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DEEP-TECH INNOVATION:
A MULTI-METHOD STUDY TOWARD
A CONCEPTUAL FRAMEWORK AND RESEARCH AGENDA

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Deep-Tech Innovation: A Multi-Method Study toward a Conceptual Framework and Research Agenda
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ABSTRACT

The term “deep-tech innovation” has attracted growing attention in research, policy, and practice, but it is applied inconsistently and lacks an agreed-upon definition. This limits cumulative knowledge building and blurs how deep-tech innovation relates to adjacent concepts. We address this gap by developing a framework that treats deep-tech innovation as a distinct object of inquiry. Using a multi-method design that combines a systematic, integrative, concept-centric literature review and semi-structured interviews with deep-tech founders, we identify twelve defining attributes structured across three levels: invention, venture, and ecosystem. At the invention level (the conceptual core), we specify six attributes: three foundational attributes that capture the scientific and technological basis of the invention, and three attributes that describe its characteristic exposure profile. The remaining six attributes capture recurring implications at the venture level (staged financing strategies, dual scientific and commercial maturation, and the multidisciplinary broadening of teams) and the ecosystem level (multi-actor interactions, specialized incubation support, and industrial de-risking and scaling partnerships). We use this framework to delineate the boundaries of deep-tech innovation, distinguish it from adjacent concepts, and propose an agenda for future research.

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Introduction

Innovations at the frontier of science and technology, such as quantum computing, fusion energy, and advanced materials, have recently been grouped under the label *deep tech*. These innovations originate in frontier research and target complex societal and technological challenges with potential broad impact (Raff-Heinen and Murray 2025). Firms have long worked with advanced technologies, but deep tech has only recently been discussed as a distinct category and is sometimes framed as a "fourth wave of innovation" (de la Tour et al. 2021). This increased attention is closely linked to the rise of deep-tech ventures – that is, startups that carry these innovations from the lab toward real-world use and face distinctive challenges in doing so (Ramge and Vera 2024). Examples include the Swiss robotics company Anybotics based on leading-edge autonomy or the green-steel startup Boston Metal in the United States (US) based on novel electrochemistry. In both cases, the work began in academic settings, and members of the research teams went on to build companies around their inventions. Deep-tech ventures typically develop within ecosystems that combine research infrastructure, specialized talent, public funding, and private investment (Budden and Murray 2025; Diamandis et al. 2025; Raff-Heinen and Murray 2025). In recent years, public and private actors have launched funding programs and specialized incubation and acceleration initiatives to support deep-tech innovation (BMWK 2023; Siota and Prats 2022; Tekic et al. 2023). Only recently, the European Union announced the Scaleup Europe Fund, a dedicated instrument to strengthen support for deep-tech startups (European Commission 2025).

In parallel with its increasing prominence in practice and policy, deep-tech innovation has also drawn increasing attention in academic research, including work on innovation processes (de Véricourt and Gurkan 2024), business models and product–market fit (Bellavitis et al. 2024), commercialization challenges (Arora et al. 2024), and corporate patent value (Krieger et al. 2024). The existing research on deep-tech innovation, however, still lacks the shared conceptual grounding needed for cumulative knowledge building. At present, there is no commonly accepted understanding of what counts as *deep-tech innovation* and how it should be defined as an object of inquiry – that is, an *epistemic object* (Rheinberger 1997). This reflects a recurring problem in innovation research: new phenomena are introduced under labels that remain conceptually thin and contested (Appio et al. 2021; Downs and Mohr 1976; Garcia and Calantone 2003; Varadarajan 2024). Similar conceptual ambiguities have been reported for concepts such as digital technology (Appio et al. 2021), smart products (Raff et al. 2020), business models (Foss and Saebi 2016), design thinking (Micheli et al. 2018), and the concept of innovation itself (Garcia and Calantone 2003; Varadarajan 2024). Because management research is cumulative, "standing on the shoulders of prior knowledge", progress depends on shared agreement about the defining attributes of a concept, clear specification of its boundaries, and explicit distinction from adjacent concepts (Bacharach 1989; Furman and Stern 2011; Garcia and Calantone 2003; Sutton and Staw 1995). These conditions are not met in current work on deep-tech innovation, and conceptual ambiguity prevails.

First, the literature does not agree on the *defining attributes* of deep-tech innovation. Existing work proposes divergent conceptualizations, sometimes developed on an ad hoc basis, and offers no shared agreement on the conceptual core of the concept (de Apodaca et al. 2022; Myers and Albats 2024; Priego et al. 2025; Romasanta et al. 2021). Some accounts treat deep-tech innovation mostly as a relabeling of technology-intensive ventures or emerging technologies (Myers and Albats 2024; Siegel and Krishnan 2020) or define it by reference to the underlying technologies. Others describe it as a distinct category grounded in breakthrough science and engineering (de Apodaca et al. 2022), long development cycles, and intertwined technological and commercialization risks (Priego et al. 2021; Raff et al. 2024).

Second, the literature is unclear about the *scope* and *boundaries* of the concept. Existing work tends to conflate analytically distinct dimensions of deep-tech innovation, for example, by blurring its core (what it is) with organizational and systemic aspects (how it emerges and behaves). For instance, the need for specialized venture capital is frequently cited as a defining attribute (Kask and Linton 2023; Schuh and Hamm 2022; Siota and Prats 2022), even though it arguably reflects downstream consequences of the invention's asset-heavy profile and long development timelines (Romasanta et al. 2021; Wareham et al. 2024). For theoretical knowledge building on deep-tech innovation, it is thus important to distinguish its conceptual core from its implications, the vehicles through which it is advanced, and the systems from which it emerges (Goertz 2006; Podsakoff et al. 2016).

Third, ambiguity about the defining attributes and boundaries of deep-tech innovation is compounded by the lack of a clear *distinction from adjacent concepts*. Several other concepts overlap with deep-tech innovation in important ways, including high tech, academic spin-offs, radical or breakthrough innovation, and digital innovation (Chandy and Tellis 1998; Storey and Tether 1998). Although each of these captures selected aspects of deep-tech innovation, none reflects the specific combination of attributes that jointly characterize it as a distinct phenomenon. For this reason, it requires separate conceptual treatment (Cabanes 2025).

These forms of ambiguity create several risks for the nascent research stream on deep-tech innovation (Podsakoff et al. 2016). Without a clear and shared conceptualization, misclassification becomes more likely. Some innovations may be labeled as "deep tech" even if they do not reflect its defining attributes, whereas others may be overlooked despite fitting those attributes. This reduces the comparability of research findings, increases the chance that new research simply repeats earlier work, weakens explanatory power, and limits cumulative knowledge building (Garcia and Calantone 2003). Additionally, conceptual ambiguity makes it harder to transfer and integrate evidence from research on adjacent concepts because it remains unclear how deep-tech innovation differs from them and when findings from those areas apply (Chandy and Tellis 1998; Phene et al. 2006; Shane and Ulrich 2004). Lastly, the absence of conceptual clarity makes it difficult to link deep-tech innovation systematically to existing theory in innovation management and related fields, which limits its integration into scholarly debates (Suddaby 2010; Yadav 2018).

These gaps need to be addressed if research on deep-tech innovation is to develop cumulatively. Such progress requires concepts that are clearly defined, consistently identifiable, and treated as stable objects of inquiry (Garcia and Calantone 2003; Goertz 2006; Podsakoff et al. 2016; Rheinberger 1997). We therefore aim to conceptualize deep-tech innovation and distinguish it from adjacent concepts in innovation research. On this basis, our work follows three guiding questions:

1) *Which defining attributes constitute the conceptual core of the deep-tech innovation?*
2) *What implications do these defining attributes have at the organizational and systemic level?*
3) *How can deep-tech innovation be distinguished from adjacent concepts?*

To address these questions, we combined a systematic, integrative, concept-centric literature review of 35 sources drawn from peer-reviewed research as well as selected practitioner and policy outlets, 17 semi-structured interviews with deep-tech founders, and a final conceptual consolidation workshop to synthesize the attribute set into a layered framework (Tranfield et al. 2003; Webster and Watson 2002).

Ultimately, our study produces a conceptual framework of deep-tech innovation that specifies twelve attributes across three analytical layers by distinguishing (a) six attributes that specify the conceptual core (the deep-tech invention) from (b) three venture-level and (c) three ecosystem-level attributes that capture recurring organizational and systemic requirements and dependencies. The framework is then used to delineate conceptual boundaries relative to adjacent concepts and to derive a structured research agenda for future work.

For research, the framework establishes a common conceptual foundation that enables more consistent theorizing and empirical work. In addition, ecosystem stakeholders may use it to coordinate support activities, structure programs better, and communicate more effectively across diverse actors. For policymakers, the framework offers a consistent classification language for deep-tech innovation, supporting more targeted and coherent policy design.

Study Design and Concept Development

We adopted a sequential multi-method design consisting of a systematic, integrative, concept-centric literature review, semi-structured founder interviews, and a synthesis and conceptual consolidation workshop. The literature review served as the starting point for identifying and synthesizing attributes of deep-tech innovation across academic and practitioner sources. Building on this literature-derived attribute set, we then conducted interviews with founders of deep-tech ventures to assess how these attributes are reflected in practice and to refine their specification where needed. A final synthesis and conceptual consolidation workshop with three professors, two doctoral researchers, and two student assistants supported consolidation of the framework across analytical layers. This approach followed established guidance for concept development in management research, which emphasizes systematic synthesis and iterative refinement across complementary sources of evidence (Podsakoff et al., 2016).

Literature Review

To synthesize the literature, we conducted a systematic, integrative literature review that was explicitly concept-centric and attribute-based (Cronin and George 2020; Templier and Paré 2015; Webster and Watson 2002). Following guidance for literature reviews in management and innovation research (Rojon et al. 2021; Templier and Paré 2015; Webster and Watson 2002), we implemented a transparent and replicable procedure comprising four steps: systematic searches of a major database and selected additional repositories and outlets;

screening based on predefined inclusion and exclusion criteria; backward and forward citation tracking; and iterative coding and synthesis of deep-tech-related attributes drawn from the reviewed material.

In contrast to descriptive systematic reviews that aim for exhaustive coverage of a clearly bounded literature, this integrative approach emphasized conceptual synthesis. It involved identifying recurring themes and attributes in heterogeneous sources, including practitioner-oriented publications, to consolidate existing conceptualizations into a coherent framework (Cronin and George 2020; Templier and Paré 2015). Figure 1 summarizes the search and selection process.

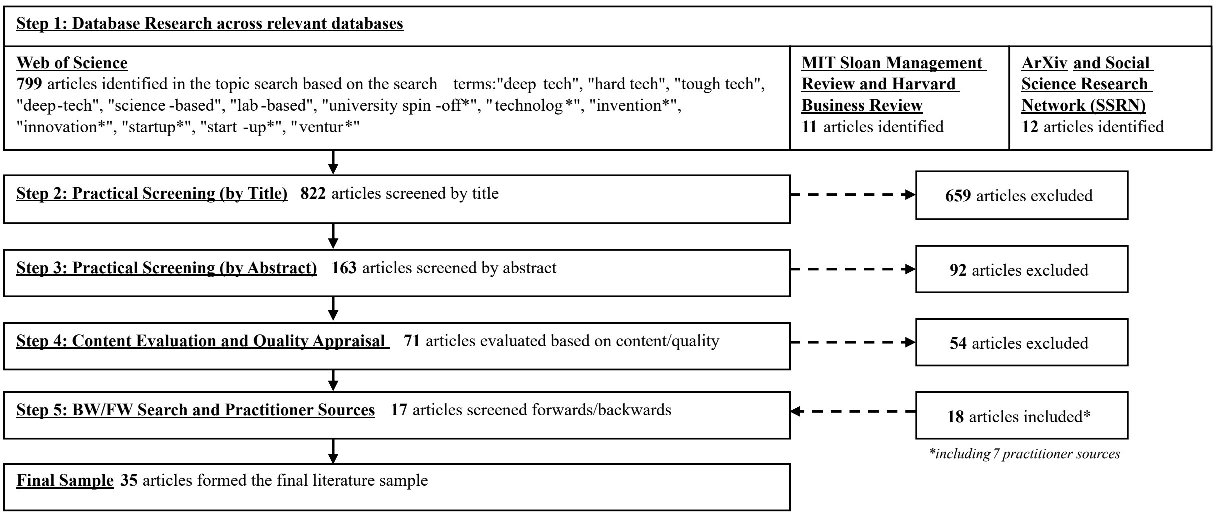

Figure 1. Flow Chart of the Literature Search Process

Literature Search and Selection

Given the new and multidisciplinary character of deep-tech innovation as a research area, the search strategy was designed to capture contributions from fields such as general management, innovation, and entrepreneurship (Cabanes 2025; de la Tour et al. 2017). We conducted searches in the *Web of Science Core Collection*, targeting peer-reviewed journals using combinations of the terms “deep”, “tough”, “hard”, “science-based”, “lab-based”, or “university spin-off”, in combination with “tech”, “technolog*”, “invention*”, “innovation*”, “startup*”, or “ventur*” in titles, abstracts, and keywords. The search covered publications from January 2015 through May 2025, corresponding to the period since the term *deep tech* was introduced by Chaturvedi (2015). The search string was developed iteratively through pilot searches and refinement of keywords in consultation with academic experts and practitioners.[1] In addition to the Web of Science, we conducted targeted searches in two practitioner-oriented outlets (*Harvard Business Review* and *MIT Sloan Management Review*), as well as in the preprint repositories ArXiv and SSRN. Non-peer-reviewed sources were cross-validated against the academic literature where possible, and their conceptual claims used as inputs to the synthesis rather than as standalone evidence (Rojon et al. 2021; Templier and Paré 2015). This approach is consistent with guidance for integrative reviews in emerging research areas, where practice-oriented sources often precede conceptual clarification in the academic literature and can inform concept development when handled transparently (Cronin and George 2020). The initial search yielded 822 potentially relevant records. After title and abstract screening to detect duplicates and sources without a management focus, 71 records remained for full-text retrieval and review.

Content Screening, Quality Appraisal, and Final Sample

For the screening and selection stages of the review, we applied predefined inclusion and exclusion criteria consistent with integrative review methodology (Cronin and George 2020; Templier and Paré 2015). Sources were included if they (1) explicitly discussed deep-tech innovation, deep-tech ventures, or closely related concepts (e.g., science-based ventures or advanced technology innovation); (2) included conceptual, definitional, or empirical material relevant to the characteristics, processes, or outcomes of deep-tech innovation; and (3) contained sufficient detail to extract information on attributes. Sources were excluded if they mentioned deep tech only in passing, focused exclusively on sector-specific technical details

[1] In interviews with 15 deep-tech experts in the United States and Europe from relevant accelerator and incubation programs (e.g., The Engine, Intel Ignite), investors (e.g., The German Federal Agency for Breakthrough Innovation SPRIND), and venture builders (e.g., MIT Proto Ventures), we asked which features they consider characteristic of deep-tech innovations and used the answers to refine our literature search string.

without broader innovation or management relevance, or did not offer clear conceptual or empirical contributions. Beyond the thematic focus, several quality considerations guided the selection of articles. These included the assessment of the journal or conference in which the work appeared. To judge the quality of sources, the *Financial Times (FT50)* list and the *Academic Journal Guide (AJG)* journal ranking served as reference points. Applying this outlet-quality criterion in addition to the other criteria resulted in a final set of 17 academic papers.

To reduce the risk of missing influential contributions, we supplemented this set through backward and forward citation tracking (Templier and Paré 2015; Webster and Watson 2002), which added 11 additional sources. In addition, given the links between deep-tech innovation and policy and investment debates, we included selected practitioner-oriented and policy reports that have influenced early conceptualizations and subsequent academic discussion, including reports from The Boston Consulting Group (Cabanes 2025; de la Tour et al. 2017; Harlé et al. 2020), which added 7 further sources. Together, these steps added 18 sources, resulting in a final literature sample of 35 publications for data extraction and attribute coding. Figure 2 shows the year-by-year distribution of the final sample and the share of academic and non-academic sources.

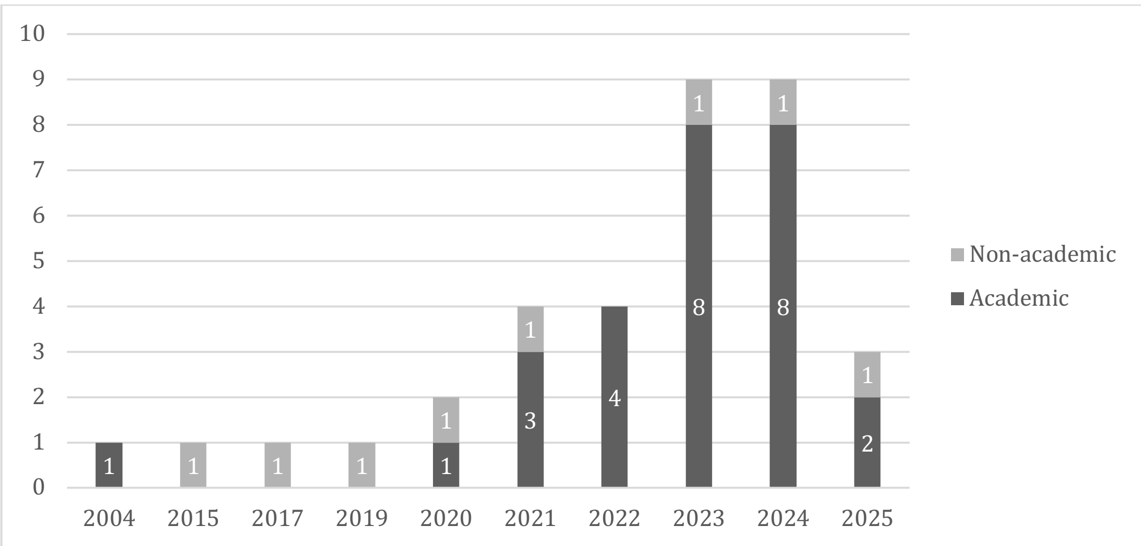

Figure 2. Final Paper Sample Year-by-Year Distribution

Data Extraction, Attribute Coding, and Thematic Synthesis

Following established procedures for concept-centric reviews, we extracted passages from the 35 sources that (a) defined or characterized deep-tech innovation, (b) contrasted deep tech with other types of innovation, or (c) described attributes, capabilities, or process characteristics associated with deep tech (Templier and Paré 2015; Webster and Watson 2002). Two researchers then independently coded the extracted material using an iterative, template-based approach informed by Gioia et al. (2013). First-order codes captured attributes described in the sources. Related codes were then grouped into second-order themes that constituted aggregate dimensions, which were used to structure the framework (Gioia et al. 2013). Coding proceeded in two rounds. In the first round, two researchers independently coded a subset of the sources, compared coding, and agreed on an initial coding template of first-order attributes that captured recurring descriptions of deep-tech in the literature. In the second round, the template was applied to the full corpus. New codes were added when additional attributes were identified, and overlapping codes were consolidated during synthesis. Regular peer debriefings supported consistency, and coding decisions were documented to ensure transparency (Aguinis and Solarino 2019). Throughout this process, we maintained an audit trail linking each attribute to the specific sources from which it was derived (Aguinis and Solarino 2019; Rojon et al. 2021). In total, 325 first-order codes were consolidated into twelve second-order themes, which form the attribute set used in the present study (Cronin and George 2020; Templier and Paré 2015).

Interview-based Validation with Deep-Tech Founders

Deep-tech innovation is usually commercialized through ventures founded by scientist-entrepreneurs and developed in specialized ecosystems (Diamandis et al. 2025; Raff-Heinen and Murray 2025). To validate and refine the literature-based attribute set using practice-based accounts (Podsakoff et al. 2016), we conducted 17 semi-structured interviews with founders of deep-tech ventures. We analyzed the interviews using the twelve attribute-based themes identified in the literature review as an analytic lens (Aguinis and Solarino 2019; Gioia et al. 2013).

Interview Sampling and Data Collection

We conducted interviews with a purposive sample of 17 founders of deep-tech ventures in the US and Europe. Participants were recruited through the authors' networks in deep-tech ecosystems. The ventures had roots in leading scientific research institutions (e.g., Harvard University, Massachusetts Institute of Technology, ETH Zurich) and operated in fields such as quantum computing, synthetic biology, advanced materials, and photonics. Table 1 provides a detailed overview of the interviewee sample.

Table 1. Details on Interviewee Sample

Interview ID	Role at the company	Technology invention
i01	CEO	Solid refrigerant technology for HVAC systems
i02	CTO	Gallium nitride on silicon semiconductor technology
i03	CEO	Hybrid rocket propulsion technology
i04	COO	Carbon capture technology based on a proprietary molten salt
i05	CEO	Ultra-high-precision spraying technology
i06	Founder and Scientific Advisor	Molten oxide electrolysis
i07	CEO	Membrane platform technology
i08	CEO	Advanced optical sensing
i09	Executive Director of Strategy	Superconducting power transmission technology
i10	CEO	Robotics platform for accelerated materials discovery
i11	CTO	Solid refrigerant technology for HVAC systems
i12	CEO	Autonomous robots
i13	Co-founder & Chief Scientific Advisor	Photonics technology based on thin-film lithium niobate
i14	Co-Founder and CEO	Hyperlocal weather intelligence
i15	Co-Founder and CTO	Quantum computing hardware
i16	Founder and CEO	Bio-computer-aided design technology
i17	Co-Founder and CEO	Chemical upcycling technology

The interview protocol followed an open narrative format. Interviews began with questions about the founder's background and the origins of the venture, followed by questions on the underlying technology and intended applications; development of the venture from inception to the present; key milestones and turning points; major challenges; and the roles of teams, investors, and ecosystem partners. This approach supported chronological accounts while avoiding leading questions drawn from the conceptual framework (Aguinis and Solarino 2019; Gioia et al. 2013). Interviews lasted 60 to 90 minutes, were audio recorded with participant consent, transcribed verbatim, and anonymized. The resulting corpus comprised approximately 100,000 words.

Interview Analysis

We analyzed the interview data using a theory-guided, deductive thematic approach. The twelve attributes identified in the literature review served as *a priori* coding categories, consistent with directed qualitative content analysis and deductively oriented thematic analysis (Braun and Clarke 2006; Hsieh and Shannon 2005; Mayring 2014).

Two researchers independently coded interview passages that provided evidence, examples, or refinements of the attributes. Each passage was assigned to a primary attribute, and disagreements were resolved through discussion and peer debriefing (Aguinis and Solarino 2019). We then synthesized the coded material for each attribute to identify recurring patterns, contextual contingencies, and cross-case variation, and to refine the attribute definitions (Braun and Clarke 2006; Mayring 2014). Throughout, we maintained an audit trail linking each analytic claim to the underlying interview passages and verbatim quotes (Aguinis and Solarino 2019).

The resulting synthesis is presented in Section 4, which uses interview material to illustrate how the twelve attributes manifest across technological domains and stages of venture development.

Framework Development and Synthesis

Following identification of the twelve attributes in the literature review and their use as *a priori* categories in the interview analysis, we conducted a final integrative synthesis step in a conceptual consolidation workshop involving three professors, two doctoral researchers, and two student assistants to organize the attribute set into a conceptual framework (Raff et al. 2020; Webster and Watson 2002). Although the twelve attributes were coded and defined as distinct elements, synthesis of the literature and interview material suggested patterned relationships among them, indicating that a broader structure might underlie the attribute set. For example, attributes such as *long development timelines* and *multilayered uncertainty* were frequently described in conjunction with more fundamental features of deep-tech innovation, such as *integrating hardware assets* or building on *scientific breakthroughs and defensible IP*. In addition, several attributes were described less as characteristics of the invention itself and more as recurring organizational and systemic requirements associated with ventures developing these innovations and the ecosystems and attendant resources in which they mature. In particular, we organized the attributes into (a) six foundational attributes specifying the deep-tech invention as the conceptual core, (b) three venture-level attributes, and (c) three ecosystem-level attributes. In the workshop, the twelve attributes were reviewed in depth, compared with concrete cases of deep-tech innovation, and then grouped into higher-order categories that support a layered framework.

The conceptual consolidation was guided by a process review of innovation as "taking ideas from inception to impact" (Budden and Murray 2019), and it considered the invention (i.e., the "front end" of the innovation) alongside the actors and ecosystems involved in development and commercialization (Markham et al. 2010; Nasirov et al. 2021). Importantly, the workshop served as a structured synthesis step rather than as an additional independent data source.

Findings: A Layered Framework of Deep-Tech Innovation

The workshop produced a framework structured into three analytical layers. The first layer comprises six defining attributes that form the conceptual core of deep-tech innovation (i.e., the deep-tech invention itself). The second and third layers comprise three venture-level attributes and three ecosystem-level attributes, respectively, which capture recurring requirements and dependencies associated with development and scaling deep-tech innovations. Figure 3 presents the resulting framework.

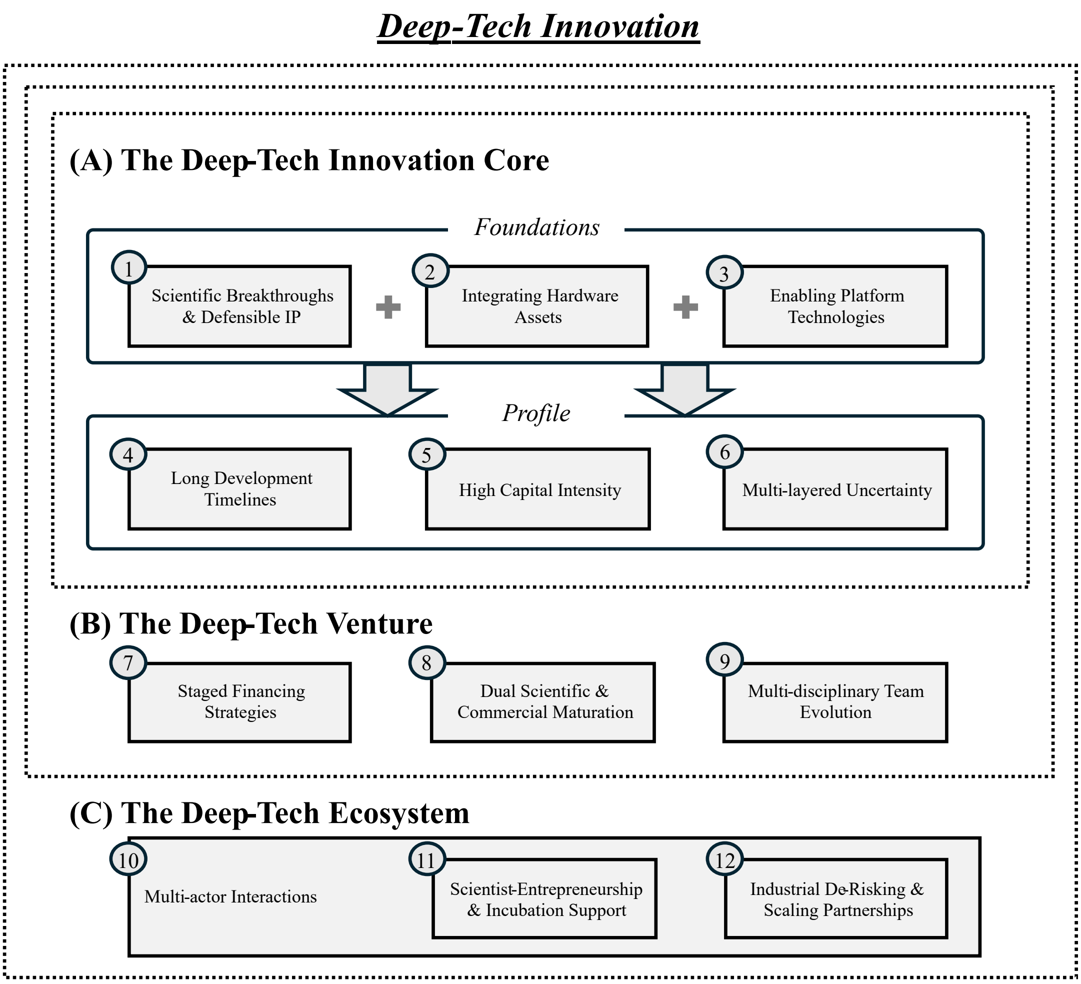

Figure 3. Deep-Tech Innovation Framework

In the following sections, we describe each layer in relation to the reviewed literature and the interview data. Subsequently, we examine how the twelve attributes altogether influence how deep-tech innovations are developed, commercialized, and scaled.

Conceptual Core of Deep-Tech Innovation

In our framework, the core of deep-tech innovation is specified at the level of the deep-tech invention itself. This core is defined by six attributes that distinguish deep-tech innovation from related forms of innovation. Of these, three foundational attributes capture the scientific and technological basis of the invention, and three further attributes describe its broader profile.

Scientific Breakthroughs and Defensible IP

Deep-tech innovation originates in substantial scientific discoveries or meaningful engineering advances that push the knowledge frontier (Priego et al. 2021). Many deep-tech innovations begin in university laboratories or large-scale research infrastructures (Chen and Lei 2021; Wareham et al. 2024). They draw on advanced scientific understanding to create technologies that were "previously inconceivable" (de Véricourt 2023). This starting point can yield unique technological capabilities that are difficult to reproduce (de la Tour et al. 2017) and therefore depend on intellectual property (IP) protection to establish defensibility and barriers to entry (de la Tour et al. 2019; de la Tour et al. 2021). In this sense, the value of the innovation is tied to its scientific or technical substance and depends on extending or moving beyond the state of the art rather than recombining existing components (Romasanta et al. 2021).

Our interview data suggest, however, that scientific novelty is not only a starting point but remains central throughout venture development. Founders described a non-linear process in which feasibility risks persist after spin-out and must be addressed alongside early commercial learning. In one interview, a founder reported that they began to identify "genuine industrial problems" only after leaving academia and had to bridge a gap between technology push and market needs (i03-06). In another interview, a founder described the need for a “co-evolutionary dynamic”, in which commercial constraints had to be integrated into parallel research decisions early on, including what the founder termed “cost-informed discovery” (i07-01). Elsewhere, a founder described extended periods of early experimentation (“test tube stage”) before system integration became feasible (i12-05). In another case, a founder reported having to develop bespoke measurement tools or equipment when standard solutions did not fit the novelty of the underlying science (i11-05). Finally, one founder emphasized that early validation often relies on lab-based evidence and “scientific style data” when established market metrics are not yet available (i16-12).

Integrating Hardware Assets

Because deep-tech innovations result from substantial scientific discoveries or meaningful engineering advances out of research infrastructures, they predominantly take the form of hardware-intensive systems (de Apodaca et al. 2022; de la Tour et al. 2021; Reisdorfer-Leite et al. 2023). Unlike digital innovations, which can emerge from almost anywhere, including dorm rooms, deep-tech ideas take shape as physical products or asset-heavy industrial processes, such as a novel process for creating green steel. In this sense, they are rooted in “atoms rather than bits” and require integration of complex hardware assets (Raff et al. 2024). Development therefore often involves multiple advanced disciplines working together to build functional systems, such as new materials or energy infrastructure, rather than discrete components (Peña and Jenik 2023). Scaling can require specialized manufacturing capabilities and costly physical infrastructure, at times described as “heavy industrialization” (de la Tour et al. 2017; Reisdorfer-Leite et al. 2023). Thus, the central challenge is not only technical novelty but also system-level integration of novel physical technologies into reliable, tangible assets (Candelon et al. 2023a; Candelon et al. 2023b).

Interview data underline how this hardware intensity influences validation and scaling. In one interview, a founder emphasized that iteration is costly and slow in hardware settings, noting that "you can't iterate through deployments" when each cycle requires substantial resources (i10-03). As a result, deep-tech innovators described relying on simulations, component-level testing, and other "soft validation" approaches before committing to expensive physical pilots (i10-03). Elsewhere in the interviews, a founder described validation as requiring system-level demonstrations (i10-09) rather than minimum viable products. Similar examples included operating a physical pilot plant for extended periods to capture real-world performance data (i05-09), or executing a complex physical feat such as a suborbital launch (i04-10). The move from laboratory results to market-ready systems can therefore resemble a "non-linear scaling challenge", in which scaling is not a smooth ramp-up but a discontinuous engineering effort to reproduce benchtop results in industrial-grade systems. In some cases, founders reported having to build bespoke supply chains for components that "nobody makes" (i07-11; i06-05). In this sense, hardware intensity is not a static feature of deep-tech innovation but affects how ventures test feasibility, demonstrate performance, and scale reliably.

Enabling Platform Technologies

Deep-tech innovations have a platform-like character in that they provide foundational capability upon which multiple downstream applications can be built (Romasanta et al. 2021; Wareham et al. 2024). Unlike end-user products, these technologies function as enabling technologies, such as a new material, a quantum computing architecture, or a synthetic biology platform, that can support commercial applications (Meyer et al. 2024). Early on, this breadth can create "application uncertainty". Even when the underlying science is sound, the most valuable use case may not be clear at the outset (Arora et al. 2024). As a result, deep-tech innovation follows a "technology-first" pathway in which commercialization requires deliberate search and selection of an initial application domain (Myers et al. 2024). In some instances, this process can involve shaping new value chains rather than entering established markets (Romasanta et al. 2021).

Interview data illustrate how this platform character influences early venture decisions. In one interview, a founder described infinite optionality as both a "blessing and a curse", noting that the same core technology (e.g., molten oxide electrolysis) can support very different applications, from "putting men back on the moon" to terrestrial metal extraction (i07-08). This flexibility can provide resilience, allowing ventures to redirect their efforts if an initial market proves less promising or if a window of opportunity is missed (i03-11). At the same time, one founder described a practical burden of selection, where the main challenge is choosing a viable "beachhead" application rather than generating demand (i01-01). In another interview, a founder described pursuing parallel innovation strategies, commercializing an initial application while developing a next-generation platform for a different future market (i15-14). Finally, one founder noted a recurrent communication challenge in translating "technology-heavy stories" into narratives that can be understood by varied stakeholders (i08-03).

Altogether, the three foundational attributes describe the core configuration of deep-tech innovation: it involves an invention that is scientifically novel, physically embodied, and is platform-like in its application potential. This combination of attributes helps explain why deep-tech innovation projects tend to face extended timelines, high capital demands, and multilayered uncertainty. We next turn to the three profile attributes related to time, capital, and uncertainty.

Long Development Timelines

Bringing complex physical systems from scientific proof-of-concept to industrial reliability takes time, and deep-tech innovation therefore tends to involve long development timelines. Reported time horizons range from five to 15 years from initial scientific discovery to market readiness (Raff et al. 2024; Reisdorfer-Leite et al. 2023; Romasanta et al. 2021). These reflect the uncertainty of scientific de-risking and the need for physical or biological validation, which does not always follow a predictable, linear path (de Apodaca et al. 2022; de Véricourt 2023). As a result, technology maturation can remain decoupled from commercial launch, with ventures spending long phases in pre-revenue development before market entry becomes feasible (de Véricourt 2023). In this sense, the timeline is constrained by the underlying science and the physical or biological processes involved.

Interview data are consistent with this temporal profile and the frictions it can create. In one interview, a founder described a "temporal mismatch" between deep-tech development cycles and the expectations of investors or corporate innovation timelines (i07-03). In another interview, a founder reported development phases lasting more than a decade before early commercialization (i03-14), which can be difficult to reconcile with common venture-capital investment horizons of three to five years (i07-03). One founder also noted that regulatory requirements, such as approval processes for medical devices, can "slow things down" further and create periods in which commercialization is not yet possible (i09-13). Finally, one venture founder reported delaying external financing to retain the freedom to pursue long-term development without near-term commercial pressure (i03-03).

High Capital Intensity

Deep-tech innovation projects require substantial and sustained capital to operate through long pre-revenue periods (de la Tour et al. 2021; Raff et al. 2024). This capital intensity follows from two attributes discussed earlier: the need for specialized physical infrastructure, such as wet labs, clean rooms, and pilot plants (de la Tour et al. 2017; Reisdorfer-Leite et al. 2023), and the protracted development cycle that requires continued investment before revenues are feasible (de la Tour et al. 2021). This combination creates a high cumulative burn rate, primarily driven by the costs of maintaining intensive research and development (R&D) activity ahead of commercialization (de Apodaca et al. 2022). Because of this, deep-tech ventures face a first-of-a-kind funding gap in which financing needs for industrial scale-up peak while technical and market risks remain substantial (Harlé et al. 2020).

Interview data underscore capital intensity as a barrier to entry and scaling. Two founders emphasized that the "scaling-up phase" generates extreme capital demand for preproduction and inventory (i06-14, i13-14). One founder also pointed to a mismatch between conventional venture-capital time horizons and return expectations and argued for capital partners with enough patience to understand that "things take more time than you think" (i16-03). In another case, a founder reported "zero interest" from investors in funding manufacturing infrastructure (i14-11), suggesting gaps in the local ecosystem. The interviews also suggest variation in how ventures manage these constraints. One founder noted that some ventures rely on non-dilutive grants to bridge the gap (i10-14). In one interview, a founder reported remaining "entirely bootstrapped" for years by tightly controlling asset accumulation (i03-10). Similar accounts described a related logic of "ecosystem arbitrage," including shifting manufacturing to regions such as Taiwan to access superior infrastructure at a "fraction of the money" (i11-06, i17-05).

Multi-layered Uncertainty

Finally, deep-tech innovation projects operate under pervasive, multi-layered uncertainty. They must simultaneously navigate technological uncertainty (can the core science work and be produced at scale?), market uncertainty (is there demand for this "previously inconceivable" technology?), and regulatory uncertainty (will standards and approval pathways evolve to permit deployment?) (de Apodaca et al. 2022; de Véricourt 2023). Together, these uncertainties create a particularly deep "first-of-a-kind valley of death", where information asymmetry and capital intensity make risk assessment difficult for investors (Romme et al. 2023; Schuh and Hamm 2022). Unlike for digital startups, where risks may be approached sequentially, deep-tech ventures face an entangled risk profile in which technical feasibility, commercial viability, regulatory considerations, and ecosystem readiness must be addressed in parallel.

The interview data illustrate how founders experience this risk profile as a series of interlocking "structural deadlocks". In one interview, a founder described a "chicken-and-egg" market risk in which growth is constrained by the absence of enabling infrastructure (e.g., lack of launch capacity for satellites, i04-13). In another, a founder reported having to build a supply chain for components that did not yet exist, such as inert anodes (i07-11). Elsewhere, a founder described a case in which the venture's first product was "technologically interesting" and "pretty for the media", yet failed due to a lack of product–market fit (i06-07), illustrating that technical success does not guarantee market adoption. In another interview, a founder noted that regulatory risk can operate as a barrier to entry when incumbent standards do not translate to novel systems (i01-12). Finally, interviewees also pointed to ecosystem-level limitations, including a "lead investor problem" in which generalist funds lacked the domain expertise to evaluate the technology, but specialist funds were reluctant to lead large rounds (i04-03). Related accounts emphasized the need to distinguish "technology tourism" from genuine interest (i09-03) and, during critical phases, to secure non-dilutive resources to survive the "valley of death" (i06-02).

Conceptually, these three attributes are closely linked to the foundational attributes described above. Scientific breakthroughs embodied in tangible, platform-like technologies with uncertain applications almost inevitably imply longer and more capital-intensive development cycles and deeper, multidimensional risk exposure than many other forms of innovation. Not every long, risky development project qualifies as deep tech, but in our framework, these exposure characteristics are defining because they occur systematically in conjunction with the scientific and technological foundations described above.

In sum, the six defining attributes specify the deep-tech invention. It is characterized by (1) scientific breakthroughs embodied in (2) tangible, physical systems with (3) enabling platform potential. This foundational architecture is associated with (4) extended development timelines, (5) high capital intensity, and (6) pervasive, multi-layered uncertainty.

Venture- and Ecosystem-level Implications of Deep-tech Innovation

Our framework distinguishes between the defining attributes of the deep-tech invention and the broader venture- and ecosystem-level attributes associated with it. Evidence from the literature and interviews suggests that the defining attributes of the deep-tech invention are linked to recurring organizational and systemic patterns. We therefore identify six further attributes, three at the venture level and three at the ecosystem level, which capture the typical implications of the invention-level profile and reflect how deep-tech innovation is typically carried out in practice.

The Deep-Tech Venture

Staged Financing Strategies

To manage high capital needs while binary technical risk remains unresolved, deep-tech ventures require financing that changes as technical uncertainty decreases (Schuh and Hamm 2022; Wareham et al. 2024). Compared with many digital startups, which scale with a single asset class (i.e., venture capital), deep-tech ventures draw on different funding sources at different stages (Schuh and Hamm 2022). Early work is frequently supported by non-dilutive public funding to bridge the "valley of death" (Chen and Lei 2021; Wareham et al. 2024), whereas later industrial scaling requires private capital with expertise to assess complex engineering risks (Kask and Linton 2023). When a type of capital does not match the stage at which a venture finds itself, the venture may fail despite technical promise (Arora et al. 2024).

Interview data illustrate how founders structure financing in stages, how this influences strategic decisions, and common challenges associated with this process. In two interviews, founders reported using grants and awards to fund early proof-of-concept work (i18-10, i05-06). In another interview, a founder explained how specialized pre-seed funding was used to support "order-of-magnitude" scaling milestones (i12-06, i12-09). We were told that a recurring challenge is the "lead investor problem", in which generalist venture capital investors lack the technical capacity to assess risk, forcing founders to seek domain-expert partners (i04-

01). In another interview, a founder emphasized the difficulty of securing funding during high-risk pivot phases, including reliance on "rescue capital" from strategic investors (i13-12). Across these accounts, founders framed financing as a staged process in which success depends on synchronizing the "right capital" with the "right milestone" to bridge the gap from lab-scale validation to industrial deployment.

Dual Scientific and Commercial Maturation

Given their platform-like character and uncertainty about which applications will ultimately prove commercially viable, deep-tech ventures must manage a dual maturation or readiness process in which technological feasibility and commercial viability develop in tandem (de Véricourt and Gurkan 2024). Rather than following a linear "technology transfer" model, development proceeds through iterative experimental cycles of design–build–test–learn, in which scientific de-risking is coupled with market exploration (de la Tour et al. 2021). Ventures therefore operate in what de Véricourt & Gurkan (2024) describe as a "two-dimensional innovation space": they must improve the technology while also identifying and validating viable applications before a clear market exists (Harlé et al. 2020).

Interview accounts illustrate this dual maturation as a "non-linear, iterative process" in which scientific de-risking and commercial discovery must evolve in lockstep. One founder pointed to the need to avoid a "research trap" in which PhD-style work continues without sufficient attention to commercialization (i13-03), by engaging in early "customer co-development". Others emphasized "active[ly] listening" to customers well before product maturity to refine technical specifications and value propositions (i06-01, i10-01). Several founders noted that pilot projects can serve two purposes at once: demonstrating technical feasibility while also testing market demand (i12-12, i15-07). Some reported deliberate overinvestments in the first one or two reference customers to build credibility for subsequent market entry (i15-13, i13-11). One founder recalled discovering that customers cared mainly about cost reduction rather than sustainability, which prompted a shift in how the offering was positioned (i12-10). Finally, even modest early revenue, such as small, paid sample orders, can reduce uncertainty by providing tangible evidence of market interest for investors (i18-16).

Multi-disciplinary Team Evolution

Successful development, commercialization, and scaling in deep-ventures requires teams to evolve as the technology and market approach mature (Clarysse and Moray 2004). Founding teams are usually built around technical champions from academia, but long-term success depends on progressively integrating commercial leadership and specialized non-technical expertise (Clarysse and Moray 2004; de la Tour et al. 2021; Romasanta et al. 2021). Over time, teams move through alternating periods of relative stability and major reconfiguration as roles, governance, and capabilities are adjusted (Clarysse and Moray 2004). This process requires bridging different "thought worlds" of science and business; if that translation work is not managed carefully, divergent internal narratives can produce "innovation blindness" and lead to coordination breakdowns during scaling (Schou 2024).

Interview data illustrate that these dynamics involve operational and interpersonal challenges. One founder noted that building the right team can require actively hunting for talent that is not readily available through standard hiring channels (i12-02). Another described a phased approach to hiring, bringing in creative early-stage generalists ("anti-experts") during exploration, then shifting toward experienced "industry veterans" as the demands of execution increase in the scaling phase (i07-02). Others emphasized the value of "translator" roles, often consisting of leaders with hybrid scientific and commercial backgrounds, to connect scientific potential with commercial decision-making (i11-01, i18-02). Recruiting senior industry talent into a high-risk setting was described as difficult (i08-11), and some founders reported addressing this by emphasizing "impact and ownership" over stability. Finally, one founder emphasized deep trust between co-founders as a non-negotiable asset for weathering the "psychological stresses" of long development cycles (i12-04), while another noted that co-founder conflicts can result in a co-founder leaving to become a direct competitor (i17-03).

The Deep-Tech Ecosystem

Multi-Actor Interactions

Because deep-tech innovation builds on scientific research and involves substantial capital requirements, deep-tech ventures do not develop in isolation. Instead, they are embedded within innovation ecosystems that include diverse public and private sector actors (de Apodaca et al. 2022; de la Tour et al. 2021; Guzman et al. 2023). In contrast to many digital startups, deep-tech ventures operate at the "crossroads of fundamental research and industrial application" (de la Tour et al. 2017). This usually requires simultaneous collaboration with research universities, government agencies, specialized investors, and established corporations. For these ventures, this dependence is existential: these ecosystems create crucial "interdependencies", such as access to intellectual property, specialized talent, and regulatory pathways that allow resource-constrained ventures to work effectively with complex physical assets (Priego et al. 2025; Romasanta et al. 2021). As a result, commercialization depends less on the agility of a single firm and more on the ability to orchestrate a "dynamic, decentralized" network of partners (de la Tour et al. 2019).

Interview data reinforce this notion of embeddedness. Several founders noted that deep-tech ventures are "born networked", typically emerging from institutional contexts such as university laboratories or specialized programs rather than informal settings such as garages (i05-05, i13-06). This embeddedness persists as a survival strategy but often requires active choices: some founders described a process of "ecosystem arbitrage", whereby critical operations are moved to favorable jurisdictions, such as testing in the United Kingdom or manufacturing in Taiwan, to overcome deficits in their local environment (i04-09, i03-10). One founder also pointed to a "disconnect" in which academic work can overlook industrial needs (i03-06), requiring founders to bridge the gap by recruiting industry veterans to their boards for credibility (i09-04, i14-02). Several founders emphasized that success remains intensely local, attributing their survival to co-location with industry giants and dense peer networks (i06-03, i05-04). Finally, one founder highlighted the "slower clockspeeds" of institutional partners such as national space agencies, which often serve as their first customers and funders (i04-11).

Scientist-Entrepreneurship & Incubation Support

The scientific origins of deep-tech ventures create a need for specialized support infrastructure that helps bridge the gap between academic discovery and venture formation (Wareham et al. 2024). Unlike generalist incubators that focus on business model iteration, deep-tech support systems must address the specific needs of "scientist–entrepreneurs" and provide a phased pathway from initial entrepreneurial interest to formal spin-out (Diamandis et al. 2025; Meyer et al. 2024). This includes dedicated deep-tech incubators, university-based entrepreneurship courses, and fellowship programs (e.g., Activate, Breakthrough Energy) that provide the necessary institutional home for developing and de-risking early concepts without immediate commercial pressure (Diamandis et al. 2025; Meyer et al. 2024). Beyond skill-building, this infrastructure can also provide informal certification and external validation for founders who lack prior business experience (Clarysse and Moray 2004; Diamandis et al. 2025).

The interview data support this role of support programs as early catalysts. Two founders described how structured interventions, such as MIT's Blueprint program or the "Climate and Energy Ventures" course, helped convert them from "skeptical academics" into convinced entrepreneurs (i12-08, i05-08). Others emphasized that these programs can function as "signaling platforms": winning a fellowship or joining a reputable accelerator (e.g., Nucleate) "elevates the venture above the noise" and provides the external validation that helps attract initial investors (i01-06, i17-11). One founder also emphasized the role of university technology transfer offices in securing early IP protection (e.g., patents), which can help turn a research project into a defensible asset when engaging external partners (i17-07).

Industrial De-Risking & Scaling Partnerships

Finally, beyond initial venture formation, deep-tech commercialization requires a second layer of ecosystem support focused on industrial de-risking and scaling (de la Tour et al. 2019; Reisdorfer-Leite et al. 2023). The long and expensive development stages common to deep-tech require access to “tailored support” systems that go far beyond standard venture capital (Kask and Linton 2023). This includes large-scale demonstration facilities for pre-commercial testing, specialized testbeds, and access to networks of complementary partners that can support the industrialization process (Kask and Linton 2023; Wareham et al. 2024).

The interview data indicate that specialized de-risking partnerships and shared infrastructure are essential for bridging the gap between lab prototypes and industrial deployment. Importantly, these partnerships are not just about funding but about sharing physical assets, supply-chain access, and jointly defining milestones that fit the long and uncertain cycles of deep-tech development (Raff et al. 2024). Some founders explained that large industrial partners can provide critical physical capacity, such as pilot plants, existing process lines, or utility-scale testbeds that startups cannot build alone, enabling validation under real operating conditions (e.g., carbon-capture plants or grid-equipment pilots) (i05-15, i10-13). Others point to university cleanrooms and national labs as shared infrastructure for producing first-of-a-kind devices, providing access to advanced fabrication and testing tools that would otherwise be prohibitively expensive for a single venture (i14-09, i03-08). Over longer horizons, founders also describe multi-year collaborations with corporates (such as utilities or manufacturing incumbents) as providing technical feedback alongside supply-chain access and early letters of intent (i10-12, i10-15). Thus, such partnerships can serve as a mechanism through which the platform potential of a deep-tech technology is translated into deployable industrial applications, with implications for how value chains develop (Candelon et al. 2023a; de la Tour et al. 2019).

Overall, the six venture- and ecosystem-level attributes capture how deep-tech innovation is typically developed and scaled around the invention. In our framework, they are not part of the conceptual core but reflect recurring organizational and systemic requirements that accompany its time, capital, and uncertainty characteristics. This distinction allows us to separate what deep-tech innovation *is* from what is required to *carry it forward*, and it sets up the following section, which positions deep-tech innovation relative to adjacent concepts.

Clarifying Conceptual Boundaries of Deep-Tech Innovation

Establishing a robust conceptual foundation for research on deep-tech innovation requires not only definitional clarity but also clear demarcation from adjacent concepts used in innovation research and practice (Garcia and Calantone 2003; Podsakoff et al. 2016). Building on our framework, we therefore distinguish deep-tech innovation from four particularly relevant adjacent concepts that emerged from our literature review and the ongoing consultations among the research team: *radical* or *breakthrough innovation* (innovation core), *digital innovation* (innovation core), *academic technology spin-offs* (venture level), *and high-tech* (system or sector level).

Deep-Tech Innovation and Radical or Breakthrough Innovation

Concepts such as radical and breakthrough innovation classify innovations by the degree of technological and market discontinuity and their potential to transform or create market structures (Chandy and Tellis 1998; McDermott 2002; Phene et al. 2006; Verganti 2008). Deep-tech innovations have the potential to reshape industries or enable new markets, but some operate in highly specialized niches in which discontinuity is primarily technological (de la Tour et al. 2017; Harlé et al. 2020). Conversely, radical or breakthrough innovations do not necessarily involve the scientific breakthroughs, hardware intensity, and enabling platform character that define deep-tech innovation in our framework, particularly in digital or service settings (Chandy and Tellis 1998; McDermott 2002). Existing radical and breakthrough innovation concepts primarily categorize *the degree of novelty and discontinuity in innovation outcomes*, whereas deep-tech innovation, as conceptualized here, is distinguished by a configuration of definition attributes covering scientific and technological foundations and a characteristic time, capital, and uncertainty profile (Cabanes 2025; Meyer et al. 2024). Relying on "radical" or "breakthrough" innovation alone to study deep-tech innovation can therefore obscure attributes that are central to deep tech, including scientific depth, physical embodiment, long development horizons, and multi-layered uncertainty.

Deep-Tech Innovation and Digital Innovation

Digital innovation is commonly defined as the creation or recombination of digital technologies to generate novel value propositions, organizational forms, or interactions, often in software-centric or data-driven settings (Fichman et al. 2014; Hund et al. 2021). A recurring emphasis in this literature is the fluidity of digital innovation (Pesch et al. 2021): digital artifacts (i.e., software-based or data-based innovation objects) can be modified rapidly, remain malleable over time, and are easily transferred to different contexts (Yoo et al., 2010).

Deep-tech innovation differs in several respects. In our framework, the core invention is structurally far more rigid insofar as it is physically embodied and hardware-intensive. It deals with atoms rather than bits. This ties development and scaling to material limitations, marginal costs, and operational complexity (de la Tour et al. 2021; Raff et al. 2024). Digital components may be part of deep-tech ventures (e.g., AI for robotics), but they function as enablers to a physical core invention (the robot) rather than constituting the innovation itself. As a result, innovation approaches that are widely used in the digital context, including build–measure–learn logics and related design-thinking routines, cannot be transferred uncritically to deep tech, in which iteration cycles are limited by physical constraints and linear scaling costs (Cabanes 2025).

In sum, digital innovation and deep-tech innovation may intersect in practice, but they are conceptually distinct: digital innovation is organized around re-combinable digital artifacts, whereas deep-tech innovation is defined by a configuration of scientific and technological foundations and a materially constrained development profile.

Deep-Tech Innovation and Academic Technology Spin-offs

Academic technology spinoffs are defined primarily by their organizational origin in universities or public research organizations and by their mandate to commercialize or develop technologies generated in those settings (Fini et al. 2011; Rasmussen and Borch 2010; Shane and Ulrich 2004; Walter et al. 2011). Many deep-tech innovations are indeed carried forward through academic spinoffs (Cabanes 2025; Meyer et al. 2024). However, academic origin and the exploitation of university-based IP are neither necessary nor sufficient conditions for an innovation to qualify as deep-tech: academic spinoffs can commercialize incremental or moderately novel technologies, including digital innovations (e.g., an AI researcher founding a startup around software-based innovations). Conversely, deep-tech innovations can also originate in research settings outside universities (e.g., corporate or mission-oriented laboratories). Treating "academic technology spinoffs" as interchangeable with "deep-tech ventures" therefore conflates the *organizational vehicle* with an *innovation type*, which risks false positives (spin-offs that are not deep-tech) and false negatives (deep-tech ventures without an academic or research spin-off origin) (de Apodaca et al. 2022; Schuh et al. 2022).

Taken together, academic spin-offs are best understood as one organizational form through which research-based innovation can be developed and carried forward. At the same time, the category is broader than deep tech, encompassing diverse technology domains (e.g., information and communication technologies) (Walter et al. 2011) and degrees of novelty. Thus, academic spin-offs are not an appropriate substitute unit of analysis when the aim is to capture the defining attributes and associated venture- and ecosystem-level implications that characterize deep-tech innovation and deep-tech ventures.

Deep-Tech Innovation and High Tech

High tech is commonly defined at the organizational level through sectoral affiliation and R&D intensity (e.g., Chyi et al. 2012; Coad and Rao 2008). Firms in technology-intensive industries are usually labelled high tech when they allocate a substantial share of their resources to R&D activities (Balkin et al. 2000; Collins and Smith 2006; Colombo and Grilli 2010). This classification relies on the level of research and development effort and the industry context, but it says relatively little about the nature of the underlying technology, its scientific depth, the temporal structure of development, or the associated capital and uncertainty profile (Storey and Tether 1998; Yli-Renko and Autio 1998). Deep-tech innovation, as conceptualized in our framework, refers to a configuration of attributes centered on substantial scientific or engineering advances at the technological frontier. These advances are embodied in tangible, asset-intensive enabling technologies or platforms and are generally associated with long and uncertain development paths, high capital intensity, and a strong dependence on multiple complementary ecosystem actors and supporting infrastructures that jointly create the necessary conditions under which deep-tech innovation can emerge (Cabanes 2025; de la Tour et al. 2017; Meyer et al. 2024). By contrast, being high tech does not automatically involve frontier scientific or engineering advances. It also does not require asset-intensive development paths to the same extent as deep tech, nor does it depend on an equally dense set of complementary ecosystem actors and supporting resources (see Vedula and Fitza 2019). Relying on the high-tech label can therefore conflate firms that invest heavily in technology, including software-based firms (e.g., Bosch-Sijtsema and Bosch 2014), with ventures commercializing laboratory-based deep-tech inventions.

Altogether, the term “high tech” functions as a rather broad industry classification, whereas deep-tech innovation refers to a more specific innovation configuration. Deep-tech ventures and ecosystems may be situated within high-tech sectors, but sector membership alone does not capture the defining attributes of deep-tech innovation or the venture- or ecosystem-level requirements that usually accompany it.

Positioning deep-tech innovation relative to adjacent concepts

The above comparisons underscore that no single adjacent concept fully captures deep-tech innovation as conceptualized in our framework. Figure 4 summarizes this positioning: the deep-tech invention shows only partial overlaps with radical or breakthrough innovation, and is distinct from digital innovation; deep-tech ventures may take the form of academic spin-offs but are not equivalent to them; and deep-tech ecosystems can be situated within the broader high-tech domain without being reducible to it. This positioning alongside adjacent concepts studied in the innovation literature underscores the need for clearer conceptual delineation to support cumulative knowledge building on deep-tech innovation.

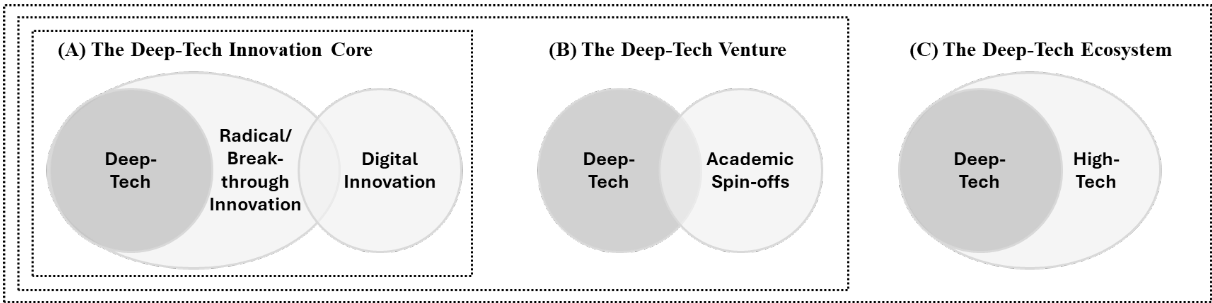

Figure 4. Conceptual Boundaries of Deep-Tech Innovation

Discussion, Contributions, and Future Research

This study addresses the conceptual ambiguity surrounding deep-tech innovation by developing an empirically grounded framework that supports cumulative knowledge building. It specifies the attributes that define deep-tech innovation at its core, clarifies its boundaries by distinguishing the innovation core from recurrent venture- and ecosystem-level attributes, and positions deep-tech innovation relative to adjacent concepts in innovation research (Garcia & Calantone, 2001; Bacharach, 1989; Sutton & Staw, 1995). In the following, we discuss the implications of our findings and outline an agenda for future research organized around the three layers of our framework.

The Deep-Tech Innovation Core

A central contribution of this study is to define deep-tech innovation as a distinct concept with explicit boundaries. In our framework, the innovation core (the deep-tech invention) is characterized by six attributes: (1) scientific origins, (2) tangible hardware intensity, and (3) platform character, which are associated with (4) extended development timelines, (5) high capital intensity, and (6) multilayered uncertainty. Conceptualizing deep-tech innovation at the level of individual invention and development projects provides a clearer epistemic object for cumulative research and a more precise basis for distinguishing deep-tech innovation from adjacent concepts (Podsakoff et al. 2016). Future empirical work can build on this boundary structure by using attribute-based indices to enable transparent and more accurate case selection and systematic comparisons across innovation categories.

The conceptualization also points to two directions for future research. First, our framework underscores the central role of basic science in deep-tech innovation, consistent with recent research (Norn and Hoang 2025; Raff-Heinen and Murray 2025) while also drawing attention to tensions between the path-dependent dynamics of scientific discovery and the demands of commercialization. Although university technology transfer has been studied from multiple perspectives (e.g., Libaers 2013; Melnychuk et al. 2021), the specific characteristics of deep-tech settings remain underexplored. In many such contexts, scientific exploration continues in parallel with commercial validation even after a project leaves its original research environment. Future research could therefore examine how mechanisms such as "cost-informed discovery" can be integrated into early-stage research without compromising scientific integrity, and which organizational arrangements enable the combination of open-ended inquiry with the demands of focused market application.

Second, our framework highlights the physical asset intensity of deep-tech invention (Raff et al. 2024), which is reflected in tangible, hardware-intensive systems like quantum, fusion, or robotics. This characteristic limits the transferability of widely used build–measure–

learn approaches such as Lean Startup or Design Thinking. Developed for the most part in digital contexts, these approaches reduce uncertainty through minimum viable products and rapid cycles of customer feedback, for example, by running A/B tests on software configurations to generate learning and refine an offering (Dahlander and de Véricourt 2024; Subramanian 2025). In deep-tech settings, by contrast, prototyping and iteration are slow and costly, and relevant early customers may not yet be identifiable (Kruachottikul et al. 2023). Our findings therefore point to a need for research on innovation approaches suited to asset-heavy deep-tech development contexts. Future studies could examine how deep-tech ventures may substitute physical iteration with "soft validation" techniques such as advanced simulation and digital twins (Myers and Albats 2024), and how these practices affect the pace and reliability of the development process.

The Deep-Tech Venture

Our second contribution lies in outlining the venture-level implications that follow from the conceptualization of the deep-tech innovation core. A central theme is the "blessing and curse"-nature of the platform character of deep-tech inventions. Because they are typically technology-push in origin, deep-tech innovations often function as enabling platforms with a wide range of potential applications. For this reason, ventures face a strategic tension: they must articulate a sufficiently focused application to secure resources while at the same time preserving the broader technological potential of the underlying platform. Empirically, ventures address this tension by using early prototypes and pilot projects to explore multiple application domains, selectively applying use cases to generate interest and learning, and then converging on a domain that offers the highest likelihood of early traction. Such beachhead markets can provide near-term revenue and validation without foreclosing longer-term platform repositioning. Future research should examine how ventures navigate this trade-off between focus and optionality, including how they validate technologies within selected application domains and markets without prematurely limiting future development paths (Arora et al. 2024; Myers et al. 2024). It would also be valuable to study how different portfolio strategies and technology narratives influence stakeholder expectations and influence the feasibility of subsequent pivots across application domains.

Relatedly, our findings indicate that deep-tech ventures commonly experience a dual maturation process in which scientific de-risking and commercial discovery must progress in tandem. This challenges linear stage-gate models and suggests the need for venture-development accounts that explicitly treat technical and market learning as interdependent. Future research should examine how ventures coordinate technical progress and commercial validation over time, with particular attention to pivoting in hardware-centric contexts. In contrast to software, pivots in deep tech frequently entail substantial sunk capital, long lead times, and considerable physical re-engineering. Understanding the conditions under which such pivots become necessary, and the practices through which they can be executed without derailing development (Priego et al. 2021), remains an important research direction.

In addition, our framework points to the importance of fit between investors and the underlying technology. In deep tech, capital is necessary but not sufficient for success, since ventures also depend on investors who can evaluate technological risk and strategic potential with appropriate technical understanding. Many ventures therefore assemble funding architectures that combine different forms of funding, such as non-dilutive grants, specialized venture capital, and strategic corporate financing. They may also use ecosystem signals, such as competitive fellowships (e.g., the ETH Pioneer Fellowship) or deep-tech accelerators (e.g., Activate Boston) to attract investors willing and able to support technologically complex, capital-intensive, and high-risk development trajectories. Future research should examine how investor capabilities beyond the provision of funding, such as domain expertise, positions within industrial networks, or experience with infrastructure finance, shape development paths in deep tech, and how different funding architectures influence outcomes such as time to first industrial deployment, survival probabilities, and strategic flexibility (Arora et al. 2024).

Finally, the evolution of the founding team emerged as an important success factor (Clarysse and Moray 2004; Moorjani et al. 2024). Deep-tech ventures often originate in research teams and then expand to gradually include commercial leadership, industry expertise, and operational specialists as development and scaling demands change. In this process, founders may shift from primarily technical roles in the early phases to roles that require broader organizational leadership and engagement with industrial partners and markets. Bringing together capabilities and working logics from science and business is challenging and places substantial demands on leadership and coordination. Future research could therefore examine which sequences and combinations of team competencies best support different types and stages of deep-tech ventures, and how leadership practices at the micro level help bridge scientific and commercial communities, reducing the risk of prolonged lock-in to research trajectories on the one hand, and premature narrowing of commercial options on the other.

The Deep-Tech Ecosystem

The third contribution is related to the conditions that enable deep-tech innovation. Our findings underscore that deep-tech ventures are usually embedded in multi-actor systems that provide essential functions and resources for incubation, de-risking, and scaling. Because deep-tech innovation is infrastructure-intensive and high-risk, ventures rarely progress without access to facilities, regulatory pathways, and legitimacy that are held by universities, public research infrastructures, corporations, investors, and specialized intermediaries. Moreover, the combination of specialized infrastructure (e.g., synthetic-biology pilot lines), patient capital, and scientific talent is rarely available in a single location. As a result, ventures must assemble resources from disparate global ecosystems. Future research could examine how regional deep-tech ecosystems are built, how stakeholders and resources are attracted and coordinated, and under which conditions such ecosystems can be intentionally designed rather than developing organically over time. Relevant cases for study and comparison in this regard may include intentionally designed initiatives, such as current efforts in the Heilbronn region of Germany, and more organically grown ecosystems such as Kendall Square in Cambridge, in the US.

A further ecosystem-level issue, which is closely linked to the asset intensity of deep-tech innovation, is the recurring infrastructure gap. Founders consistently report that the path from laboratory research to market entry is constrained by limited access to shared physical infrastructure. Facilities such as cleanrooms, wet labs, grid-connected demonstration sites, and chemical pilot plants are costly, scarce, and difficult for individual startups to build on their own. As a result, access to such infrastructure often becomes the main limitation to whether and how quickly deep-tech ventures move from proof-of-concept to commercial application (Diamandis et al. 2025; Reisdorfer-Leite et al. 2023). This motivates research on the design and governance of physical innovation spaces that support deep-tech innovation. Future work could specify what technical capabilities and operating conditions these spaces must meet to address the varied needs of deep-tech projects, and which stakeholders can sustainably supply and manage them. This includes first-of-a-kind industrial experimentation, where facilities may need tight control of external disturbances (e.g., vibration or temperature variation) and must meet safety and disposal requirements when hazardous materials are involved, while still remaining modular enough to accommodate changing technological needs. Such spaces may also supply specialized shared equipment that individual deep-tech founders cannot finance on their own. Beyond technical characteristics, research could examine how the social and organizational design of these spaces influences knowledge exchange, cross-domain interaction, and learning. Spaces such as LabCentral or The Engine in Cambridge, US, offer useful cases for this line of inquiry.

Table 2. Research Agenda

Thematic area	Potential questions for future research
Deep-Tech Innovation Core	• How can early scientific inquiry adopt cost-informed discovery practices without eroding the autonomy required for open exploration? • How can deep-tech teams manage the tension between the path-dependent nature of basic science and the need to progress toward commercial milestones after leaving the research environment? • What validation portfolios (e.g., simulations, digital twins) best facilitate rapid iteration in asset-heavy deep-tech projects? • Which elements of established agile innovation approaches (e.g., design thinking) can be applied in deep-tech contexts, and through which mechanisms do they create value in asset-heavy settings? • In which areas do deep-tech projects require adjustments to existing innovation approaches or entirely new ones, and what design principles should guide their development?
Deep-Tech Venture	• How can deep-tech ventures structure early search processes to test multiple application domains while still presenting a clear and fundable initial use case in a beachhead market? • How can deep-tech ventures credibly signal progress to key stakeholders in the absence of revenue? • How can deep-tech ventures coordinate scientific de-risking and commercial validation over time, and which formats and mechanisms enable the interdependence of technical and market learning? • How can "translator" leaders bridge scientific and commercial thought worlds as ventures transition from researcher-dominated teams to commercially oriented, industry-focused organizations?
Deep-Tech Ecosystem	• How can regional deep-tech innovation ecosystems best assemble and coordinate specialized infrastructure, patient capital, and scientific talent, and what conditions enable effective coordination among universities, research institutes, corporates, investors, and intermediaries? • To what extent can deep-tech innovation ecosystems be created through deliberate planning, and how do designed ecosystems compare with organically developed ones in their ability to cultivate deep-tech innovation? • How should physical innovation spaces be designed and governed to meet the technical and operational requirements of deep-tech ventures, including first-of-a-kind experimentation, modular infrastructure, and access to specialized shared equipment? • Which new ecosystem actors (e.g., specialized brokers, facility design teams) are emerging to support deep-tech innovation, and what capabilities do they contribute? • How should the social and organizational design of deep-tech innovation spaces support interaction, knowledge sharing, and integration among diverse innovators while preserving opportunities for serendipitous learning? • Which engagement formats and governance arrangements enable effective collaboration between deep-tech ventures and corporate partners? • How do corporate engagement models dynamically evolve, and which internal resources and capabilities must incumbents build to absorb deep-tech innovations effectively?

Dependence on industrial partners in later-stage growth raises a related set of questions about corporate involvement. Deep-tech ventures originate from new approaches in advanced science and engineering, but the problems they address frequently sit within established industries. This creates demand for structures that connect ventures and incumbents under conditions of high technical uncertainty, substantial capital needs, and long development horizons. Prior work suggests that the form of collaboration must change as a venture progresses (Harlé et al. 2020). Future research could assess how sequences of support, from university programs to deep-tech builders to corporate partnerships, shape venture development, and how incumbents design engagement approaches that evolve from early exploration to shared industrialization and market creation. Table 2 summarizes the research agenda and key questions.

Conclusion

In this paper, we reviewed the literature on deep-tech innovation and complemented the resulting synthesis with in-depth interviews with deep-tech founders. On this basis, we developed an attribute-based framework that clarifies how deep-tech innovation can be defined and distinguished from adjacent concepts. The framework specifies the defining attributes of the deep-tech innovation core, differentiating them from recurring venture- and ecosystem-level attributes that tend to accompany development and scaling, and positions deep-tech innovation relative to adjacent concepts. By providing a clearer conceptual foundation and boundary structure, the framework can serve as the basis for more consistent operationalization, sampling, and comparison in future research, thereby enabling more structured and cumulative advancement of knowledge in the field (Furman & Stern, 2006). To support this aim, we outlined an agenda that identifies avenues for systematic research across the framework layers. Last, the framework may help ecosystem stakeholders better coordinate support activities and communicate more effectively, while providing policymakers with a consistent classification language for more targeted and coherent policy design.

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