this firm and any others have had with navigating the processes of adoption and implementation could be used to construct a guidebook for other firms and for technology developers. By standardizing the process for gathering this information, firms may begin to crystallize various user requirements for alternative IPH technologies. As indicated by our interviews, however, firms' willingness to voluntarily share knowledge of successful IPH decarbonization with other firms depends on the degree to which they perceive the knowledge as a competitive advantage.

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5.1 Moving to a user perspective: potential policy implications

It is useful to consider the potential implications of the configurational nature of IPH technologies for demonstration upscaling given the emerging emphasis on technology demonstration and deployment projects in the United States. Unlike generic technologies, user requirements for IPH are mediated as essential parts of adoption and implementation processes. As a result, effective demonstration and deployment policies for IPH technologies may need to be designed differently than those that require far less information about users and their local contexts (i.e., solar photovoltaics and onshore wind turbines [46]).

Bossink et al. [22] identify factors for supporting the upscaling of clean energy technologies from demonstration project to more general and widespread use. Several of these factors may be affected by the essential need for IPH technologies to consider unique user requirements and contexts and uncertain system dynamics, including coordinating the flow of demonstrations through technology portfolios, creating complementary technologies and infrastructure, and developing economies of scale through learning and benefits standardization.

In the case of technology portfolios, it may be critical to include the types of user requirements and contexts we identified during our interviews (Table 1) in order to represent a sufficiently wide range of IPH instances. Such was the need for firms that were considering adopting early solar IPH technologies. These users preferred a larger number of small demonstration projects under a wide range of applications to a small number of large demonstration projects [81].

The South Coast AQMD staff's experience can also be seen as reflecting the need to include a wide range of user contexts as part of a technology portfolio. Staff initially expressed confidence that over time existing restaurant-sized electric ovens could be scaled up for use by commercial bakeries [73], a characteristic consistent with generic technologies. Yet, of the 224 commercial food ovens and roasters originally identified to meet zero-emission standards by 2030 [82], only 57 are slated to meet these standards in the final amended rule [73]. The anticipated cost of electricity cited as one reason for removing emissions limits, as was the "uncertain technical feasibility" of certain categories of electric baking ovens [73: 2-32] that reflected unique user requirements. Had the staff's technology assessment been premised on understanding the extent and significance of unique user requirements and not on collecting solely techno-economic information, then perhaps a more appropriate scope of ovens would have been initially identified.

The configurational nature of IPH technologies may underscore the upscaling factor related to creating complementary technologies and infrastructure. The requirement that local infrastructure deliver not only a sufficient quantity of an alternative energy carrier, but also that the energy carrier be verified zero-carbon was frequently mentioned in our interviews, as well as documents related to the South Coast AQMD Rule amendments. Both examples of successful implementation of electrified IPH from our interviews discussed how the firm collaborated closely with the local utility and how the utility could provide sufficient zero-carbon electricity to the facility at an acceptable price. Conversely, industrial

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firms responded to the proposed South Coast AQMD rule amendments with concerns about equipment and other infrastructure needed to meet increased facility load and did not indicate they were coordinating with their local utility.

Regarding the scaling factor of creating economies of scale, configurational technologies are characterized by different learning dynamics than generic technologies. This is captured in the differences between the more radical learning by trying and the more incremental learning by doing and learning by using. Interviewees discussed how pilot production lines and other in-house capabilities were used during the implementation process for new technologies. Likewise, external equipment testing facilities may be helpful for bridging the adoption and implementation processes of industrial firms with the development process of IPH equipment suppliers. Although the South Coast AQMD discussed how test kitchens were available and could support technology development, there was no indication that policy could play a role in creating and promoting test facilities, as had been done internationally to establish the performance and reliability of domestic heat pumps [83].

Fleck stated that policy for developing configurational technologies should recognize that "industry is the laboratory" [69: 651]. Only time will tell if the experiences of firms participating in recent demonstration and deployment programs will translate into more widespread adoption and implementation of decarbonized IPH configurations.

6 Conclusions

By exploring IPH adoption and implementation processes through interviews with industrial firms and document analysis, we find that due to the largely configurational nature of IPH technologies it could be essential for accelerating decarbonization to establish a new, crosscutting user-centered approach to address the extent and necessity of user requirements and contexts. This exploratory study uncovered multiple technical and nontechnical user requirements and contexts (Table 1) relevant to the adoption of IPH. Information on user requirements and unique local contexts are at the core of distinguishing configurational technologies from their opposite, i.e., generic technologies. These sets of information are necessary inputs to processes that determine the identity of an IPH technology and its technical and nontechnical components. The need to adapt IPH technologies to such a diverse combination of user requirements and local contexts underscores their configurational nature.

We conclude that efforts to decarbonize industry could benefit from reframing the current focus on technologies and technology developers to a more user-centric perspective. Focusing on the technical aspects of decarbonization technologies misses the need to also incorporate the unique nontechnical user requirements and local contexts for successful adoption and implementation of alternative IPH technologies. Additionally, the processes of technology adoption and implementation may offer unexplored opportunities to develop identity, systematicity, and more certain system dynamics that may help accelerate industrial decarbonization. The learning by trying that has occurred with successful implementation of alternative IPH technologies has led to improvements in subsequent

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configurations and has indicated the role of technological and organizational co-adaptations in making those configurations a success.

This work is exploratory and does not represent the full spectrum of industrial users in the United States. We conducted a relatively small number of interviews relative to the size and variety of industrial firms in the United States. The experiences and opinions reflected in these interviews therefore represent a thin slice of the organizational activities and technologies related to IPH. A much more extensive interviewing effort would help build up the understanding of intra- and interindustry comparison of the processes that firms undergo to adopt and implement alternative IPH technologies.

A challenge for this research and any follow-on is that we simply do not have many examples of industrial firms in the United States that have completely decarbonized their IPH. Future work could provide additional insights into the mediation processes of IPH adoption by interviewing representatives from other firms and in other industries, particularly small and medium-sized enterprises. Ultimately, firms' involvement in recent demonstration and deployment policies may offer new opportunities to greatly expand socio-technical analysis and reveal new avenues to accelerate industrial decarbonization.

7 Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to develop the title based on an earlier abstract. After using ChatGPT, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix A: Interviews conducted

Table A2 Summary of interviewee industry, general position, type of organization, and job function

Interviewee	Industry	General Position	Job Function
A1[1]	NA	NA	NA
A2	NAICS 326 Plastics and Rubber Products Manufacturing	Vice President	Sustainability
A3*	Multiple[2]	Manager	Sustainability
A4*	Multiple[2]	Engineering manager	Data center
A5	NAICS 325 Chemical Manufacturing	Engineer	Works with many facilities
A6	NAICS 311 – 312 Food and Beverage Manufacturing	Manager	Sustainability
A7**	NAICS 327 Nonmetallic Mineral Product Manufacturing	Manager	Works with many facilities on sustainability
A8	NAICS 311 – 312 Food Manufacturing and Beverage Manufacturing	Manager	Environment and sustainability
A9a***	NAICS 325 Chemical Manufacturing	Environmental affairs	Climate
A9b***	NAICS 325 Chemical Manufacturing	Engineer	Sustainability
A10**	NAICS 327 Nonmetallic Mineral Product Manufacturing	Manager	Sustainability and energy
A11***	NAICS 325 Chemical Manufacturing	Fellow	Energy efficiency, water, decarbonization
A12	NAICS 325 Chemical Manufacturing	Director	Sustainability

Footnotes:

*, **, *** denote interviewees that work for the same company (e.g., A3 and A4 work for the same company).

[1] Interviewee declined to either have their interview recorded, or to respond to interview questions in detail.

[2] The largest process heating operations are associated with a business unit in Food Manufacturing (NAICS 311).

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Appendix B: Interviews and configurational features

Table B3 Summary of interviewees and where shaded cells indicate when interview responses were consistent with configurational aspects of industrial process heat technologies.

Interviewee	Industry	Lack of Identity	Lack of Systematicity	Unclear System Dynamic
A1[1]	NA	NA	NA	NA
A2	NAICS 326 Plastics and Rubber Products Manufacturing			
A3*	Multiple[2]			
A4*	Multiple[2]			
A5	NAICS 325 Chemical Manufacturing			
A6	NAICS 311 – 312 Food and Beverage Manufacturing			
A7**	NAICS 327 Nonmetallic Mineral Product Manufacturing			
A8	NAICS 311 – 312 Food Manufacturing and Beverage Manufacturing			
A9a***	NAICS 325 Chemical Manufacturing			
A9b***	NAICS 325 Chemical Manufacturing			
A10**	NAICS 327 Nonmetallic Mineral Product Manufacturing			
A11***	NAICS 325 Chemical Manufacturing			
A12	NAICS 325 Chemical Manufacturing			

Footnotes:

*, **, *** denote interviewees that work for the same company (e.g., A3 and A4 work for the same company).

[1] Interviewee declined to either have their interview recorded, or to respond to interview questions in detail.

[2] The largest process heating operations are associated with a business unit in Food Manufacturing (NAICS 311).

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Appendix C: Interview questions

1. What is your job function?

2. How long have you been in your position? With the company?

3. What types of products does your facility/facilities produce?

4. What are the major heating processes in your overall production process (drying, heat treating, cooking, etc.)?

5. In the past have there been any significant changes made to these heating processes (equipment replacement, retrofits)?

    a. Who was involved in those changes (departments, people)?
    b. Why were the changes made?
    c. Were there any metrics used (e.g., financial, operational, other) to evaluate the changes? If so, what were they?
    d. In your opinion, were there any difficulties or problems in operations after the changes?
    e. In your opinion, were those difficulties expected or unexpected?
    f. In your opinion, who solved the problem(s) and how were they solved?

6. Who is involved when repairs or adjustments to the heating process equipment are needed?

7. What fuel(s) is currently the main source of heating used in your processes?

8. Do you have contracts in place for delivery of those fuels? If so, how often are they renegotiated?

9. Do you personally know of any other companies in your industry or other industries that are either evaluating or adopting alternative sources of process heating?

10. In your opinion, do you think your processes should or should not switch from the current fuels used providing heat to alternative sources? Why?

11. Do you know of any alternatives fuels or alternative technologies for providing heat to your processes? What are they?

12. In your opinion, who or what would be your **most** trusted sources (internal or external [suppliers, other companies]) for information about heat alternatives?

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13. In your opinion, who or what would be your **least** trusted sources (internal or external [suppliers, other companies]) for information about heat alternatives?

14. How would you evaluate an alternative source of heat for your production process?

    a. What types of metrics would you use?
    b. In your opinion, what are your main goals for using metrics?
    c. In your opinion, what are the most important performance considerations for an alternative?
    d. What information or data about the existing heating and/or production processes would be required for an alternative system?
    e. Who or which departments would be involved in selecting an alternative?
    f. Who or which departments would be involved in integrating the alternative into the facility?
    g. In your opinion, who or which department is ultimately responsible for success or failure of the alternative?

15. In your opinion, what is the biggest barrier for an alternative source of heat or using an alternative heating technology?

16. If the response to #15 is cost, if you had an alternative heat solution available that met your cost targets, what would be the steps to integrating it and using it in your facility(ies)?

17. In your opinion, what effects would you expect an alternative source of heat to have on your department, you job function, or your production processes?

    a. Do you see those as positive, negative, or neutral?
    b. How significant are the effects?

18. Given that we'd like to speak with people from environment, safety, and health/sustainability, facilities/energy managers, and production departments, who else should we interview?

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Appendix D: Document analysis of proposed amendments to South Coast Air Quality Management District Rule 1153.1

The California South Coast Air Quality Management District (South Coast AQMD) encompasses Orange County, western Riverside and San Bernardino counties, and part of Los Angeles County [1]. In November 2014, Rule 1153.1 was adopted to establish limits of nitrogen oxides (NOx) and carbon monoxide (CO) emissions from commercial food ovens, roasters, and smokehouses [2]. In 2021, South Coast AQMD staff began developing the proposed amendments to the rule, which would require transitioning to zero-emission technologies where feasible. After public feedback, working group meetings, and further analysis, proposed amendments were ultimately adopted on August 4, 2023

Table D4 List of documents in response to California's South AQMD proposed amendments to Rule 1153.1 Emissions of Nitrogen from Commercial Food Ovens [3] analyzed for characteristics of configurational technologies.

Citation	Description
[3]	Language of Rule 1153.1 Emissions of Oxides of Nitrogen from Commercial Food Ovens, amended on August 4, 2023.
[4]	Comments on the proposed amended rule by M. Scott Weaver, Principal & Practice Area Leader, Air and Climate Services for Ramboll.
[5]	Comments on the proposed amended rule by Mark Park, Corporate Compliance Manager for United States Bakery Company.
[6]	Comments on the proposed amended rule by Mark Schieldge, Chief Operating Officer of Snak-King, LLC.
[7]	Comments on the proposed amended rule on behalf of Bimbo Bakeries USA, Inc. from Joseph Steirer, Senior Engineer for Yorke Engineering, LLC.
[8]	Comments on the proposed amended rule from Rasma Zvaners, Vice President of Regulatory & Technical Services for the American Bakers Association.
[9]	Comments on the 8th working group meeting from Rasma Zvaners, Vice President of Regulatory & Technical Services for the American Bakers Association.
[10]	Presentation by South Coast AQMD officials at a public workshop on March 30, 2023.
[2]	Presentation by South Coast AQMD officials at the working group's 7th meeting on March 8, 2023.
[11]	Presentation by South Coast AQMD officials at the working group's 8th meeting on June 7, 2023.
[12]	South Coast AQMD draft staff report on proposed amended rule.

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book/Proposed-Rules/1153-1/par-1153-wgm7-presentation.pdf?sfvrsn=18 (accessed August 8, 2023).
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