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# Measuring Innovation: Perspectives from Engineering Education and Clean Energy

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A dissertation  
submitted in partial fulfillment of the  
requirements for the degree of

Doctor of Philosophy

University of Washington

2024

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**Abstract**

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Measuring innovation is key to realizing innovation in practice. One of the primary reasons why measurement is important stems from the fundamental principle that what is measured is, in turn, what garners attention and action. Systematic measurement of innovation can enable researchers and practitioners to propose and undertake strategic interventions that enable effective action and use of resources. However, a large proportion of innovation measures developed in literature are catered towards researchers, economists and analyst who are removed from the innovation process. These measures do not address the needs of the practitioners and actors who are actively involved in innovative activities. Therefore, the foundational question that this dissertation seeks to answer is: How can innovation be measured in a way that bridges the study of the innovation process with its practice? To answer this research question, I weave together three studies where I produced contributions to diverse domains. I leverage the robustness of the technological innovation system (TIS) framework to ground my research. The first study looked at industry sponsored engineering design capstones as a "laboratory" for small-scale innovation. Through this study the first framework of measurement emerged, one that categorized measures of innovation as evaluative and actor-centric. The second study took a broader approach to investigate perceptions of innovation measures across diverse actors in an innovation system. This study resulted in the second measurement framework that placed measures on an availability-influence framework that balanced the availability of different measures with their decision-making influence. The final study validated this framework by applying it to assess the long duration energy storage (LDES) innovation system. The study

not only yielded strategic interventions that could enhance LDES innovation, but also validated the process of using the frameworks that emerged in previous studies to assess innovation systems. Together, these three studies yielded two novel frameworks that are born out of studying innovation and the practices of innovation in diverse, interdisciplinary settings. This dissertation provides an expansive, cross-disciplinary view of how measures that evaluate the process of innovation can be combined with measures that encompass the diverse practices of innovation. Through this work, I argue that combining the study of the system of innovation with the practice of innovation can help bridge the gap between both realms and can ultimately enhance both.

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## DEDICATION

*Be patient toward all that is unsolved in your heart and try to love the questions themselves, like locked rooms and like books that are now written in a very foreign tongue. Do not now seek the answers, which cannot be given you because you would not be able to live them. And the point is, to live everything. Live the questions now. Perhaps you will then gradually, without noticing it, live along some distant day into the answer.*

*-Rainer Maria Rilke*

*If you feel safe in the area you're working in, you're not working in the right area. Always go a little further into the water than you feel you're capable of being in. Go a little bit out of your depth. And when you don't feel that your feet are quite touching the bottom, you're just about in the right place to do something exciting.*

*-David Bowie*

To those willing to live the questions, wade out of their depth and weave worlds together to forge  
new answers.

## ACKNOWLEDGMENTS

A PhD is an arduous quest that fundamentally changes one's worldview about how to think, question and probe existing knowledge. As a novice, it is easy for this quest to go completely awry without the support and guidance of a good mentor. In that vein, I would first like to offer my deepest gratitude to my advisor Dr. Denise Wilson. My PhD quest would have gone completely off the rails without her wise and compassionate mentorship. Thank you Denise for taking a chance on me and my "non-traditional" topic and helping me make it into something that I am proud of. Your guidance, compassion and faith in my abilities has made me the researcher I am today. Thank you for being my loudest advocate and wisest confidante and for believing in my work when I did not believe in it myself. You have set the bar of mentorship to infinity and have not only taught me how to be a good researcher but also an advocate for others and a mentor.

I would like to extend my gratitude to my committee Dr. Payman Arabshahi, Dr. Kristi Morgansen Hill and Dr. Nidhi Agarwal for being so open to my work, actively supporting it and offering insightful directions. Thank you for also being an advocate and making this process so easy and smooth. I would especially like to thank Dr. Arabshahi for his support, for giving me the opportunity to work for ENGINE, a program that is so important to my journey, and make it my own. You have been incredibly kind and open to all the ideas I brought to the table and encouraged me to pursue them. ENGINE was the spark that became the fire fueling this dissertation, and it would not have been so without your unwavering support and trust in my abilities. I also want to thank the College of Engineering Industry Capstone programs team, specifically Jill Kaatz and Dorian Varga. Thank you both for working with me, allowing me to run experiments with the program and offering your time and support outside work. Your encouragement and recognition has always made my heart glow and kept me pushing forward.

I would like to thank the Buerk Center for Entrepreneurship for opening up a world of opportunities that allowed me to experience the process of "doing innovation". I would like to thank Jessica Roberto and Ken Horenstein for their mentorship during my fellowships. Working with you was imperative in understanding the human and messy side of innovation. I would also like to extend my gratitude to Nirav Desai for always being open to talk about innovation ecosystems, bounce ideas and providing me with the opportunity to work with Moonbeam Exchange, an experience that showed me the economic development side of innovation.

I would like to extend my thanks to my UW friends Yana, Maneeshika, and Neha for their listening ear and unequivocal encouragement throughout the process. I would also like to thank the advising team specifically Brenda Larson and Stephanie Swanson who helped me through some of my hardest times, looked out for my well-being and supported difficult transitions without which I won't be here today. I would also like to thank all of my friends Kelli, Sharon, Rashmi, Anushka, Manleen, Tim, and Natalie who have kept me sane throughout the process especially during COVID-19. The Greenlake runs, music jam sessions, weekend and latenight chats, IMA sessions, latenight Karak tea and ice cream conversations, and art jams are what kept me alive through some of the most challenging parts of this journey.

I would like to thank Andrew Ward for always being there, wading with me through the blood, sweat and tears until the end. Your love, compassion and perseverance helped me reach the end. I could not have done this without my sister Sonal who has been my loudest cheerleader forever. Thank you for your diamond-strength support, you are the younger one, yet teach me so much. I would like to thank my Seattle family especially Rajeev chacha, Shalini chachi, Pooja bua for giving me a home away from home that is just as loving. Your presence and support has been so foundational in this entire journey. Most importantly, I would like to thank my parents Renu and Sanjeev for trusting me and giving me wings to fly. Thank you for your unending love, sacrifices, support and the numerous opportunities you have given me that make me who I am.

## Chapter 1

### INTRODUCTION

When one thinks about technological advancement, names such as Thomas Edison, Nikola Tesla, and Alexander Graham Bell come to mind. These iconic figures have left a deep-rooted mark on the world of innovation. However, it is deceiving to attribute the advancement of technology solely to the brilliance of individuals. Instead, studies consistently demonstrate that technological progress is a collective endeavor that rarely rests on the shoulders of a solitary genius. Research has shown that individuals working in isolation are not only less likely to achieve breakthroughs but are also prone to generating suboptimal outcomes [170]. More often than not, novel technologies emerge almost simultaneously from the efforts of two or more groups working independently of each other [110]. In essence, technological innovation is a collaborative process undertaken by a multitude of actors, institutions, and networks [59].

The dynamics of innovation are complex, historical, and in a constant state of flux. They rely on a myriad of contextual factors, including geographical location, industrial sectors, and the nature of the technology in question [114, 39, 23, 30]. Take, for example, renewable technologies. The successful invention, diffusion, and adoption of these sustainable solutions hinge on governmental funding for research and development, the adaptability of domestic industries to new technologies, market incentives that encourage the production of sustainable innovations, and the availability of a skilled workforce equipped to work on these emerging technologies. Such interactions among actors, institutions, networks, and systems result in the process of technology transition being an exceedingly complex one. It stretches across long timeframes and encompasses broad socio-technical structures. While the trajectory of technological innovation can be deliberately influenced by the systems, structures, organizations, and institutions involved, the endeavor is anything but straightforward. This complexity is summarized in what is known as the Collinridge Dilemma, as articulated by David Collinridge [37]:

*“When change is easy, the need for it cannot be foreseen; when the need for change is apparent, change has become expensive, difficult and time consuming.”*

The dilemma states that efforts to control the process of technological innovation runs into a double-bind problem. The most effective time to target interventions to guide technological change is when a technology is just emerging. However, in the early stages of a technology, its impacts (economic, social, ethical etc.) are uncertain introducing considerable risk to any intervention. It is until the technology is significantly developed and widely adopted that its financial, social, and economic impact is revealed [162]. This central uncertainty especially in the early stages of a technology’s development creates a precarious foundation and a constantly shifting target for strategic interventions by practitioners, who are actors in the innovation process.

Strategic interventions, in turn, hinge on the ability to measure the current state of technological development accurately. Measurement implies comparison and assumes that the systems or entities being measured are qualitatively similar. However, innovation, by its very essence, implies originality. It involves the creation of something qualitatively new, resulting in novel performance outcomes. While certain aspects of these outcomes, such as fuel efficiency or cost reductions, can be measured in a quantifiable manner, broader comparisons may lose their meaning. This is because innovation inherently brings about changes to incumbent structures through new processes of learning and knowledge organization [34]. For instance, while it is possible to compare the technical efficiency of electricity generation through solar power versus conventional oil and gas methods, it becomes increasingly challenging to assess the trade-offs in terms of cost and systemic changes when considering factors like reduced emissions. Therefore, the pressing question that emerges is: how do we measure innovation effectively? More specifically, how can we measure innovation in a way that is relevant to the practitioners actively engaged in the innovation process and capable of guiding strategic interventions? This question forms the foundation of this dissertation.

Two significant problems are identified in the current landscape of measuring innovation. Firstly, conventional measures or indicators of innovation, particularly those centered around research and development (R&D), often emphasize aspects of the process that are straightforward to measure. Consequently, they tend to overlook activities that are pivotal to the innovation process but considerably more challenging to quantify such as engineering design, product development and knowledge

exchange. These gaps result in an incomplete picture of the innovation landscape [76]. This stems from an availability bias, where measures that are readily available might be perceived as accurately representing the innovation process, which is usually not the case. Secondly, existing measures of innovation are predominantly evaluative, they focus on evaluating the state of an innovation system rather than guiding action to move innovations forward. These evaluative measures primarily cater to economists and policymakers, i.e., those who study innovation. They frequently disregard the perspectives and needs of practitioners who are actively participating in the innovation process. This misalignment results in a noticeable gap between those actively "doing" innovation and those tasked with measuring it [73, 161], .

Hence, the overarching objective of this work extends beyond identifying the gaps in current measures of innovation. It strives to advocate for a shift towards actor-centric measures that consider the viewpoints and requirements of those directly involved in innovation efforts. In essence, the goal is not merely to highlight the missing pieces of the puzzle but to build a compelling case for why actor-centric measures are essential in the contemporary landscape of innovation measurement. To sum up:

*The dissertation's objective is to make a substantive contribution to the understanding of measures of innovation. It achieves this goal by delving into the roles played by various actors and institutions in innovation systems, grappling with the challenges inherent in measuring innovation accurately, and underscoring the urgency of adopting "actor-centric" approaches to measurement. The ultimate aim is to enhance comprehension of the innovation process, equipping actors with the insights needed to navigate the complex terrain of technological advancement effectively.*

### **1.1 Measures of Innovation: What exists and what is missing?**

*"When you can measure what you are speaking about, and express it in numbers, you know something about it...[otherwise] your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in thought advanced to the stage of science."*

*-Lord Kelvin, 1824-1907*

Measuring innovation is key to realizing innovation in practice. One of the primary reasons why

measurement is important stems from the fundamental principle that what is measured is, in turn, what garners attention and action. This strategic significance is underscored by the ability of innovation measures to serve as signals for an organization's innovation strategy and use resources more efficiently by better identification of problems and implementation of remedial solutions [45]. By systematically gauging innovation, actors and organizations can focus efforts on defined innovation objectives and streamline associated processes [22]. Ultimately, measuring innovation allows actors to better identify and evaluate new business and learning opportunities in an informed manner. In essence, the absence of a robust innovation measurement framework diminishes the likelihood of securing returns on innovation investments and increases the likelihood of overlooking promising opportunities [19].

While the advantages of measuring innovation are becoming increasingly apparent [54, 157], what is less clear is how to actually measure innovation in practice. Measuring innovation is a formidable challenge, as it involves capturing a multifaceted and dynamic phenomenon that extends beyond conventional quantitative measures. In the realm of innovation measurement, there exists a complex landscape of methodologies and indicators designed to capture the abstract nature of innovation. The question of how to measure innovation has been asked repeatedly by researchers, policymakers, managers, and economists (e.g., [13, 53]). Quantifying innovation is far from straightforward, as it encompasses a spectrum of intangible elements such as ideas, learning, competencies, capabilities, and knowledge generation, which resist easy measurement. Given below is a broad classification of different measures of innovation that exist in literature [66]. Chapter 2 provides further details on existing measures and how they fit within the conceptual framework adopted by this dissertation.

1. **STI (science, technology and innovation) measures:** These measures predominantly revolve around research and development (R&D) activities. Indicators in this category include research expenditure, patents, publications, and bibliometric analyses, which examine citation patterns and research networks.
2. **Technometric indicators:** These indicators delve into the technical performance characteristics of products, providing insights into the technological capabilities and performance of innovations [164, 163, 84].

3. **Synthetic indicators:** Developed mainly for benchmarking and comparison purposes, synthetic indicators are often created by consultants or organizations like the World Economic Forum. They aim to offer a consolidated view of innovation performance [40].
4. **Specialized Databases:** Various databases focus on specific aspects of innovation. For instance, some databases track technological collaboration among firms or collect data on large firms' innovation activities [144, 145], or the MERIT-CATI database on technological collaboration developed by John Hagedoorn [86].
5. **Innovation Surveys:** National and sub-national agencies often conduct surveys to collect data on innovation activities within specific regions or sectors.

While the above categories of measures provide a good and broad starting point for studying innovation measurement, they leave much room for elaboration. For example, while quantitative outputs like patents and publications provide some insight into the intensity of invention, they do not provide insight into the quality of and the activities underlying those publications and patents. Additionally, they also do not help understand knowledge exchange and collaborations that may have occurred to manifest the publications and patents. To comprehensively understand innovation, measures must encompass the diverse determinants impacting innovation processes and offer evidence of their far-reaching influence. This is particularly crucial for understanding how knowledge exchange and collaborations evolve and affect various innovation systems and sectors, as the lack of comprehensive measures hinders such activities. [73, 154].

Measuring innovation is further complicated by the dynamic and evolving nature of innovation environments. There is a myriad of sources that can affect the course of an innovation, anything from a decline in public funding for research to economic recession or even a pandemic (as was the case in 2020). These complexities make it challenging to isolate specific variables, causes, and effects accurately. The diversity of innovation measures reported in academic literature often proves too theoretical for practical application [1, 44], and organizations may have varying perspectives on what should be measured. Consequently, a lack of measurement strategy can lead to irrelevant data collection, insufficient data gathering, or even a complete absence of innovation measurement. In fact, one of the fundamental challenges in measuring innovation lies in the unavailability of suitable

data and methodologies [3, 58]. Existing measures, such as those focused on expenditures, publications, and patents, fall short in evaluating the commercial potential of innovations, particularly in their early stages. Developing additional measures that can be applied during these nascent phases remains an ongoing concern. Furthermore, the absence of standardized measurement frameworks leaves both scholars and practitioners seeking more clarity and guidance in their pursuit of meaningful innovation measures [17, 58].

In conclusion, the measurement of innovation is a complex endeavor that extends beyond traditional quantitative measures. While existing measures offer valuable insights, there remains a pressing need for more comprehensive measures that can capture the essence of innovation in diverse settings and cater to different actors in the system. Understanding how to discover and apply relevant measures in specific contexts is as vital as the development of standardized measures in the field of innovation measurement.

## **1.2 Research Conceptual Framework**

The preceding discussion asserts that existing classes of innovation measures fall short in two critical aspects: (1) adequately capturing the wide spectrum of activities, particularly collaborative and knowledge exchange endeavors that drive an innovation system, and (2) providing practitioners and participants in innovation systems with tools to propel their innovations of interest forward. Consequently, the overarching objective of this dissertation is two-fold: (1) to highlight and propose measures for alternative yet equally important activities that drive an innovation system forward, and (2) to underscore the importance of and exemplify the development of actor-centric measures for innovation that are tailored to specific contextual domains.

The analyses presented in this dissertation are grounded in the theory of innovation and innovation system. This work adopted the conceptual lens provided by the Technological Innovation Systems (TIS) framework, which is defined as:

*A dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology [30].*

The TIS framework provides a lens to study innovation by focusing on a technological field and studying the systemic features, such actors, institutions, network, technologies and most importantly, all the interactions between them [31]. Instead of placing sole focus on the technology itself, the TIS framework emphasizes the broader ecosystem within which technological innovations emerge and develop. The framework emphasizes not only the significance of developing new knowledge and stimulating knowledge flows between various actors, institutions, and networks, but also the need to leverage this knowledge into business opportunities and adoption [182]. To this end, a TIS consists of two components: a structural component and a functional component.

The structure of a TIS encompass a range of actors, institutions, organizations, and the networks that are involved in innovation activities in a particular technological field. These actors can include universities, research institutions, government entities, companies, business, and various other actors. In addition to a structural element, a TIS consists of seven fundamental functions that are crucial to its working. These functions provide a comprehensive view of how innovations are fostered, developed, and diffused within a given context. While the specifics might vary, these functions are.

1. F1. Knowledge Development
2. F2. Knowledge Exchange/Diffusion
3. F3. Entrepreneurial Experimentation
4. F4. Guidance of Search
5. F5. Resource Mobilization
6. F6. Market Formation
7. F7. Legitimation

Further details of the framework are provided in Chapter 2. Traditionally, the TIS framework is applied to conduct studies in a specific technology or technological field. While a key portion of

this dissertation is in the flavor of a traditional TIS study (See Chapters 6 and 7), other parts of this work leverage the robustness of the TIS framework to assess knowledge flows and interactions between specific actors outside a technological context. The main reason why this framework was used to guide this dissertation is because unlike other types of innovation system frameworks, the structural and functional elements of TIS provide the ability to study various levels of interactions that influence innovations; from the micro scale (between actors) to a macro scale (national policies and multiple actors). Therefore, the framework provides a flexible yet relevant lens through which innovation measurement can be understood as it pertains not only to those who are “doing” innovation (structure: actors, intuitions, networks etc.) but “how” they are “doing” innovation (function: knowledge development, knowledge exchange etc.).

### ***1.3 Research Design and Aims***

This dissertation work on understanding innovation measurement was guided particularly by the functions of a Technological Innovation System (TIS) in the US context and consequently culminated in three studies.

#### **1. Study 1 (F1 & F2): University-Industry Partnerships for Education**

**Aim: Develop relevant measures to assess the value of U-I collaborations for engineering design education**

The F1 and F2 functions of a Technological Innovation System focus on Knowledge Development and Knowledge Exchange respectively. In the US, universities are the seat of deep technological knowledge development. They are also the locus of education for preparing a workforce ready to participate in innovation activities. The direct knowledge (through research and patents) and indirect knowledge (through education and training) developed at universities typically find their way to industry. Therefore, symbiotic relationship between universities and industry is crucial for driving the innovation economy, as knowledge developed at universities is disseminated to industry through research, patents, and education.

The measures of university-industry interactions for direct knowledge development and ex-

change (research intellectual property and entrepreneurship) have garnered substantial attention and investigation in literature. However, measures associated with university-industry interactions for indirect knowledge development and exchange through education remain understudied [124, 125]. Traditionally, measures employed within educational settings, including those associated with university-industry partnerships, have predominantly been centered on learning outcomes (knowledge development among students). While these traditional measures may work in settings where students are learning knowledge fundamental to their field (for example, basic circuits theory in electrical engineering), they fall short in settings where students are engaged in more innovative activities such as design, particularly when collaborating with industry partners. University-industry partnerships for project and design-based courses not only help develop indirect knowledge, but they also enable the exchange of such knowledge between the two actors. To that end, this study focused on proposing and validating measures for university-industry partnerships in an engineering design capstone to address the lack of measures that capture the nuances of knowledge development and exchange between universities and industry in an education context.

The primary objective of this study to craft measures that effectively gauge the value of University-Industry (U-I) collaborations in engineering design education. Innovation measurement within the educational context is a broad endeavor, and this work narrows its focus to a specific category of U-I partnerships for education: industry-sponsored engineering capstone design experiences. To accomplish this objective, the investigation is centered on the development of pertinent measures linked to student experiences and learning outcomes in the context of capstone projects.

The study contributes to the framework of innovation measurement by introducing two main types of measures:

- (a) **Evaluative Measures:** These are measures that assess the output or outcomes of an innovation system. In the context of this capstone study, evaluative measures will include measures of the engineering design knowledge developed (transferred from mentors to) in students. Given below is an example of an evaluative measure that emerged in this

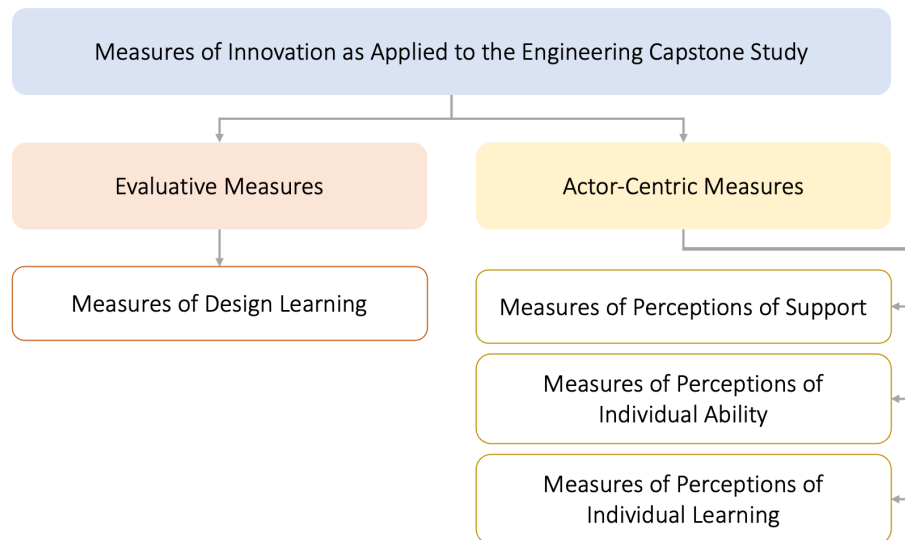


Figure 1.1: Evaluative and Actor-Centric Measures in Study 1

study.

- **Measures of Design Learning:** Problem scoping measures
- (b) **Actor-Centric Measures:** Actor-centric measures are specific to different actors in the innovation system and are contextualized to their activities. These measures include criteria that actors use to assess the success and failure of their own activities in an innovation system. In the context of the capstone, these measures are mainly measures of perception regarding what students in a capstone perceive as being important to their design education.
- **Measures of Perceptions of Support:** Team support and industry mentor support
  - **Measures of Perceptions of Individual Ability:**

- **Measures of Perceptions of Individual Learning:** Engineering Design and Decision-Making and Adaptability

Figure 1.1 illustrates the two types of measures that emerged from study 1.

## 2. Exploring Actors' Perspective on Innovation Measures

**Aim: Evaluate Actors' Perspectives on Research and Entrepreneurship Measures for Innovation**

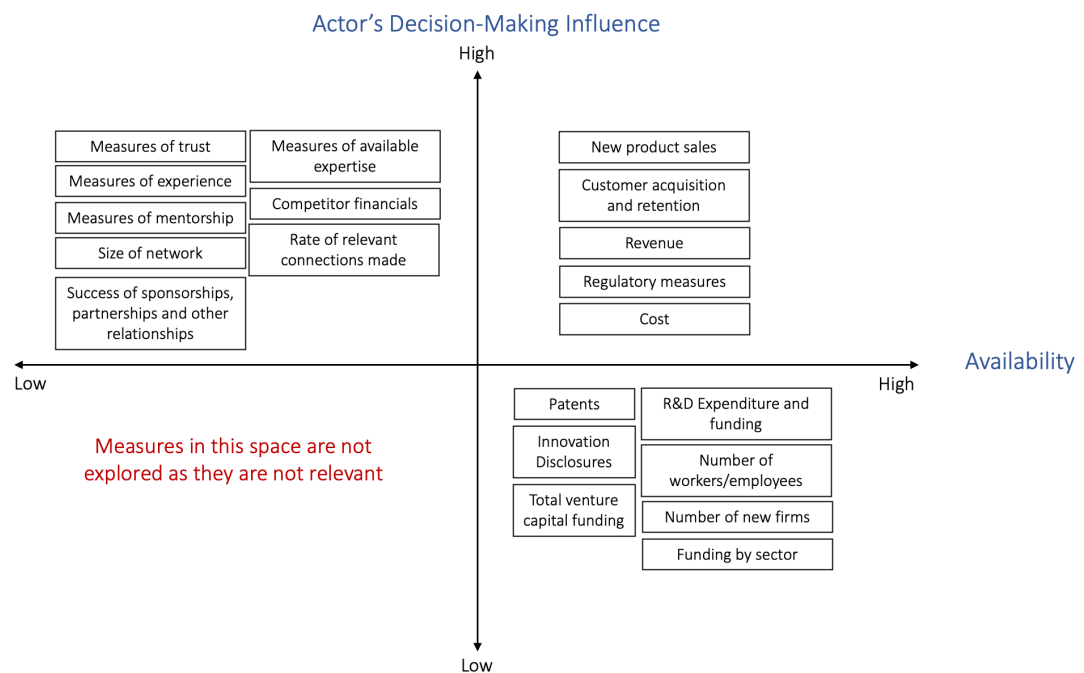


Figure 1.2: Availability and Influence Paradigm of Innovation Measurement

Building upon the preceding study, which delved into the often-overlooked realm of university-industry collaborations in education, Study 2 broadens the investigation to assess the perspectives of diverse actors within an innovation system. The previous study highlighted two

key categories of innovation measurement, namely, evaluative measures, and actor-centric measures. There is abundant literature on evaluative measures of innovation. However, the literature on actor-centric measures is lacking and fragmented across different disciplines. Therefore, a broader study was conducted regarding perspectives of diverse actors in an innovation system pertaining to what measures of innovation they find relevant for their activities and what is missing. Therefore, while the prior study identified and proposed measures in the context of university-industry interactions for education, the current study explores a more comprehensive understanding of innovation measures from the standpoint of actors involved in research and entrepreneurship. In essence, this study bridged the gap between the core functions of a university (research and education) and opened it up to the interactions among different actors including universities. The study leaned towards obtaining perspectives on entrepreneurship and research activities and shift focus towards addressing functions F3, F4, F5, F6 and F7 of a Technological Innovation System (TIS).

The rationale behind this study lies in the observation that existing innovation measures, primarily developed by researchers and economists, may not sufficiently address the needs, experiences, and perspectives of various actors and practitioners within innovation systems. Moreover, theories regarding actor interactions are scattered across multiple disciplines, contributing to the fragmented nature of actor-centric measures. The goal of this study was to understand the extent to which the evaluative measures of innovation from literature were useful to actors in the field and what measures do they use or would like to use to conduct their activities. IS, which has not been addressed in the previous study.

Utilizing a qualitative think-aloud approach, the study employs an interactive data dashboard representing commonly accepted measures for innovation activities. This dashboard served as a tool during semi-structured interviews with participants from diverse actor groups, including university actors, corporate entities, entrepreneurs, government representatives, and a miscellaneous "other" category. The study involved 13 participants from six distinct actor groups: university actors, corporate actors, entrepreneurs, government actors, and a miscellaneous "other" category. The data was analyzed using a systematic thematic analysis guided by the technological innovation systems (TIS) framework.

Two key findings emerged from this study. First was the emergence of an innovation measurement framework based on the availability of measures versus their influence on actors' decision-making (Figure 1.2). Note that the measures in the figure are not exhaustive but are representative of the type of measures in each category. The framework revealed that most of the commonly used evaluative measures from the innovation systems literature lie in the quadrant for measures that are readily available but do not have very high influence on actor's decision-making. The second finding was the need for narrowing the scope of the study to an industry, sector and/or technology to get a clearer view of practical actor-centric measures that can help propel innovations in that field towards wider adoption.

### 3. TIS Analysis of Long Duration Energy Storage Technologies

#### **Aim: Integrate Innovation Measurement Frameworks for Assessing Innovation in Long Duration Energy Storage Technologies**

This study serves as a culmination of the innovation frameworks established in this dissertation, applying them to a specific sector—long duration energy storage (LDES) technologies. Adhering to the Technological Innovation System (TIS) analysis methodology, the study encompasses both structural and functional analyses, incorporating evaluative measures specific to the LDES context. The structural analysis identifies key players and actors in the LDES space, while the functional analysis delves into the health of various functions within the LDES TIS, guided by corresponding measures, unveiling inducing and blocking mechanisms operating in the LDES TIS, derived from the structural and functional analyses. Next, actor-centric measures tailored to practitioners in the field are obtained by analyzing six use cases of LDES technologies. Finally, both evaluative and actor-centric measures are "parsed" through the availability-influence framework developed in Study 2. By incorporating actor-centric measures and revealing the different levels of accessibility of measures, this study aims to demonstrate how to reconcile the disparities between conventional innovation measures and the practical requirements of those involved in innovative endeavors.

Through a systematic progression of studies, this the dissertation has endeavored to bridge

critical gaps in existing paradigms. The initial study delved into the underexplored arena of University-Industry (U-I) collaborations in engineering design education, spotlighting the inadequacy of conventional measures and necessitating the creation of novel, actor-centric measures. Building upon this foundation, the second study expanded the inquiry, probing the perspectives of various actors within innovation systems and unveiling a nuanced interplay between evaluative and actor-centric measures. Here, the availability vs. influence paradigm emerged as a guiding framework, revealing the differential impact of measures on decision-making. Finally, the process of innovation measurement through the two frameworks developed in this dissertation (evaluative-actor centric and availability-influence) were validated by applying them in a case study to assess the long duration energy storage innovation system.

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Collectively, these studies advocate for an innovation measurement framework that transcends conventional measurement strategies restricted to analysts and researchers and accommodated the diverse the perspectives of key actors. By emphasizing the integration of evaluative and actor-centric measures, this dissertation aspires to reshape how innovation is gauged, providing a dynamic toolkit that resonates with the practical needs of those steering the course of technological evolution. In summary, this dissertation redefines the parameters of innovation measurement, prioritizing the integration of actor perspectives alongside the evaluation of innovation systems. The proposed measurement framework aims to enrich the understanding of innovation processes and contribute

to the creation of more effective measures. The contribution seeks to foster a more insightful, adaptable, and actionable approach to innovation measurement, propelling the field toward a future of informed, collaborative, and transformative endeavors.

## 1.4 Dissertation Outline

Figure 1.3 depicts the research flow for this dissertation.

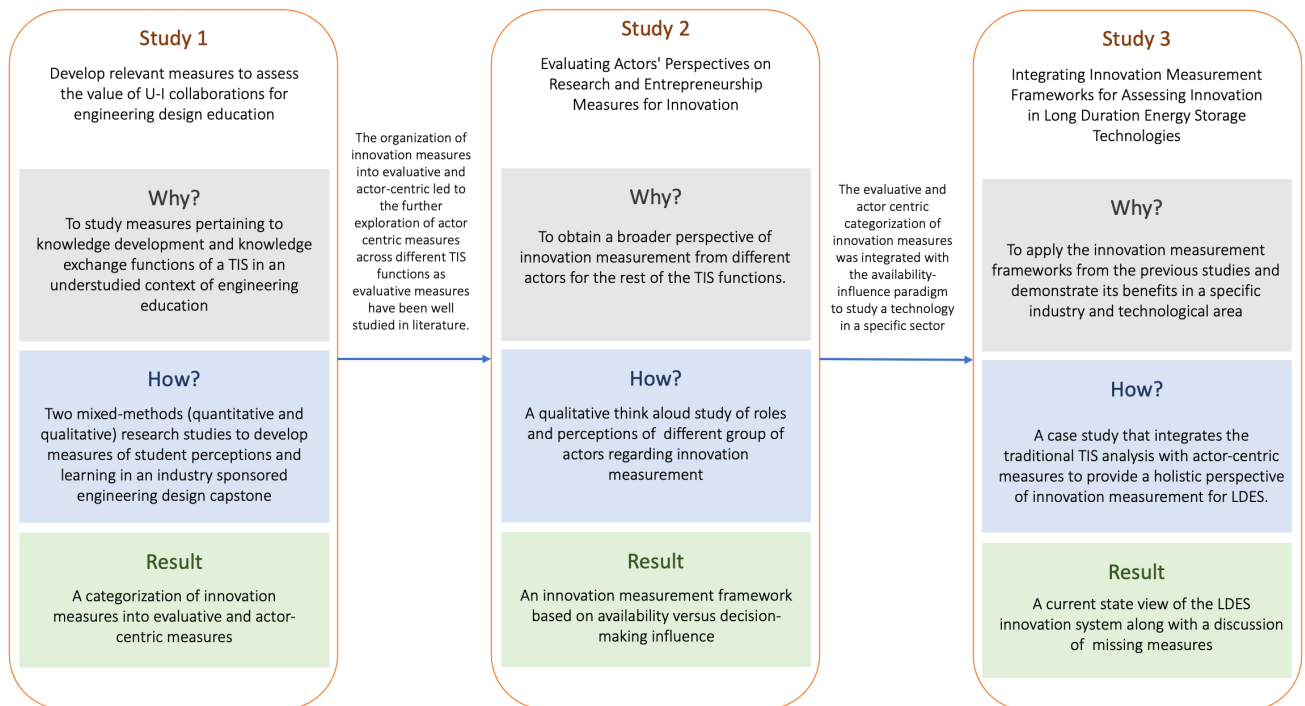


Figure 1.3: Research Design

The remainder of this dissertation is structured as follows:

- Chapter 2 serves as the theoretical foundation for innovation measurement. It provides a detailed overview of the Technological Innovation Systems framework along with examples of existing measures as they pertain to this framework.

- Chapter 3 serves as a methodological guide for this dissertation, outlining the systematic approach used in each study. As a whole, this dissertation adopts a mixed-methods approach that integrates both qualitative and quantitative methods analysis to construct a narrative of aspects of innovation measurement.
- Chapter 4 discusses Study 1. It provides a brief introduction to university-industry partnerships in the context of education and gaps in measuring innovation within these partnerships. It then presents research conducted on evaluative and actor-centric measures that emerged in the context an industry sponsored engineering design capstone program
- Chapter 5 discusses Study 2. It provides a background on the tools developed for the study, namely the interactive dashboard, describes the setting, instrument, methodology, results, and conclusions for the study.
- Chapter 6 provides a brief introduction to long duration energy storage (LDES) technologies as part of Study 3. This introductory chapter acts as a bridge to Chapter 7, where the study delves deeply into the innovation systems analysis of long duration energy storage technologies.
- Chapter 7 discusses the evaluative TIS analysis for LDES technologies which inform a deeper dive into the inducing and blocking mechanisms operating within the LDES TIS, followed by an exploration of actor-centric measures within the LDES TIS. The chapter ends with strategic recommendations for enhancing the functioning of the LDES TIS based on findings derived from the application of the innovation measurement frameworks developed in this dissertation
- Chapter 8 presents a conclusion and summary of the main results of the dissertation, reiterating the main findings from the different studies. The chapter also offers critical reflections on the findings of the dissertation as they relate to the author's own experiences in the practice of innovation.

## Chapter 2

### THEORY

#### ***2.1 Foundations of Innovation Measurement***

The concept of innovation and technological change has a rich and enduring history, dating back to the dawn of human civilization when the first spark of fire was harnessed, agriculture was cultivated, and the Industrial Revolution transformed societies. However, the systematic study of innovation as a phenomenon didn't gain rigorous scholarly attention until the mid-20th century when Joseph Schumpeter, an influential economist, popularized the concept of "creative destruction" in the 1940s [165]. Schumpeter's idea of creative destruction provided a framework for understanding how technological advancement disrupts industry structures when established firms fail to adapt swiftly and are supplanted by new entrants. This notion spurred scholars to delve into the definition and examination of technological innovation from both quantitative and qualitative perspectives. Consequently, various definitions of technological innovation have proliferated in the literature, reflecting the complex nature of the phenomenon and its different facets across various disciplines [93]. For a comprehensive interdisciplinary understanding of innovation, Baregheh et al. (2009) conducted a content analysis of 60 definitions from diverse fields, including business and management, economics, organizational studies, innovation studies, and entrepreneurship, as well as technology, science, and engineering. They synthesized these perspectives into the following definition of innovation:

*"Innovation is a multi-stage process whereby organizations transform ideas into new/improved products, services, or processes, in order to advance, compete and differentiate themselves successfully in their marketplace.[10]"*

This definition underscores two key features of innovation. First, it encompasses not only the creation of new products but also the development of novel processes. Innovation extends beyond

the introduction of new tangible objects, such as new solar cell designs or software applications, to encompass inventive processes of accomplishing tasks, such as more efficient techniques for producing specific chemicals or improved hiring processes to secure employees who are a better fit for a given organization. Consequently, relying solely on technical measures that compare product features is insufficient to capture the wide array of phenomena encompassed by innovation. Second, innovation transcends mere novelty. It involves not only the creation of new or enhanced products and processes but also the imperative to bring them to the market and make them available to potential users. In essence, innovation is a holistic process that involves both invention, which pertains to the creation of novel technologies, and adoption, which includes commercialization. Thus, measuring invention alone is inadequate, necessitating the incorporation of market-based and economic measures that gauge the diffusion and adoption of new technologies and technological processes.

The field of economics by far has the most copious literature on technological innovation and change. Within economics, there exist many theories which place innovation front-and-center, but none emphasize its importance more than evolutionary economics. Evolutionary economics offers a distinctive perspective on technological innovation, contrasting with the static equilibrium assumptions often found in dominant neoclassical economic theory. Neoclassical economics focuses on obtaining an equilibrium determined by pricing mechanisms. On the other hand, evolutionary economics places innovation at its heart to explain economic growth and change. In the context of this dissertation, three key themes from evolutionary economics are particularly relevant to innovation measurement [128, 56]:

- **Disequilibrium:** Evolutionary economics challenges the conventional notion of static economic equilibrium, where supply and demand align perfectly. Instead, it views innovation as a dynamic, non-linear process characterized by experimentation, trial and error, and unexpected breakthroughs. This perspective embraces the concept of "creative destruction," where the innovation process can disrupt established industry structures. The inherent uncertainty of innovation renders the idea of an "optimal policy" irrelevant and impractical. Instead, evolutionary economics emphasizes the continuous transformation that occurs as organizations seek to adopt new technologies, strategies, and behaviors to gain a competi-

tive edge. Innovation, in this view, is not a linear progression but involves feedback loops between different stages and actors. Consequently, meaningful measures of innovation must capture the dynamic nature of this process, including interaction between actors and account for incremental changes that can have profound technological and economic implications over time.

- **Bounded Rationality:** While traditional economics often assumes "strong" rationality in agents, implying that they possess complete information and the ability to make fully informed decisions, evolutionary economics acknowledges the concept of bounded rationality. This means that decision-making is constrained by the available information, and agents can learn and adapt over time. In the context of innovation measurement, this perspective extends beyond traditional R&D activities to encompass a broad spectrum of activities, including design, engineering, education, entrepreneurship, and more, all of which contribute to the invention and commercialization of emerging technologies. Consequently, effective measures of innovation should be capable of capturing this diversity of innovative activities and the learning processes that underlie them.
- **Heterogeneity:** Unlike mainstream economics, which often assumes uniformity among economic actors, evolutionary economics recognizes the inherent heterogeneity of these actors. This heterogeneity implies that economic agents have unique identities, knowledge, competencies, interests, routines, norms, and values. Moreover, they operate within diverse systemic, organizational, and institutional contexts and pursue different goals. This diversity of actors and their contexts underscores the need for measures of innovation that cater to the distinct needs and objectives of various actors involved in the innovation process. Such measures should be actionable and relevant to the specific goals and interests of different participants.

The evolutionary economics lens, as applied in this dissertation, provides a solid foundation for critically examining the assumptions underlying existing innovation measures and for shaping the development of future measures. It reframes innovation as a dynamic, collaborative, and complex process involving a multitude of actors, organizations, individuals, and institutions engaged in

interactive learning and encompassing activities beyond traditional R&D. Therefore, measures of innovation must reflect this dynamic, multifaceted nature of the innovation process.

## **2.2 *Systems of Innovation***

Evolutionary economics provides a compelling model for emerging technologies as a potential disruptor that propels technological change. Evolutionary economics views innovation as a path-dependent process occurring through learning interactions between various actors, organizations, and institutions [57, 128]. These interactions in a given market determine which innovations are successful. Kline and Rosenberg's (1986) chain-link model of innovation [100] and innovation systems theory [75, 114] postulate innovation as a nonlinear process characterized by such interactions and feedback loops between multiple actors in the process who are constantly learning. The complexity of the innovation process as described calls for interdisciplinary approaches to examine the interactions between actors, the uncertainties in the process, as well as the complex responses to intervention. This informs how innovation may be measured. The lack of a clear universally accepted definition for innovation poses a significant challenge when it comes to measuring innovation because there is no single, precise framework to rely on. However, existing theories of innovation such as evolutionary economics can be applied to adopt a specific lens towards innovation measurement.

A subset of the evolutionary economics framework that grounds the work of this dissertation is the systems perspective of innovation, which has gained recognition in contemporary academic literature. The concept of "innovation systems" has its roots in scholars like Lundvall [114] and Freeman [75] and even dates back to Friedrich List's work in the 1800s, such as "The National System of Political Economy" [112]. Innovation systems focus on the interactions between institutions and organizations, encompassing two key concepts: innovation and systems. Given below is a brief review of what these two concepts entail:

**Systems Concept:** A system can be defined as something composed of a set of components and relationships between these components. In a common characterization of a dynamic open system, inputs are transformed into outputs via activities performed by agents/actors within an environment.

**Innovation Concept:** The concept of innovation has a long history with many fluid and vague interpretations. Contemporary definitions of innovation are based on two criteria: 1) a degree of

newness of an outcome/product/process, and 2) a degree of usefulness or success in the application of something new. The outcome/product/process can be “new” to the world, or new to a nation, a firm etc [10].

Based on these two definitions, a system of innovation (SI) can be defined as components and relationships between those components that determine and impact the process of innovation. That is, it is a set of actors/agents interacting with each other in an environment that results in innovation. The goal of the SI framework is not to offer a general theory of innovation but to serve as a basis for developing hypotheses about relationships between specific variables within SIs [59]. While there are multiple definitions of SIs, most of these definitions share the following commonalities [182].

1. SI literature considers innovation to be a learning process whereby technological change is viewed as a recombination of knowledge which is generated by and/or distributed amongst multiple actors who exchange knowledge, a feature consistent with evolutionary economics. These actors can consist of organizations and institutions which can be public, private, non-profit etc.
2. SIs place a lot of emphasis on the role of institutions in establishing the rules and routines that create the environment where actors can participate in the innovation process. Therefore, these institutions can either be drivers or barriers in the innovation process.
3. The system perspective for innovation implies that innovation is a product of rich relationships and interactions between the elements of the system. It cannot be viewed as a linear, isolated function of single elements. Simply analyzing innovation processes from the lens of a single actor or institution may not provide a holistic view of the entire process.
4. The SI framework has typically been used to design interventions that support innovation policy and strategies. The SI framework advocates for considering the interactive feedback among actors and nonlinear nature of the innovation process when designing policy or recommending strategies to business leaders. Failure to view innovation through this lens may result in undesirable and uncoordinated technological development.

This dissertation extends the application of the SI framework to innovation measurement, particularly emphasizing the diverse array of actors in innovation systems. Traditional approaches often aggregate data at higher levels, neglecting the individualized measures employed by different actors. Recognizing this diversity, an actor-centric approach is proposed, advocating for flexible and adaptable measures that align with the distinct objectives and preferences of various participants in the innovation landscape. This nuanced perspective seeks to redefine how innovation is measured, embracing the dynamic and multifaceted nature of the process.

### *2.2.1 Types of Innovation Systems*

The systems of innovation (SI) literature comprise of different types of SIs based on the system boundaries, which can be geographical, technological, or economical. The most common SI approach is the National Innovation Systems (NIS) approach [114], where the unit of analysis/system boundary is a nation. The goal of most NIS studies is to evaluate the innovation performance of nations and often compare them to each other to explain differences in innovation success and related growth [114, 75]. The NIS framework is a sound policy analysis tool but is limited as a research framework due to its immense scope. As a result of the large scope, NIS analyses tend to combine the influence of many actors, institutions, and interactions for the sake of brevity and controlling the scope of the analysis. Therefore, it might be a suitable tool for policymakers at a national level but may not be ideal for more granular and micro-level analyses. To mitigate the scope of NIS, the Regional Innovation Systems (RIS) approach has been developed [39], which focus on assessing the innovative performance at a regional level. The RIS framework is based on the observation that the geographical distance between actors in an innovation system has a significant influence on the region's innovative performance. Unlike NIS, which focus on interactions between national-level actors, RIS tend to include analyses at the level of firms and other individual organizations.

Other SI approaches break with the geographical focus and places emphasis on either the industry sector or technology. One such approach is the Sectoral Innovation Systems (SIS) approach [23], which focuses on assessing and comparing the innovative performance of specific industrial sectors. According to the SIS literature, a sector is characterized by the technology, the knowledge and the practices operating within it. The SIS approach uses firm data to conduct empirical analyses

of sector performance. Another SI approach, which also forms the conceptual framework for this dissertation is the Technological Innovation System (TIS) approach and is discussed in detail in the following section.

### **2.3 Technological Innovation Systems (TIS)**

Unlike a NIS, RIS or SIS, a Technological Innovation System is focused on a specific technological area. The goal of TIS analyses is to assess the development of a specific technological innovation by understanding the actors, institutions, networks, and processes that support or hinder it. When compared to NIS, RIS and SIS, a TIS analysis can be applied at a more granular level to study individual technologies that make up a sector or their evolution in a region or nation [88, 118]. Further, unlike the other SI approaches, the TIS approach explicitly characterizes the dynamics of the innovation system in terms of the flow of knowledge and competence instead of goods and services. However, it also recognizes that knowledge and competence flows are not enough to propel technological innovation and that there is a need to leverage this knowledge to create business and economic opportunity, highlighting the role of an entrepreneur. In fact, the TIS approach places individuals at the center of innovation, an element that is attenuated in the more macro-level SI approaches [30, 182].

#### *2.3.1 Structure of a TIS*

A TIS framework consists of two key elements: a structural element and a functional element. The structure of a TIS consists of actors, institutions, and technologies. The structural aspect of a TIS remains relatively consistent over time as the actors, institutions, networks, and technology that form a TIS do not change much.

1. **Actor:** This category involves organizations contributing to the emerging technology often as a developer, adopter, regulator, financier etc. There is a large variety of relevant actors in a TIS ranging from private to public actors. The choices, actions of and the interactions between actors of the TIS are usually responsible for generating, diffusing, and utilizing technologies.
2. **Institutions:** Institutions can be considered as ‘the rules of the game in a society, or, more formally, the humanly devised constraints that shape human interaction’. Institutions can be

categorized as formal or informal [130]. Formal institutions are rules that are codified and enforced by some authority (often as laws, policies, and firm decisions), while informal institutions are more organically shaped by the interaction between actors. Institutions define the rules, policies, and the general norms of the environment in which a technology is developed, diffused, and utilized in.

3. **Networks:** Networks are an important aspect of actor interactions that enable the exchange of knowledge and interactive processes of learning. Industry associations, research communities, policy networks, user-supplier relations etc. are all examples of networks. Networks between actors are based on a balance of trust and competition, where actors with seemingly different interests may connect with each other to obtain valuable information and knowledge, which enables the development and utilization of emerging technologies. The dynamics within a TIS emerge from a balance of conflicts between actors, institutions and technologies and complementarities that arise from relationships within and among networks.
4. **Technological factors:** Technological factors include the technologies in focus and the associated technological infrastructure along with factors such as costs, safety, and reliability. These factors are important to understand the interactions between technological change and institutional change. For instance, if a government subsidizes R&D supporting a specific technology's development, which yields positive results, that may pave the way for further support, including practical demonstrations and adoption. This may in turn, lead to further technological improvements and adoption.

### 2.3.2 *Functions of a TIS*

The functions of a TIS describes a set of key activities that are conducted by actors, institutions and networks that form the structure of a TIS. A TIS is comprised of seven different functions based on the work of [16] :

1. **Knowledge Development:** This function involves various learning activities such as R&D activities, laboratory experiments, and adoption trials. This function is essential for the development of a novel technology. From an evolutionary perspective, the Knowledge Development

function is associated with the creation of variety within a system. That is, increasing intensity of Knowledge Development implies an increasing number of technological options and its applications available within the system. This function is typically undertaken by universities and other research institutes.

2. **Knowledge Exchange:** Activities as part of this function involve partnerships between actors and institutions in a TIS, usually forming a network. These activities may occur through meetings, conferences, or other informal means. Knowledge Exchange is crucial to an SI, as innovation happens only when actors with different backgrounds and capabilities interact and learn from each other. Knowledge exchange between different actors can also help develop a mutual understanding, which may make it more likely for institutions to be adjusted to the new technologies and vice versa.
3. **Entrepreneurial Experimentation:** The TIS literature considers an entrepreneur to be core to its performance. An entrepreneur converts novel knowledge into business opportunities by performing market-level experiments to prove the utility of an emerging technology in a commercial environment, therefore bridging the gap between invention and innovation.
4. **Guidance of Search:** This function indicates activities within a TIS that center around the requirements and expectations of actors with respect to the emerging technology. Guidance of search can range from individual decisions to formal institutional choices such as policy targets. This function can be thought of as a selection mechanism that filters out the knowledge developed in F1 by influencing the allocation of resources and support, thus determining the trajectory of technologies competing in a TIS. An effective guidance of search process is usually a collaborative endeavor between different actors that encompasses and aligns their expectations for the emerging technology.
5. **Market Formation:** This function comprises of activities that may result in the creation of demand for the new technology in focus through various mechanisms such as financing the utilization of the new technology or taxing incumbent competing technologies. In evolutionary

economics, markets are thought to be the ultimate selection mechanism that decides whether a technology is adopted.

6. **Resource Mobilization:** This function refers to the allocation of and access to financial and human capital for an emerging technology. Typically, these activities include investments, grants, and subsidies. They also involve the development of infrastructure such as educational and R&D systems.
7. **Legitimation:** This function describes activities that result in recognition and legitimization of emerging technologies by mobilizing interest groups, passing legislation or political lobbies. In these activities, actors may employ persuasion or influence to gain traction and support from other actors in a TIS to propel a technology of their interest.

The structural and functional components of a TIS provide a basis for assessing the functionality of a given TIS. That is, it allows one to take stock of the strength and weaknesses of the innovation processes and be able to assess how well a system is functioning. The assessment of how well a TIS is functioning further enables researchers, policymakers, and analysts to identify inducing and blocking mechanisms that support or hinder the development of the TIS being studied. Therefore, a TIS framework provides a systematic way to assess the functioning and health of an innovation system enabling the development of concrete and actionable recommendations that can further enhance the functioning of TIS.

The TIS if applied appropriately, can capture a part of reality that corresponds to the innovation processes being studied. Nevertheless, the TIS conceptual framework is initially loosely defined by the researcher. Therefore, the framework allows for a lot of flexibility for the researcher to choose system boundaries and/or focus on specific aspects of the TIS function, which is what this dissertation does. The only strict boundary applied to this work is that all the analyses are conducted in a US context. A TIS may stretch across national and sectoral boundaries. However, the geographical limitation was applied for multiple reasons: (1) to limit the scope of the analyses, (2) national institutions are a crucial context for factors that shape innovation [114], and (3) the recommendations that may emerge from a TIS analysis may only be applicable up to a national level, especially if the recommendations are policy recommendations.

### 2.3.3 Measuring TIS Functions

Leveraging TIS as a conceptual framework to guide the study of innovation measurement, the question arises; how does one measure a TIS and the activities occurring within a TIS. Table 1 presents a list of measures corresponding to the different TIS functions as described by Bergek et. al in their scheme for conducting a TIS analysis [16].

Number	Function	Measures
1	Knowledge Development	Citations, volume of publications, number size and orientation of R&D projects, number of professors and researchers, number of patents.
2	Knowledge Exchange	Number of co-publications, number of partnerships, assessments by managers, learning curves, number of conferences, meetings, and workshops, number of university spin-offs
3	Entrepreneurial Experimentation	Number of new firms relevant to the TIS, number of diversifying established firms, number of different types of applications, breadth of technologies used, and complementary technologies employed.
4	Guidance of Search	beliefs in growth potential, incentives from prices (ex. taxes), extent of regulatory pressures, articulation of interest by leading customers, number of market and policy reports.
5	Market Formation	Market size, number of customer groups, actors' strategies, standards, purchasing needs.
6	Resource Mobilization	Volume of capital, seed, and venture capital funding, change in volume and quality of human capital (number of university degrees and jobs), government grants, and subsidies.
7	Legitimation	Regulatory support, public support, number of policies and legislation

Table 2.1: Examples of Measures for TIS Functions

The above table provides a good starting point for measures pertaining to various functions of a TIS. A few observations can be made about the measures mentioned in Table 2.1. First, not all measures are quantitative, some measures such as “beliefs in growth potential”, regulatory support etc. are qualitative in nature, making measurement challenging. Second, the measures in the table are general and do not consist of information specific to a certain technology. Third, the measures do not pertain to specific actors. The typical user of these measures is a researcher or analyst studying a specific TIS and do not cater actors participating in the system. Lastly and relatedly, the measures are evaluative, that is, they describe how innovation is occurring as an observer, but do not provide measures that actors in the system can use to enhance the performance of TIS

functions they are involved in. These observations reveal that in addition to evaluative measures there is a lack of measures that actors and practitioners operating in an innovation system can use to assess their own performance and enhance the development and function of a TIS.

#### **2.4 Why Would TIS Actors Want to Measure Innovation?**

The previous section established that existing measures of innovation are predominantly evaluative and used by researchers and analysts to assess the performance of an innovation system. The section also revealed a key observation that there is a lack of an integrated measurement framework that incorporates evaluative measures with measures used by actors in an innovation system. This raises the question: why is it important to develop measures tailored to actors within an innovation system?

The diverse array of actors within an innovation system, each possessing distinct goals, expectations, and interests, necessitates different measurement tools aligned with their specific contexts to measure their innovation activities and performance. Actor-centric measures offer a comprehensive view of how various actors' activities either enhance or hinder the innovation system's progress. Furthermore, actor-specific innovation measures can also empower actors to assess their own performance, facilitating targeted recommendations to improve innovation contributions to the overall innovation system.

To understand the activities different actors may want to measure, a conceptual model categorizing five key actors in innovation systems was adopted. The model was developed by researchers at Massachusetts Institute of Technology (MIT) based on historical analyses of well-developed innovation systems and global experiences with developing systems [27] This conceptual model was selected because it combines traditional actors (such as universities, industry, and government) with newly recognized actors such as entrepreneurs and venture capital to provide a more comprehensive categorization of all the actors in a TIS. The five key actors are:

1. **Universities:** Universities play an important that varies widely across innovation systems. They provide novel research, technical and entrepreneurship education, facilities, talented scientists, and students etc. A variety of actors within a university can participate in an innovation system from Technology Licensing/Transfer Office to researchers, faculty, and stu-

dents. The amount a university contributes to an innovation system varies. For example, MIT and Stanford have played a seminal role in establishing the Greater Boston and Silicon Valley innovation ecosystems respectively. However, that is not the case for many other regions. Therefore, a strong university does not imply a strong innovation ecosystem [185]. Universities use innovation data for two main purposes: (1) to study innovation, and (2) to measure the university's performance within an innovation ecosystem. Academics use innovation data to study the impact of innovation on economic development, organizational changes, technological advancement, and social transformation. Research studies on innovation are an important input to policy development. Using innovation data for research can help improve measurement framework for data collection innovation data and analysis [80]. Additionally, many universities today measure their research and technology transfer outputs by using research expenditure, patent, and publication data. This information helps universities quantify their impact on a given innovation system.

2. **Corporations:** Large corporations play an important role in system-building by developing and attracting talent, contributing to risk capital through corporate venture funds and providing facilities such as laboratories and equipment that support the innovation infrastructure. For example, Google, Microsoft, and Amazon all offer special cloud credit programs that support startups and entrepreneurs and thus provide them with a platform to build on. Within corporations, managers are the primary users of innovation data. Managers often use aggregated innovation data for their industry to benchmark their organization's innovation activities and outcomes. A corporate organization may also indirectly use innovation data to guide expansion, search, learning, and other actions leading to further innovation activities within their organization [79].
3. **Government:** The role of the government is critical in building innovation systems. While government actors may not often be leaders, their role is to "set the table" and create rules and policies that enable robust innovation systems. For example, Mazzucato (2015) argues that the establishment of various government research programs and organizations (such as the Defense Advanced Research Projects Agency) during and post-World War II has fu-

eled the development of most information technologies (including the computer) today [120]. Within the government, policy analysts and policy makers are the primary users of innovation measures. From a policy perspective, innovation measures are useful for benchmarking and analyzing the innovation performance of a sector, industry, or a whole country. Therefore, innovation measures in this case also vary widely as they may be relevant to certain policy goals such as workforce development, sustainability, technological transformation economic development etc. The same measures of innovation may not apply across all goals. Therefore, an actor-centric approach is required to identify relevant measures and develop a measurement framework for data collection and analysis.

4. **Entrepreneurs:** In the context of the model, entrepreneurs refer to individuals who form enterprises with the explicit intention to harness a competitive advantage based on new innovations (new technology, scientific insights, supply chains etc.) and quickly scale beyond local markets. Because of their experience on the “frontlines” of innovation, entrepreneurs motivate ecosystem-building efforts by communicating the support they need from other actors. Therefore, entrepreneurs are critical actors in innovation ecosystems. Traditional innovation measurement theory does not consider the types of measures required by an entrepreneur to measure performance and “conduct” innovative activities. Given the importance of entrepreneurs in an innovation system, it is vital to consider their perspective and develop measures centered around their activities, goals, and outcomes.
5. **Risk Capital:** This group refers primarily to investors who provide necessary funding to entrepreneurs to scale their business. Risk capital actors not only fund promising startups but also provide mentorship and support. They are necessary to the ecosystem, as they accelerate the emergence of new innovative enterprises [102]. Like entrepreneurs, traditional innovation measurement theory also does not integrate data required by risk capital actors to measure their innovative activities and performance. Performance measures for both entrepreneurs and venture capital are much better studied in the entrepreneurship and management literature, but not in the context of innovation systems. The role of risk capital in accelerating innovative activities is well-known in literature. Therefore, it is important to include measures that cater

to risk capital's perspective on measuring innovation activities and outcomes.

The five actors discussed above are not the only players in an innovation system. There are many other key players such as accelerators and incubators that help startups grow by providing the training, mentorship and resources needed by entrepreneurs to scale their business. Examples also include lawyers and consultants who help various actors negotiate intellectual property rights, conduct market or user research, build partnerships etc. The variety and diversity of the players in an innovation system highlights its complexity. The varied goals and conflicting interests across actors emphasize the need for flexible, adaptable measurement approaches to comprehensively capture the dynamics of innovation systems.

## ***2.5 A New Set of Comprehensive Innovation Measurement Frameworks***

From the preceding discussion of the complex and collaborative nature of innovation, it becomes evident that a one-size-fits-all approach to measurement falls short in capturing the diverse objectives and interests of actors within a Technological Innovation System (TIS). The previous section delved into the significance of developing actor-centric measures, underscoring the need for tailored tools that align with the distinct goals of various TIS actors. The foundation laid in understanding the types of activities that characterize innovation systems and that different actors may wish to measure forms the basis for a framework that integrates evaluative measures with actor-centric considerations. This framework not only examines the current state of an innovation system through evaluative lenses but also delves into the nuanced perspectives of individual actors, providing a strategic lens to enhance TIS functioning.

Table 2.1 illustrates the central theoretical innovation of this dissertation—an integrated framework for innovation measurement. This framework systematically classifies measures into two categories: evaluative measures, which assess the overall state of innovation, and actor-centric measures, which cater to the specific needs of individual actors within the system. The measures within each category are positioned along a spectrum of availability and decision-making influence. Notably, certain measures may exhibit varying degrees of availability but wield substantial influence over actors' decisions concerning their innovative pursuits and vice versa. By organizing measures based on their category, availability, and influence, this framework facilitates the design of strategic inter-

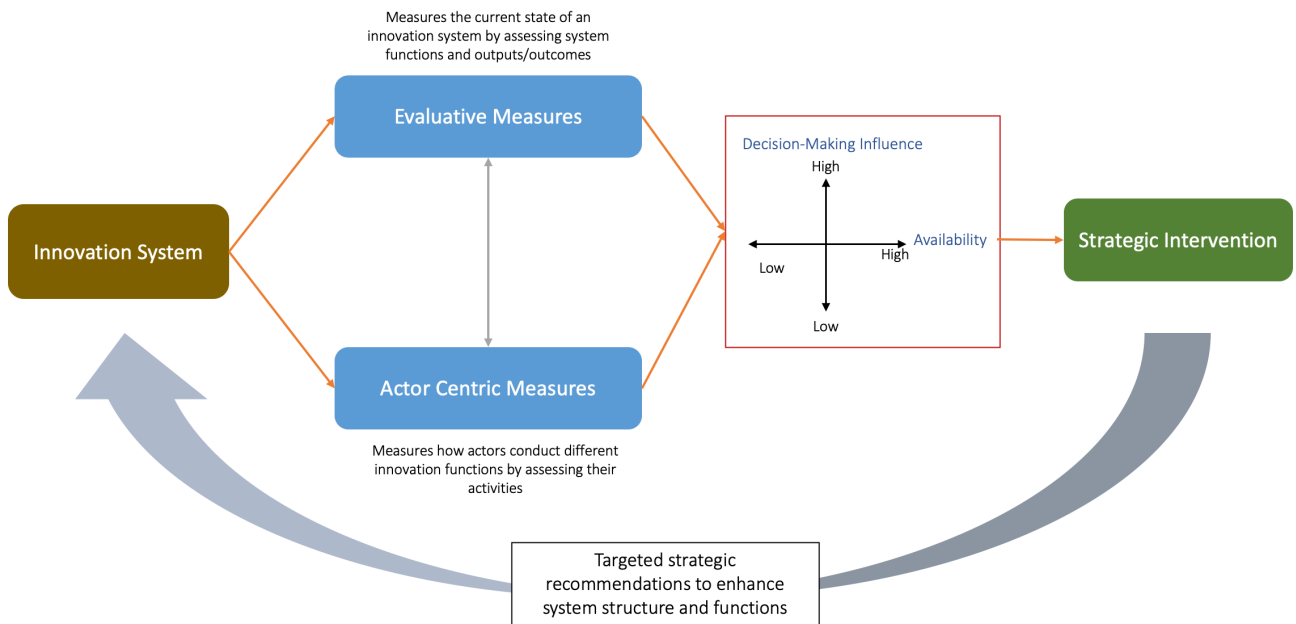


Figure 2.1: An Integrated Framework for Innovation Measurement

ventions tailored to different facets and participants in an innovation system. These interventions aim to improve the overall functionality of the technological innovation system.

### 2.5.1 Evaluative Measures

Evaluative measures assess the current state of an innovation system by observing its “outputs”, such as patents, publications, investment etc. Evaluative measures for assessing innovation system functions are well-understood in literature. Three broad areas of measures have traditionally been used for innovation analysis, each shedding light on different aspects of the innovation process [66]. These include:

#### 1. Output Measures

- (a) **R&D Data:** Research and Development (R&D) data have been a cornerstone in innovation measurement. The OECD's Frascati Manual provides a comprehensive framework for collecting R&D statistics [132]. R&D encompasses activities related to both the creation of new knowledge and the application of that knowledge. It includes basic research, applied research, and experimental development. The key criterion for distinguishing R&D from related activities is the presence of novelty and the resolution of scientific or technological uncertainties. However, certain activities, such as education, market research, and some other industrial activities related to innovation, are excluded from R&D. R&D data are often collected with great detail, classifying by sector of performance, sources of finance, socio-economic objectives, and fields of research. Despite this detailed classification, most policy analysts and researchers tend to focus on gross expenditure. R&D data is both a valuable and limited measure of innovation. R&D data are often used to examine the relationship between R&D investment and productivity. However, the full potential of this data for understanding innovation is yet to be explored.
- (b) **Patents:** Patent data is another key measure of innovation. This includes data on patent applications, grants, and citations. Patents are a legal way to protect intellectual property and can indicate technological advancements. Researchers and analysts use patent data to examine trends in innovation, technological areas of interest, and the influence of patents on economic growth. They also analyze patent citation patterns to understand the flow of knowledge and technology transfer. Additionally, patent data can highlight the geographical distribution of innovation activities and the collaboration between inventors and organizations..
- (c) **Bibliometric Data:** Bibliometric data focuses on scientific publications and citations. It provides insights into the academic and research aspects of innovation. Researchers and institutions often use bibliometric data to evaluate the impact of research, identify trends in scientific fields, and assess the influence of publications on innovation.

2. **Measures of Innovation System Functions:** These measures assess the health of the various functions of a TIS and consist of measures detailed in 2.1 Note that these measures

also incorporate the output measures discussed above.

3. **Impact Measures:** These measures assess the economic, social, and technological impact of an innovation. Commonly used measures of economic impact include GDP growth and growth in employment opportunities.

### 2.5.2 Actor Centric Measures

Actor-centric measures are measures specific to different actors in the innovation system that they may use to conduct innovative activities. Actors of a TIS may use these measures to determine success and failures pertaining to the technology for their use case. Actor-centric measures can further be categorized into 4 categories: measures of success, cost-based measures, technical measures and use case specific measures.

1. **Measures of Success:** Measures by which an actor may evaluate success. Examples of typical success measures include, money saved (profit, revenue, and cost savings), user/customer satisfaction, user/customer retention, etc.
2. **Cost-based Measures:** These measures characterize the upfront cost to an actor and may include capital investments, operational investment, tax rates, cost of participating in a program etc.
3. **Technical Measures:** These measures define the technical requirements that an actor may have as relevant to the technology and may include performance requirements (speed and efficiency) and operating requirements.
4. **Cost-based Measures:** These measures pertain to use cases that an actor is interested in. These are measures specific to a situation, setting or environment. For example, in Study 1, when evaluating university-industry partnerships for education, measures of perceptions of support and individual ability are use case specific measures, as they apply specifically to the educational setting being considered in Study 1.

Additionally, actor-centric measures may result in evaluative measures. For example, if a customer is interested in piloting a new technology from a technology developer, they might have to adhere to cost measures. If the pilot is successful, then that can be considered as a measure of Market Formation for that technology's TIS.

### *2.5.3 Availability and Influence of Measures*

Not all measures of innovation are equally available for use nor are they equally influential in helping actors make strategic decisions regarding their innovation activities. The categorization of measures by availability and influence acknowledges the varying degrees to which measures are accessible and impactful for evaluating the functions of an innovation system and for use by different actors within an innovation system. This categorization offers a more granular perspective on the utility of innovation measures. Evaluative measures, while essential for gauging the overall system performance, often exhibit differential availability and influence. Some measures might be readily accessible but hold limited sway in shaping decisions, while others possess significant influence but are less accessible. Actor-centric measures, tailored to specific actors' needs, further emphasize this dynamic. For instance, measures crucial for entrepreneurs might not align with those important for government policy makers. This framework recognizes the hierarchies of availability and influence, providing a strategic lens to navigate the landscape of innovation measurement. This paradigm shift from a one-size-fits-all evaluation to a tailored, availability-influence-informed approach enhances the precision and relevance of the innovation measurement process, contributing to a more comprehensive and actionable understanding of innovation dynamics.

### *2.5.4 Strategic Intervention*

The identification and assessment of evaluative and actor-centric measures, coupled with an understanding of their availability and influence can enable comprehensive assessment of an innovation system's performance. This thorough assessment forms the basis for crafting targeted strategies that not only enhance but also strategically influence the functioning of the TIS. The measurement framework provides insights into specific barriers hindering the system's development and success. This detailed understanding of innovation measures offers actors a well-informed direction for

strategic interventions, considering the varying degrees of availability and influence associated with different measures. The studies in this dissertation aim towards demonstrating how new and existing measures can uncover valuable findings that can help make innovative processes better. When strategically applied, these findings have the potential to refine and optimize innovative processes, contributing significantly to the overall progress of the innovation system in consideration.

#### *2.5.5 Framework Development and Validation through Studies*

The proposed innovation measurement framework was developed through refinement and validation across three key studies. Each study played a crucial role in not only developing the framework but also in contributing valuable insights that refine and validate its effectiveness in assessing, impacting, and optimizing innovation systems.

- **Study 1: University-Industry Partnerships for Education:** This study focuses on studying knowledge development (F1 of a TIS) and knowledge exchange (F2 of a TIS) in an educational context. The setting is an industry sponsored engineering design capstone program. The significance of this study to the dissertation is that it served as a foundation for organizing innovation measures into evaluative and actor-centric measures. By categorizing measures into evaluative and actor-centric dimensions, the study not only provided a unique perspective on education in an innovation context, but also laid the groundwork for understanding the effectiveness of industry-sponsored engineering capstone projects. The actor-centric measures, such as perceptions of support and individual learning, revealed critical insights into the success and challenges of collaborative educational initiatives, guiding recommendations for program improvement and thus effective knowledge development and exchange.
- **Study 2: Exploring Actors' Perspective on Innovation Measures:** The second study extended the application of the framework by presenting a broader investigation on actor-centric measures by exploring actors' perspectives as pertaining to research and entrepreneurship within a regional innovation system (Seattle). The goal of the study was to understand how evaluative measures fall short in capturing actors' needs. Using interactive visualization

tools, the study engaged diverse actors, allowing them to interact with evaluative measures and express their needs for actor-centric measures. The findings unveiled a hierarchy of availability and influence. Not all measures are equally available or influential in helping actors make decisions about their innovative activities. The study also highlighted the importance of narrowing down the scope to a specific industry and technology. This insight directly informed the subsequent study, indicating the necessity of refining the scope when applying innovation measures to achieve more meaningful and context-specific results.

- Study 3: Integrating Innovation Measurement Frameworks for LDES Technologies:** The third study provided a comprehensive demonstration of the framework’s application in the analysis of a specific technological innovation system: long-duration energy storage (LDES) technologies. By conducting a traditional Technological Innovation Systems (TIS) analysis supplemented with actor-centric measures, the study revealed the synergies and gaps between evaluative and actor-centric perspectives. The framework facilitated a holistic assessment, offering a detailed understanding of structural and functional aspects alongside the nuanced contributions and challenges faced by different actors within the LDES TIS. The availability and influence dynamics further enriched the analysis, emphasizing the importance of tailoring interventions to the specific needs and priorities of actors involved in the LDES innovation system.

In summary, these studies collectively showcase the practical utility of the proposed innovation measurement framework, emphasizing its adaptability to diverse contexts and its capacity to inform targeted strategies for enhancing innovation systems. The integrated framework not only advances theoretical perspectives on innovation measurement but also provides actionable insights for practitioners, policymakers, and other actors engaged in fostering innovation within their respective domains.

## **2.6 Conclusion**

This chapter delves into the theoretical underpinnings of innovation and its measurement. While the concept of innovation is interdisciplinary, this dissertation is firmly rooted in the innovation

systems literature. Specifically, it adopts the Technological Innovation System (TIS) framework as a foundational conceptual lens, providing a comprehensive perspective on the complex interactions and dynamics within innovation systems. Building upon this, an integrated framework for innovation measurement is proposed in this dissertation, which incorporates both evaluative and actor-centric measures, along with an exploration of availability and influence of these measures for decision-making. The objective is to comprehensively grasp the dynamics of innovation by considering diverse actors and their specific measures of success, costs, technical requirements, and use case considerations. The next chapter provides an overview of the research methods used to conduct the investigations in the three studies.

## Chapter 3

### OVERVIEW OF METHODS

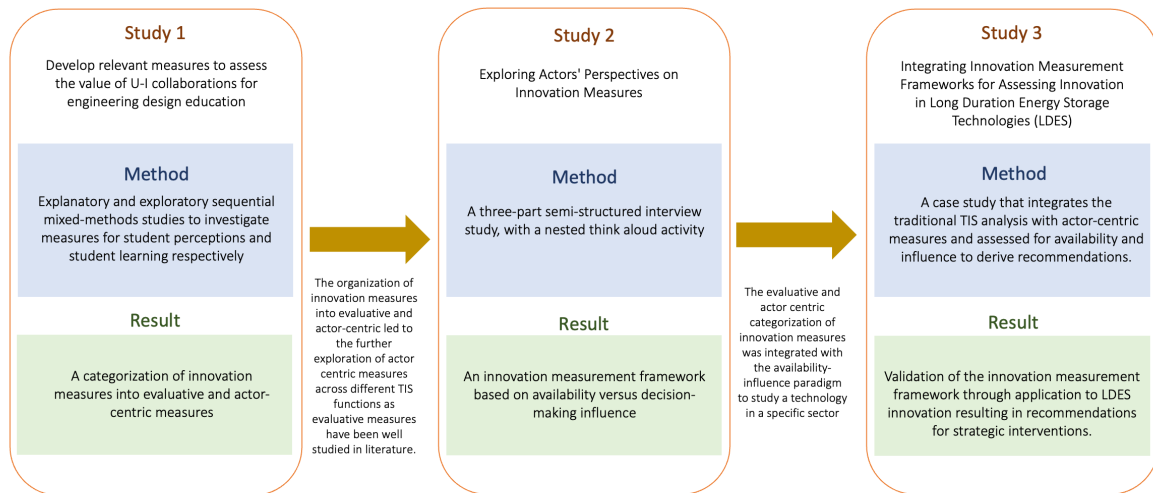


Figure 3.1: Overview of Methods

The exploration of innovation measurement initially focused on the knowledge development and knowledge exchange functions of a technological innovation system in the education domain. A comprehensive literature review uncovered significant gaps in the understanding of how education contributes to innovation systems and the associated challenges in measuring innovation within this context. To address these gaps, Study 1 delved into the innovation measures within the context of university-industry partnerships in engineering education. This subject was investigated through a detailed case study focusing on the evaluation of the value derived from knowledge development and exchange in an industry-sponsored engineering design capstone. The case study, incorporating

sequential mixed-methods research, successfully identified pertinent measures and applied them to assess various aspects of the capstone program during the COVID-19 pandemic. The result of this investigation gave rise to a dual categorization of innovation measures, namely, evaluative, and actor-centric measures.

While the literature for evaluative measures is extensive, the literature on actor-centric measures is limited and fragmented across multiple disciplines. Therefore, it became apparent that exploring innovation measures solely within the education context was limiting. Consequently, the scope expanded to understand actor perspectives on innovation measures in research and entrepreneurship domains. A qualitative think-aloud semi-structured interview study engaged diverse actors in the Seattle innovation system to assess their perspectives on the relevance of existing innovation measures and identify gaps in measurement. The result of this study yielded an availability-influence framework for innovation measurement that categorized measures into four quadrants based on how readily available innovation measures were to actors and how much influence they had on the actors' decision-making. Another key finding of the study was the role of a specific industry sector and technological domain in enabling a deeper investigation of innovation measures. Therefore, the availability-influence framework was combined with the evaluative and actor-centric framework and applied to a specific industry sector and technology in the next study.

The final study in this dissertation was a case study used to apply and validate the innovation measurement frameworks developed in the previous two investigations. The case study focused on studying how innovation can be measured in the long duration energy storage innovation system under the frameworks developed in this dissertation. To do this, first a technological innovation systems (TIS) approach was leveraged using evaluative measures of innovation, next qualitative document analyses and interviews were used to identify actor-centric measures and finally, these measures were analyzed for availability and influence to obtain recommendations for measuring innovation for the sector and technology under consideration.

The progression of this research, characterized by its sequential exploration of innovation measurement within the education, research, and entrepreneurship domains, ultimately facilitated a comprehensive understanding of the complex nature of innovation. Figure 3.1 illustrated the overarching flow of the research and corresponding methods and the subsequent sections present the specific methodological approaches adopted for each of the three sub-studies within this dissertation.

### 3.1 Study 1: U-I Partnerships for Education

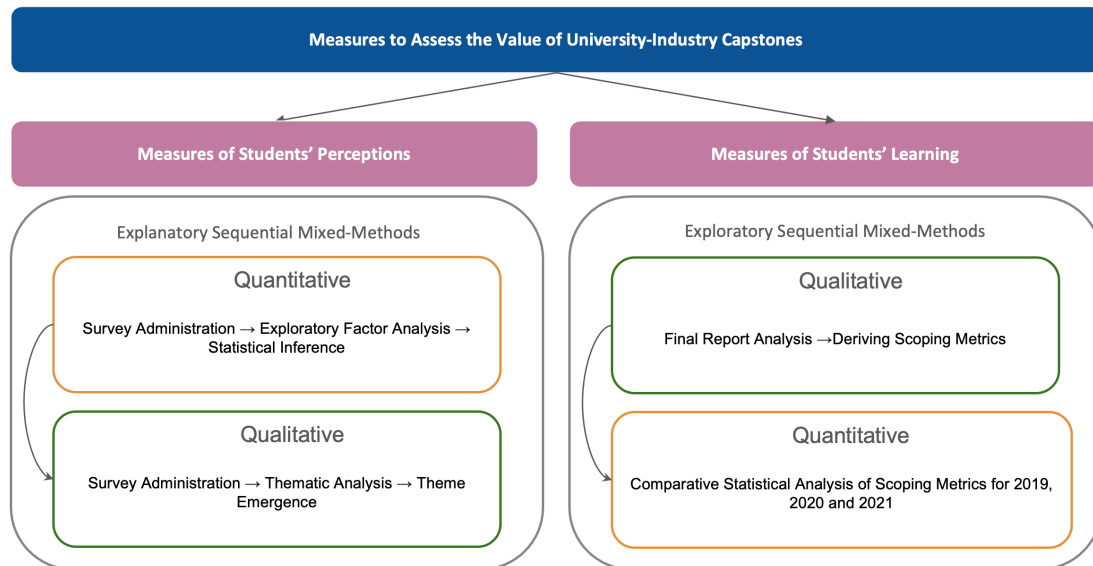


Figure 3.2: Methodology for Measuring the Value of University-Industry Capstones

#### 3.1.1 Mixed-Methods Research

This investigation utilized a series of mixed methods approaches to identify suitable measures for evaluating student experiences in the industry-sponsored ENGINE capstone program in 2019, 2020 and 2021. A mixed-methods research design integrates both qualitative and quantitative approaches to answer research questions or hypotheses. There are many different terms used for this approach including multimethod, mixed research or mixed methodology. However, recent literature such as SAGE Handbook of Mixed Methods in the Social & Behavioral Sciences and SAGE's Journal of Mixed Methods Research, favor the term mixed methods [184, 26, 42]. Mixed-methods research originated around late 1980s to early 1990s based on work from researchers across diverse disciplines such as education, management, sociology, and health sciences. The interdisciplinary beginnings of this methodology are testament to its versatility in handling research problems across multiple disciplines. A mixed-methods research design was chosen for this work to leverage the strengths

of both quantitative and qualitative research approaches such that rigorous measures could be obtained that accurately reflect students' experiences (Figure 3.2).

### *3.1.2 Study Designs*

Two distinct studies were conducted to examine two categories of measures: students' perceptions and students' learning. For the first study examining student's perceptions an explanatory sequential mixed-methods design was pursued. An explanatory sequential mixed-methods design consists of first conducting quantitative research and analysis, followed by qualitative research and analysis that builds on the results of the quantitative research [43]. The approach is explanatory because the initial quantitative results are further explained by the qualitative data. In this case, a survey instrument was used, with all data anonymized to ensure confidentiality to simultaneously collect quantitative data (using closed ended Likert-type questions) and qualitative data (using open-ended free response questions). The quantitative data was analyzed using an exploratory factor analysis to derive measures. An exploratory factor analysis primarily comprises of conducting a principal component analysis to which survey questions group together and form one type of measure [179]. Next, the qualitative survey data was analyzed by deductively coding the open-ended responses into themes that aligned with the measures found during the quantitative analyses to further explain the statistical relationships between the measures [122].

In contrast to the first study, the second study used an exploratory sequential mixed methods research design. In this case, qualitative data from students' final design reports from 2019, 2020 and 2021 were analyzed to derive scoping criteria used to evaluate students' problem scoping skills over the course of three years of the capstone program. The analysis of the final reports first involved a detailed deductive coding process, where each criterion was carefully evaluated and classified based on whether it was met, partially met, not met, or not addressed. The research team also conducted a reliability assessment of the coding process to ensure the consistency and accuracy of the data analysis. Once the scoping measures were derived, quantitative statistical analyses were conducted to compare the problem scoping performance of students during traditional in-person instruction prior to and during the COVID-19 pandemic.

Details about each methodology are provided in Chapter 4, Section 4.9.4. Figure 3.2 provides

an overview of the methodologies used in this study.

### 3.2 Study 2: Exploring Actors' Perspective on Innovation Measures

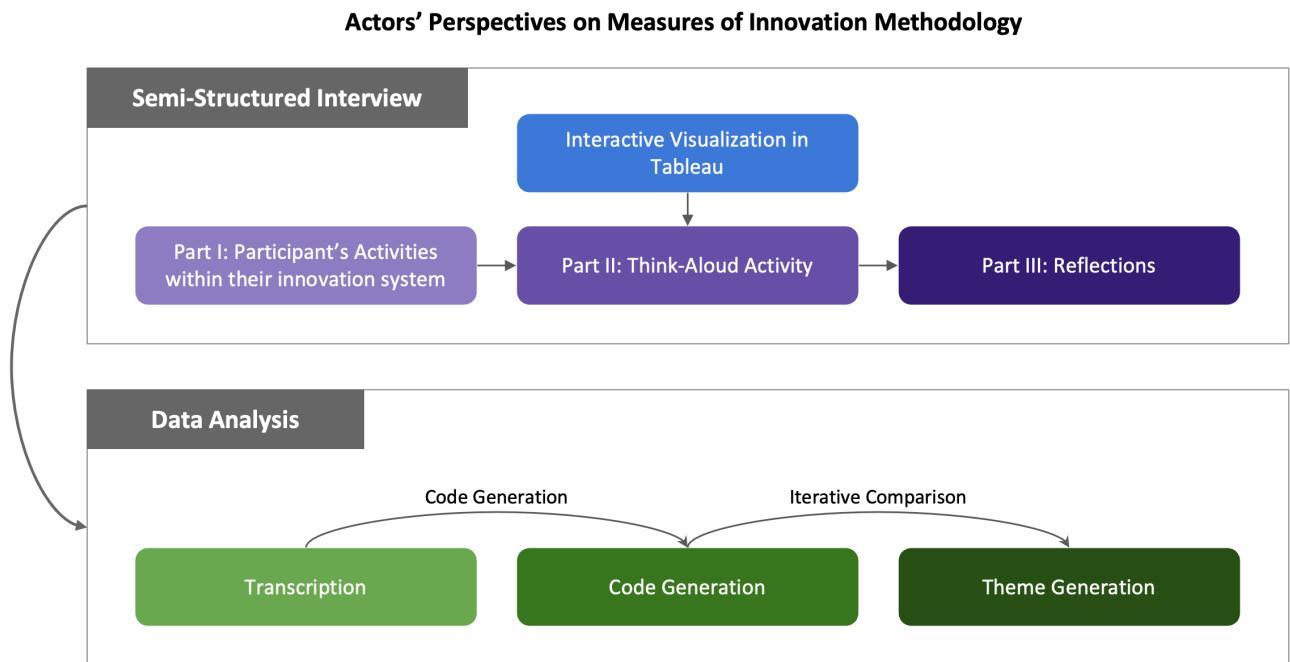


Figure 3.3: Methodology for Analyzing Stakeholders' Perspectives on Measures of Innovation

This study explored the perceptions of various actors on existing measures of innovation and was used to identify gaps in actor-centric measures. The study utilized a nested qualitative approach, which consisted of three-part semi-structured interviews, of which one part was a think aloud activity that was used to obtain participants' perspectives on how they would use existing measures of innovation as visualized on a digital dashboard (Figure 3.3). The investigation was centered around the comprehensive analysis of actor perceptions within the realm of Knowledge-Intensive Industries (KTI) across the Seattle Metropolitan Area. A total of 13 participants were selected to represent various actor groups who participate in an innovation system, ensuring a holistic understanding of the innovation system.

### 3.2.1 *Semi-Structured Interviews*

The research methodology encompassed a structured three-part interview process. The semi-structured interview is a qualitative data collection methodology in which participants are asked open-ended but predetermined questions. Unlike unstructured interviews, researchers have more control over the topics in semi-structured interviews but less control than structured interviews or questionnaires. To conduct semi-structured interviews, an interview protocol is first developed with guiding questions and list of topics covered. However, during the interview, the researcher has the flexibility to ask questions in any order they choose based on the participants' response. Questions in a semi-structured interview may range from asking for concrete information ("what is your role at your company?") to more narrative information ("how did you get your current job?"). In addition to questions, semi-structured interviews may also use probes that elicit further information. In the case of this study, the probe used was a Tableau dashboard that visualized existing measures of innovation that the participants interacted with. Semi-structured interviews are especially advantageous in research questions where typologies exist representing the relationships between concepts. In the case of this study, the groupings of participants into different actor categories provided under MIT's innovation actor framework, along with their activities fitting into the technological innovation systems framework, provided the typologies that justified the use of this method [175].

The semi-structured interviews conducted in this study consisted of three-parts that covered different topic areas. The first part of the interview focused on understanding the participants' background, roles, and tasks within the innovation system. The second part of the interview involved a think-aloud activity (See Section 3.2.2), where participants' interactions and use of existing measures of innovation were observed. The final phase involved reflections from the participants, shedding light on their information needs and the tool's utility within their respective contexts. The interview was conducted by following an IRB approved interview protocol. To ensure the validity, questions were designed carefully, to avoid any leading questions that would elicit a biased response from the participants.

### *3.2.2 Think-Aloud Protocol*

A think aloud or verbal protocol is when participants are concurrently verbalizing their thoughts while performing an activity [85]. Through a think aloud approach, a researcher can obtain rich qualitative information on what aspects of the task are the most problematic or challenging. Thinking aloud and verbal protocols have a long history in psychology and has been widely used as a scientific method for research in cognition, education, human-computer interaction, etc. [96, 69, 126]. A think aloud approach was pursued for this study as a probe to elicit fruitful discussion around the use of existing innovation measures for decision-making. In this study, participants navigated through different tabs of the visualization as they verbalized their thoughts on the usefulness of specific measures that were on display. Having the participants directly interact with existing innovation measures and talking about how they would use these measures to influence decisions they make, provided a direct and potential unfiltered understanding of the use of existing measures. To prevent biasing participants, prompts were carefully crafted to nudge the participant to keep talking without leading them to biased answers.

For both the semi-structured interviews and the nested think aloud activity, the data was processed by careful transcription of the interview recordings, followed by the generation of preliminary codes to identify meaningful data segments. The analysis unfolded through a constant comparative approach, systematically comparing themes across actor categories. This process led to the identification of key themes regarding actor tasks, information tools, information needs and perceptions of innovation measures. Figure 3.3 depicts the methodology employed in this study, offering an overview of the research approach and processes utilized. Section 5.4 in Chapter 5 further delves into the details of the methods employed.

### **3.3 Study 3: Long Duration Energy Storage Technological Innovation System**

A key insight derived from the study 2 outlined in Section 3.2 underscored the significance of studying measures specific to technologies and sectors. It was highlighted that sector-specific measures, such as analyzing employment patterns within the healthcare industry or examining funding allocations in clean energy, serve to amplify the pertinence and practicality of innovation measures. In light of this, this dissertation delved into applying and validating frameworks of innovation mea-

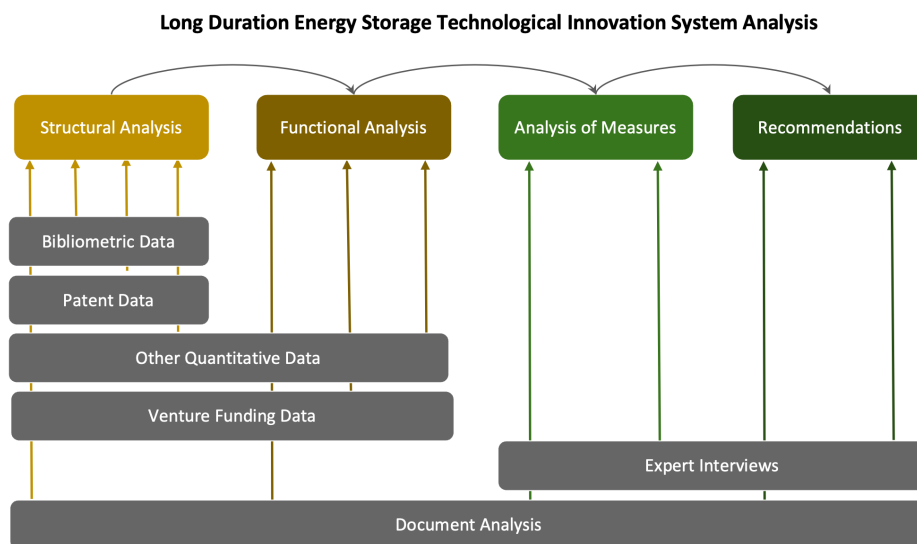


Figure 3.4: Methodology for Analyzing Long Duration Energy Innovation System

surement that emerged from studies 1 and 2 in the context of a specific technology of interest, namely, Long Duration Energy Storage (LDES) technology, with a focus on novel electrochemical and thermal long duration energy storage technologies. The study was designed as a case study to explore the application of the measurement frameworks developed in a specific context.

### 3.3.1 Case Studies

There is a lack of agreement regarding the fundamental characteristics of case studies due to its usage in many different contexts for different goals ranging from research to pedagogy. Qualitative case studies focus on one or a few units of analysis. There is no consensus on the boundaries of a case study. Some researchers would exclude case studies without a spatial or temporal variation, while other researchers may compare over 10 to 60 cases [82]. It has been widely accepted that case studies have been a major source of theoretical innovation. Unlike large-N survey studies, where the goal is to establish causal insights, case studies lean more towards a descriptive-interpretive approach. Further, case studies are advantageous for studying specific mechanisms between cause

and effect rather than focusing on the strength of a variable in impacting an effect. Cases can be selected based on multiple reasons, ranging from researcher interest and real-life impact (naturalist approach) to statistical basis for selection (positivist approach). Given that a case-study is an in-depth exploration, it relies on a wealth of diverse quantitative and qualitative data that can be obtained from observations, experiments, interviews etc.

### *3.3.2 Study Design*

For this case study, a convergent mixed methods research approach was used, that combined concurrent collection and analysis of qualitative and quantitative data. A central aspect of this approach involved using the Technology Innovation System (TIS) framework, which served as the overarching structural guide for the research investigation. The research process unfolded in the following phases. First, the structural components of the LDES innovation system were identified. This included mapping the actors, networks, and institutions involved in LDES technology innovation within the United States, enabling a detailed understanding of the participants in the LDES innovation system. Second, an evaluation of the key functions of the LDES innovation system was undertaken, encompassing knowledge development, exchange, entrepreneurial experimentation, search guidance, resource mobilization, market formation, and legitimation, using evaluative measures of innovation [16]. Third, actor-centric measures of innovation in LDES were explored by analyzing six use-cases of LDES technologies, the actors involved in each use case and the measures they used. Finally, the measures were assessed based on their availability and influence on decision-making to help craft recommendations for strategic interventions that can enhance the functioning of the LDES TIS (Figure 3.4).

Quantitative data was collected from a diverse range of sources such as publications, patents, and venture capital financial information. A bibliometric analysis using publication data provides a quantitative and qualitative exploration of the scientific and research structure of novel electrochemical and thermal energy storage technologies, offering insights into emerging trends, collaboration patterns, and key actors within the field. Concurrently, a financial analysis of LDES startups is conducted, aiming to understand the financial trajectory, funding sources, and the current state of various startups operating within the LDES. Qualitative data was collected through a document

analysis of government documents, industry reports, and credible news outlets along with ten in-depth interviews with representatives from various organizations, firms, and public actively involved LDES innovation system. The interview data was subsequently coded and analyzed according to the defined TIS functions. ecosystem. This analysis serves to provide a deeper understanding of the health of the innovation ecosystem and the significant actors involved.

In sum, the methodology employed in this case study adopted a mixed, quantitative, and qualitative approach, acknowledging the complexity of the LDES innovation landscape. Through the comprehensive evaluation of structural and functional aspects, coupled with an analysis of bibliometric and financial data, this case study offers a detailed perspective on the dynamics LDES innovation system, the measures used to evaluate innovation within it and measures that are missing or need to be considered so that LDES innovation occurs effectively. For a more detailed understanding of the methodology used to analyze the Long Duration Energy Storage (LDES) innovation system, readers are directed to Section 6.6 in Chapter 6, which provides a discussion of the specific methodologies applied within the context of the LDES innovation landscape.

### **3.4 Conclusion**

The methodology employed in this dissertation incorporated a variety of approaches, including mixed methods, qualitative analysis, think aloud protocol and a technological innovation systems (TIS) analysis. The education study (Study 1), employed surveys, and final reports to assess students' perceptions and learning experiences. For the actor perspective study (Study 2), semi-structured interviews were conducted, and thematic analysis was utilized to gain insights into actor dynamics within the innovation system. In the analysis of the LDES innovation system (Study 3), a mixed approach of quantitative data collection from various sources and qualitative data analysis was utilized, providing a detailed perspective on the dynamics of the LDES innovation landscape. Overall, the research process progressed from a focused examination of education to a broader exploration that encompassed all aspects of activities that occur in an innovation system. The work culminated in a comprehensive case study validating the innovation measurement frameworks developed in the dissertation by applying it to measure innovation in long duration energy storage technologies.

## Chapter 4

# MEASURING UNIVERSITY INDUSTRY COLLABORATIONS FOR INNOVATION

### *4.1 Introduction*

In the past, innovation has been principally associated with three major institutions: universities, industry, and government. Traditionally, these institutions operated within distinct spheres, each with a well-defined role in the innovation landscape. Universities served as hubs for education and basic research, industry acted as the engine applying this research to product development, and government moderated these roles through policy and law creation [64]. Under this model of innovation, knowledge flowed linearly from universities to industry, with no feedback loops. This traditional model of innovation, characterized by a linear flow of knowledge from universities to industry, has faced widespread criticism for its inherent limitations. Its oversights include neglecting the iterative nature of innovation, the significance of trial and error, and the incremental progression inherent in the process. Recognizing these deficiencies, newer models depict innovation as an iterative journey shaped by continuous interactions among diverse actors, networks, and institutions [65]. This evolution has blurred the once-distinct roles of universities, industry, and government. Universities are adopting more "entrepreneurial" characteristics, while industry is increasingly engaging in basic research [63]. The consequence of these changing roles is a surge in complex interactions among actors, intensifying the innovation landscape.

Universities play a pivotal role in advancing deep technological knowledge and educating a workforce poised for active participation in innovation activities. The knowledge generated through research and patents, as well as imparted through education and training, serves as a crucial channel to industry. Establishing a symbiotic relationship between universities and industry is imperative for fueling the innovation economy, facilitating the dissemination of knowledge from universities to industry through research, patents, and education. In recent years, university-industry (U-I) collaborations have gained significant interest from scholars and policy makers alike, as a tool for

technological innovation and knowledge exchange [125, 18]. University-industry collaborations refer to partnerships between one or more academic or research institutions and one or more companies for various collaborative activities focused on research and/or education. For industry, these collaborations offer a way to source state-of-the-art research and development (R&D), connect with leading scientists and identify talent. For universities, the collaborations are a way to obtain funding, provide relevant education to students and support commercialization of research results.

Historically, U-I collaborations have been common in the education and research domains of engineering. Much of the technological innovation is driven by the knowledge transfer occurring between universities and industry, especially in engineering and computer science. Some of the earliest engineering colleges and universities (especially polytechnics) were established to train engineers with relevant skills that catered to the needs of the region and the economy. However, after World War II, engineering as a field grew to become more theory focused, partially driven by WWII and Cold-War era government funding, which encouraged basic science. Consequently, universities paid little attention to industry needs [158]. However, due to various reasons explored in this Chapter, the balance is tipping again, and engineering colleges and universities are increasingly engaging industry for research and education purposes.

While U-I collaborations for research and entrepreneurship have been extensively explored in the literature, the focus on how U-I partnerships for education contribute to the innovation system has been relatively understudied. Although it is acknowledged that U-I collaborations for education enable hands-on learning, fostering skills for workforce readiness, the extent to which they contribute to developing the next generation of workers for active participation in and contribution to an innovation system is not well understood. Furthermore, a gap exists in research on U-I collaboration for education in the context of innovation, accompanied by a lack of measures to quantify the contribution and value of engineering and design work in innovation. Looking specifically through the lens of education, existing measures of project-based learning predominantly concentrate on assessment and teamwork, often neglecting the nuanced skills required for innovation. This chapter seeks to address these gaps by diving into the dynamics of U-I collaborations within engineering education, evaluating existing measures, proposing additional ones, and identifying crucial missing measures essential for a comprehensive assessment of the educational impact of these collaborations.

## 4.2 *Research Objective*

Despite the growing body of knowledge on university-industry (U-I) collaborations, significant fragmentation persists in understanding the complex dynamics of these partnerships [108]. The present state of innovation scholarship is limited in that prevailing measures predominantly address U-I collaborations for research and entrepreneurship. However, there is a gap in measures that encompass the educational dimension of these collaborations. While studies have delved into the experiences of Ph.D. students engaged in joint U-I projects, the existing literature falls short in addressing the broader value of U-I collaborations for educational activities, particularly in domains like engineering design. This gap extends to a lack of measures that can holistically assess the impact of U-I collaborations on students, industry actors, and the future workforce. Therefore, this study takes a focused approach to bridge the existing gaps in the U-I knowledge base within engineering domains. The central objective is to develop and refine measures that assess the value and impact of U-I collaborations on education.

This study is aimed at identifying measures that can enable university and industry actors to gain deeper insights into the value of university-industry (U-I) collaborations and facilitate strategic development of future collaborations that align with the goals of all actors involved. The fundamental question guiding this study is: what measures and tools are missing for assessing university-industry collaborations for innovation in the context of engineering education? By addressing this question, the research aims to contribute foundational knowledge that reveals the existing gaps in assessing U-I collaborations. To address this research aim, the study concentrates on a specific type of U-I partnership for education—the industry-sponsored engineering capstone design experiences. This deliberate focus allows for an in-depth exploration of measures pertaining to student experiences and learning outcomes in the capstone context.

## 4.3 *Background*

### 4.3.1 *A Brief History of University-Industry Collaborations*

Traditionally, universities are seen as having two main missions- teaching and research. In recent years, universities have been expected to emphasize a “third mission” of more directly contributing to industry, the economy and society [119, 148, 65]. This new “mission” is correlated to growing

university-industry collaborations. However, neither the “third mission” nor university-industry collaborations are a new occurrence as universities have historically adapted to the demands of external groups and have adapted to suit their economic, social, and political environment.

Historically, there existed two competing models of higher education, the “classical” and the “technical” [119]. The classical model integrated education and research under one institution, emphasizing generation and dissemination of basic research, with a focus on theory instead of practice. This model is foundational to how the two missions of the universities are perceived today. In contrast, the “technical” higher education institutions were focused on the “third mission” from the beginning. These included polytechnics such as Rensselaer Polytechnic Institute (RPI) and technical universities such as Massachusetts Institute of Technology and Stanford University, which were focused on explicitly providing their students with technical skills that can be used in industry. However, the “classical” model of the university gained immense prominence in the 19th and early 20th century heavily influencing American and global institutions. Consequently, by the late 20th century it was widely believed that the two missions of the university were education and research, seen as a unified whole and not separate tasks.

The Second World War fundamentally changed the science and technology enterprise in the U.S. Until World War II, research universities were on the periphery of the nations’ science and technology system. In 1940, universities and colleges accounted for only \$31 million (9.0%) of the total R&D expenditure by the US. At this time, private universities obtained their research support from endowments and non-profit foundations, and state universities from state governments. The federal government provided virtually no support for research. But in the 1940s, President Franklin D. Roosevelt established the National Defense Research Council (NDRC) and the Office of Scientific Research and Development (OSRD) chaired by Vannevar Bush to organize the nation’s scientific resources in preparation for the US’s entry into the war. In 1945, Bush’s influential science policy report “Science- the Endless Frontier” *Science- the Endless Frontier* elevated universities as the principal sites to conduct basic research. This resulted in government funding being poured into universities and industry laboratories. This gave rise to the linear model of innovation where innovation moved from basic research occurring in universities to applied research and development occurring in industry. Additionally, university education contributed to the development of a skilled workforce that supported innovation activities. However, education was more or less theoretical

instead of hands-on.

Bush's model of innovation was successfully adopted and justified large government spending on research and motivated universities to move away from catering to industry and regional needs and focus on obtaining government funding. Therefore, within engineering, universities switched to focusing more on theory instead of practice in their research and education goals, cementing their transition from the "technical" to the "classical" model of universities. However, by the 1990s many factors contributed to shifts in the environment around research and universities. Firstly, the end of the Cold War resulted in a decline in government funding for the physical sciences, causing universities to search for alternative sources of funding (such as industry). Secondly, increasing economic competition due to the entry of new players such as China resulted in a greater emphasis on science, technology, and innovation, pushing the universities towards a seemingly new "third mission" of connecting with industry to exploit intellectual property. Lastly, the economic recession of 2008 resulted in notable impacts on federal research funding resulting from constraints on public spending. These funding reductions were also accompanied by an increasing demand for accountability and "value for money" on the part of universities with respect to research funding [70, 143]. Additionally, an increasingly competitive knowledge economy also required a workforce that has skills relevant to industry. Therefore, in the 21st century, universities have increasingly sought to close the gap between the skills it provides its graduates and the skills required in industry [140].

Certain government policies also accelerated modern-day university-industry collaborations. In the 1970s, the National Science Foundation (NSF) established various Engineering Research Centers that tied federal support for research with industry participation, which incentivized universities to collaborate with industry. The Economic Recovery Tax Act of 1981 provided R&D tax credits to companies conducting R&D, motivating firms to partner with universities. And, the Patent and Trademark Act of 1980, known as the Bayh-Dole Act, gave universities the rights to intellectual property developed under federally funded research and to assign or license those rights to others, including companies [70]. These environmental factors and policy decisions incentivized universities to move from a "classical" model to pursue a "technical" model of universities focused on providing "useful" knowledge to the economy and society. Some scholars have added a third model known as the "Triple Helix" model of knowledge production [64], which focuses on closer linkages between

university, industry, and government. The model explicitly acknowledges that universities are undertaking a “third mission” of directly contributing to the economy and implies that universities that take up this mission undergo a transformation to become “entrepreneurial universities”. The Triple Helix model recognizes universities as sources of knowledge, companies, and innovations, embracing an entrepreneurial role. Regardless of how it is framed, society is shifting toward developing closer ties between university and industry activity. Data that directly validates this premise is discussed next.

#### 4.3.2 Validation for the changing roles of university and industry

Existing data supports the fact that universities and industry are likely functioning in a Triple Helix model of knowledge production where universities are becoming more “entrepreneurial” and industry is taking up more basic research. Table 4.1 shows the technology transfer activity for 2007, 2012 and 2017. Between 2007 and 2017, university technology transfer activity increased by 73.6%.

(Number of activities)			
Technology transfer activity	2007	2012	2017
<b>Invention disclosures and patenting</b>			
Inventions disclosed	14,398	19,827	24,998
Patent applications	11,797	14,192	15,335
Patents issued	3,622	5,153	7,459
<b>Licensing</b>			
All licenses, total active in the year	30,351	40,006	45,657
Licenses issued	4,354	5,130	6,283
<b>Startup companies</b>			
Startup companies formed	555	705	1080
Operational startups	3,388	4,002	6,050

Table 4.1: University Technology Transfer activity indicators: 2007, 2012 and 2017 [188]

Furthermore, as depicted in Figures 4.1 and 4.2, the proportion of research and development (R&D) activities funded and performed by the business sector have notably increased their share in the US. Specifically, in 2010, businesses performed 22% of U.S. basic research, while the sector’s role rose to 27% in 2017. In contrast, the share of U.S. basic research performed by higher education institutions declined from 50% to 48% at the same time-period. [188]. Additionally, collaboration between the business and academic sector in peer-reviewed publications increased from 43.8% in 2008 to 51.3% in 2018. These trends of collaboration between universities and industry are not

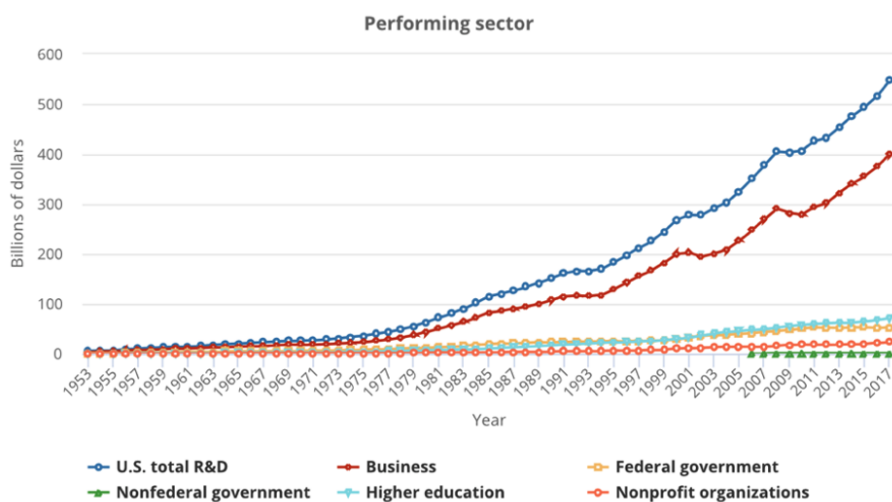


Figure 4.1: U.S. R&D by performing sector: 1953-2017 [188]

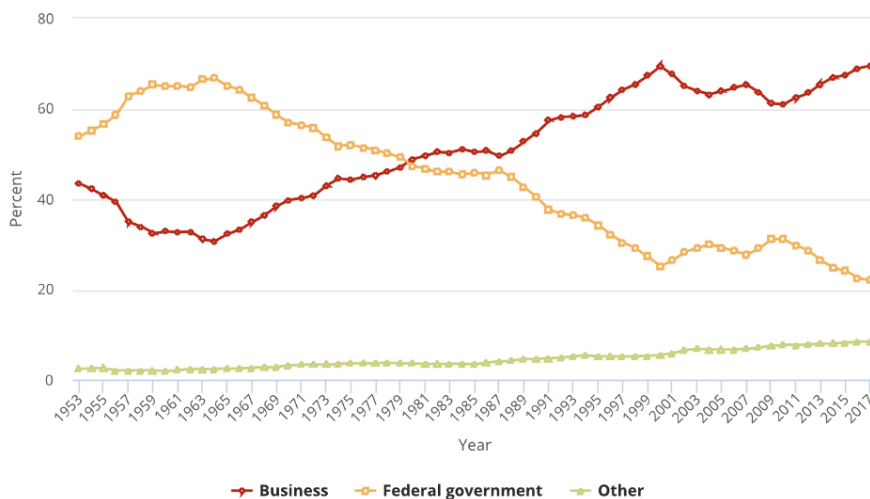


Figure 4.2: U.S. R&D by sources of funding: 1953-2017 [188]

restricted to research and development. Universities are now engaging regional actors to prepare a workforce that increases the region's innovation potential while boosting economic performance and individual achievement. They do so by partnering with industry to improve the balance between the demand and supply of relevant skills. To remain competitive and innovate, industries

need to develop workforce skills that are aligned with changing demand and technology [131]. Thus, increasing educational attainment needs to be supplemented by providing a better-targeted education that leads to improved work opportunities for a 21st century workforce [187]. University-industry partnerships provide a way for employers to collaborate with universities and develop a channel for talent, to ensure a steady flow of adequately trained and educated students. The need to convene education-based partnerships between universities and industry in STEM is backed by a strong policy mandate. The Innovations in Mentoring, Training and Apprenticeship Act of 2018 urges the National Science Foundation (NSF) to award grants to higher education institutions that partner with the private sector. Similarly, National Science Board’s Vision 2030 advocates for strengthening partnerships between educational institutions and the business sector to foster a STEM workforce with skills that cater to industry needs [189]. Thus, there is no shortage of data and policy shifts which indicate that universities, government, and industry are becoming more collaborative rather than more isolated.

#### 4.4 Types of University-Industry Collaborations

While universities and industry collaborate through a myriad of channels, their collaboration activities can be grouped into three main categories: *education, research, and entrepreneurship* (Figure 4.3)



Figure 4.3: Types of University-Industry Collaborations

#### *4.4.1 U-I Collaborations for Education*

A central mission of universities is teaching and imparting the next generation of workers with the skills to succeed in society. Universities often collaborate with industry to develop relevant curriculum either through departmental industry advisory boards, guest lectures or individuals from industry serving as adjunct faculty. Industry advisory boards are common to engineering departments and consist of members from industry who advise departments on the curriculum's relevance to industry needs. University-industry collaborations for education also occur in the form of lifelong learning. These are continuing professional development programs, where the students are often employed in industry and are looking to up-skill or pivot directions to other fields. Other ways in which universities collaborate with industry are through internships via career fairs or joint project-based courses such as capstones, where students work on industry sponsored projects. [91].

#### *4.4.2 U-I Collaborations for Research*

Another key mission of modern universities is research. U-I collaborations for research is one of the most well-studied areas in the field. Industry collaborates with universities on joint projects to get access to cutting -edge research occurring in universities, while universities are motivated to collaborate with industry to obtain funding. Other form of U-I collaborations for research includes contract research and consulting services offered by university researchers to industry clients, joint PhD dissertations and movement of graduate students from academia to industry, licensing of university generated intellectual property (IP) and other informal interactions via conferences and social network ties. The sub-field of academic entrepreneurship studies the various factors that result in the commercialization of academic research. [148].

#### *4.4.3 U-I Collaborations for Entrepreneurship*

Academic entrepreneurship literature studies factors that impact how academic research gets commercialized. Academic entrepreneurship consists of various commercialization activities such as patenting, licensing, and creating a business. In this case, often academic researchers use the services of the university technology transfer office to either license their technology to industry or create a startup around it. However, universities can also collaborate more broadly in the context of

entrepreneurship by having industry mentors participate in university run accelerators, incubators, and business plan competitions.

#### **4.5 Impact of University-Industry Collaborations**

Broadly, the value of U-I collaborations are (i) generation and transfer of knowledge (products and processes), and (ii) competence building, which leads to the development of and access to “human capital” and skills [59].

##### *4.5.1 University-Industry Collaborations for Knowledge Generation and Transfer*

University-industry (U-I) collaborations drive knowledge generation and transfer, yielding products like publications, patents, and licenses [195]. Valentin’s taxonomy categorizes benefits into financial, technological, and epistemological domains. Industries pursue U-I collaboration for ‘open innovation’, departing from secretive approaches. This fosters external and internal idea integration, offering access to cutting-edge research, reducing R&D costs, securing public grants, and sharing R&D risks. Epistemologically, collaborations help firms identify transformative scientific advances and navigate technological uncertainties [33, 73]. Universities, in turn, gain access to industry’s advanced instruments and equipment, crucial for technological progress. Financially, collaborations offer alternative funding sources amid declining national and state support. Universities acquire resources for new research, access public grants, and test theories in real-world settings. Epistemologically, U-I collaborations enhance science’s predictive power, generate tangible outcomes, and contribute to academic outputs [195, 169].

##### *4.5.2 University-Industry Collaborations for Competence Building*

Competence building, fostering a highly skilled workforce, is a key outcome of university-industry (U-I) collaborations [59]. Valentin’s taxonomy identifies education and strategy as the dual motivations for such collaborations. From an educational standpoint, industry gains access to novel knowledge, skills, and innovative talents through university collaborations. Professional education programs enable firms to enhance the expertise of their employees. Strategically, U-I partnerships serve as a cost-effective talent screening tool, creating databases of potential hires from university

students. Firms also use these collaborations to forge alliances and networks with faculty and researchers for future collaboration. For universities, partnering with industry provides practical training through research, projects, and internships. Industrial scientists contribute to education as adjunct faculty, and collaborations inform curricular enhancements, ensuring students acquire relevant, employable skills [153]. Strategically, these partnerships grant access to industry expertise for students, faculty, and researchers.

## **4.6 Barriers to University-Industry Collaborations**

While U-I collaborations are of immense value to universities, industries, and governments (as discussed in Section 1.2), there are many barriers to their formation and success. Bruneel et al identify two types of barriers: (i) orientation-related barriers and (ii) transaction-relation barriers [25].

### *4.6.1 Orientation-Based Barriers*

Orientation-based barriers in university-industry collaborations stem from divergent institutional orientations and norms [143, 25]. Universities prioritize the creation of reliable, publicly disseminated knowledge, driven by reputation-based incentives. Academic success hinges on publications, leading to status competitions among peers. In applied fields like engineering, interactions with industry alter the dynamics, with researchers' status influenced by both academia and industry recognition [199]. Conversely, industry's knowledge creation revolves around secrecy for competitive advantage through intellectual property and patents [186, 143]. The motive is private gain, and knowledge exchanges are strategic for competitive edges. The divergent nature of these operations often leads to conflicts in collaborations. Academics prefer "leaky" knowledge for acknowledgment, while industry seeks "sticky" knowledge for control and competitive advantage [24]. Conflicts may arise when university researchers aim for informal discussions and early dissemination, conflicting with industry's preference for confidentiality, delaying publication until patent applications. This discrepancy can be detrimental to the academic's career due to the winner-takes-all dynamics of university research.

#### 4.6.2 *Transaction-Based Barriers*

The Bayh-Doyle Act of 1980 incentivized universities to commercialize intellectual property (IP) generated by academics, sparking debates about potential conflicts with open science norms. Studies, such as [25] and [159], indicate complementarities between patenting and scientific performance, suggesting successful research correlates with creating commercial value. However, concerns arise about growing secrecy in academic research, as collaborations with industry partners may lead to delays in publication and refusal to share results [21]. Distributional conflicts emerge when universities aggressively seek financial benefits from IP, causing disputes with industry collaborators over commercial potential. Larger firms feel pressured into unfavorable IP negotiations, while smaller firms face delays in obtaining research results due to prolonged negotiations by university tech transfer offices [70]. The increase in university patenting is associated with a slowdown in joint research collaborations [196]. Trust decline is observed when academics use U-I collaboration results to start their businesses, impacting future collaborations [195]. The barriers between U-I collaborations fundamentally stem from the conflict between education/research as a public good and education/research for industry profit. Addressing these barriers requires aligning goals, building trust, and maintaining clear communication among actors [28, 123, 152].

#### 4.7 *A Case for Measures*

The central focus of this study revolves around evaluating the value of university-industry (U-I) collaborations for all actors involved and addressing barriers that may impede their success. This inquiry drives the establishment of measures to:

1. Quantify the importance of U-I collaborations for its stakeholders
2. Pinpoint specific obstacles hindering successful U-I collaborations and devise strategies to overcome them.
3. Assist researchers and industry decision-makers in making better-informed decisions regarding U-I collaborations by matching partnerships more effectively.

4. Direct data collection systems to inform decision-making processes related to U-I collaborations.

The absence of robust measures hinders the development of valuable theoretical and analytical frameworks necessary for understanding the role of university-industry collaborations in a knowledge-based economy [125]. Measures covering a broad spectrum of activities impacting U-I collaborations are essential to showcase their scope of influence [73, 154]. In the context of a shifting landscape where companies actively participate in science, a systematic evaluation of collaborations with universities becomes crucial for firms to justify their value and enhance the likelihood of success [147, 73]. This evaluation enables firms to make informed decisions about collaborating universities, assess the necessity of collaborations, and allocate appropriate financial, technological, and human resources. From a university's standpoint, measuring the value of U-I collaborations allows justification for partnering with industry and a thorough study of its impact on research and education outcomes. Reliable measures enable universities to navigate the tension between "open science" and financial gain from research, guiding decisions on collaboration formation. On a broader innovation system and policy level, measures are indispensable for estimating the value and role of U-I collaborations in regional development [171]. While policymakers and governments are pushing hard for U-I collaboration, there is little evidence about the scale of these collaborations and their impact on regional economic development. This is mainly due to the lack of comprehensive measures and data collection systems that can capture the diverse activities that characterize U-I interactions [124].

#### 4.7.1 Existing Measures and Indicators of U-I Collaborations

Measuring performance of university-industry collaborations is challenging because the relationship between universities and industry is facilitated by a complex set of interactions and institutions [108]. Many attempts have been made to measure aspects of U-I collaborations. Existing research on indicators of U-I collaborations can be classified into three categories: *inputs, outputs, and impacts in U-I collaborations*. These measures can operate at three levels: direct measures, proxy measures and factors (correlations) [167, 107]

### *Inputs of U-I collaborations*

Input indicators measure the intent. In literature, they are often proxies that do not guarantee an output [107, 147, 154, 36]. They represent the tangible and intangible resources that go into setting up and driving collaborations.

- **Input measures for research activities:** Research activity input indicators encompass research and development (R&D) expenditure by firms and universities, joint university-industry R&D funding, and public funding granted to universities [167, 148]. Direct input measures involve the amount of industry sponsorship for university research and the engagement of academic researchers in collaborative activities. Academic researchers' capabilities, assessed through bibliometric indicators like publications and citations, and motivation, evaluated by factors such as time spent on collaborations, demographics, commercialization experience, and scientific productivity, serve as input measures [148, 106]. The departmental climate, measured by prior U-I collaborations and supportive structures, and social network ties between firms and researchers, influenced by node centrality and industry linkages, contribute to input variables affecting U-I collaborations [147, 15, 6]. University-level input measures encompass size, R&D spending, type (R1 vs. R2), ranking, joint research programs, technology transfer office existence, industry support for spin-offs, and innovation policy [171, 36]. The geographical proximity between universities and industry partners is a significant input, with closer distances fostering collaborations [171]. Firm characteristics, including absorptive capacity, age, size, R&D spending, competitive strategy, collaboration experience, and employee education, serve as firm-level input measures [36, 171].
- **Input measures for entrepreneurship activities:** Key input indicators for measuring university-industry (U-I) collaboration in entrepreneurship encompass the presence of a technology transfer office (TTO) at universities. TTOs play a pivotal role in facilitating the commercialization of university technology, acting as intermediaries between academia and industry, fostering industry partnerships, and safeguarding intellectual property (IP) generated at universities [159]. Additional entrepreneurship input measures involve the existence of university-sponsored incubators, accelerators, and business competitions that con-

nect university-based entrepreneurs with industry mentors. In the U.S., the amount of Small Business Innovation Research (SBIR/STTR) serves as a proxy for measuring university-based spin-off activity. Entrepreneurial education is another critical aspect, with input indicators including the number of entrepreneurship courses for students and researchers and the presence of joint U-I entrepreneurship programs, such as fellowships and internships. At the regional/national level, entrepreneurial activity indicators encompass the number of venture capital firms, the amount of venture funding disbursed, the count of small businesses and startups in the science and technology industry, and regional policies related to innovation and entrepreneurship.

- **Input measures for educational activities:** The study of university-industry (U-I) collaborations in educational activities is underexplored [154, 125, 178]. Common input indicators include the percentage of students involved in internships, students' intent and motivation, and the proportion engaged in industry-based projects, particularly in engineering/technology. Another measure involves graduate (PhD) students working on industry-sponsored projects for dissertations, providing an educational experience. Adjunct faculty with dual university and industry appointments, contributing to course instruction, is an additional input. Industry-sponsored makerspaces/facilities for educational purposes, quantified by their presence and number, also serve as input measures. Entrepreneurship education is part of these activities, focusing on measures like students' entrepreneurial intention [206], entrepreneurial motivations [67], and career expectations [101].

#### *Outputs of U-I collaborations*

Output indicators measure the result of university-industry collaborations. As in the case with input measures, output measures can also be categorized by the type of U-I collaborative activity.

- **Output measures for research activities:** Commonly measured quantitative outputs of U-I collaborations for research include number of patents and patent citations resulting from collaborations, number of university licensed technologies, number of university spin-offs and bibliometric data such as co-authored publications and their impact [154, 171, 169].

However, these quantitative indicators often do not provide the entire picture. For example, patent citations to academic research only account for a small share of U-I interactions. Patents may also vary in economic importance across different sectors and may not lead to commercially successful products [90]. Therefore, other outputs such as number of new products/processes created during collaborative research (reported in final reports), number of invention disclosures and number of repeat collaborations should also be considered.

- **Output measures for entrepreneurial activities:** Output measures for entrepreneurial activities include the number of university spin-offs, market value of spin-offs, value of revenue generated by spin-offs, the survival and sustainability of spin-offs, total money raised from external investors, growth in the number of employees over time, total sales of the product resulting from commercialization etc. There also exist output indicators that measure U-I collaboration's impact on the development of a regional ecosystem. These indicators measure whether a university has affected policy change in a region, the total employment created by university spinoffs and the rate at which university students are employed by or create startups [83].
- **Output measures for educational activities:** There are not many indicators that measure the output of U-I collaborations for education, including lack of indicators for measuring the impact of collaborations on curricular innovations or development of a competence and skilled workforce [178]. Output indicators such as the number of joint U-I PhD and master's dissertation imply educational value, however they are usually studied in the context of research. A common education-based indicator of U-I collaborations is the proportion of students who get employed through U-I collaborations, including the number of graduate students hired by industry and students undertaking internships [83, 147]. Some output measures also evaluate aspects of U-I collaborations such as lifelong learning, these include the number of students enrolled in continuing education programs. The role of education in U-I collaborations is understudied and needs further investigation. Most of the literature in this field focuses on R&D, entrepreneurship, and regional development. However, there is a gap in understanding the various ways in which universities and firms collaborate for educational

purposes, how those impact actor outcomes and how collaboration for education affects R&D, entrepreneurship, and innovation as a whole [147, 59, 125].

#### *4.7.2 What is missing from the measurement literature?*

The existing measurement literature on university-industry (U-I) collaborations is extensive, encompassing inputs, outputs, and impacts across various collaborative activities. Inputs, ranging from research and entrepreneurship to educational endeavors, are measured through indicators such as R&D expenditure, collaborative funding, and academic researchers' engagement. Outputs, including patents, spin-offs, and publications, provide quantitative assessments of collaborative outcomes. However, significant gaps and challenges exist in this expansive landscape. The literature lacks a comprehensive understanding of how university-industry (U-I) collaborations contribute to education and competence building within innovation systems. There is a specific neglect of their impact on engineering and design activities in an educational context, leaving unexplored implications for both companies and students. In addressing these overlooked aspects, this study aims to provide a more holistic perspective, contributing to the innovation measurement literature. By doing so, it seeks to add to the understanding and enhance the contribution of U-I collaborations in innovation systems [178, 125, 149, 76].

### **4.8 Assessing the value of U-I Collaborations in Industry Sponsored Engineering Capstone Programs**

This study addresses a significant gap in the literature related to the measurement of knowledge development and exchange during collaborative educational efforts between universities and industry. While the quantitative evaluation of research and development (R&D) activities often relies on measures such as co-publications, citations, and R&D expenditure, the assessment of the educational value in university-industry (U-I) collaborations lacks established measures. Unlike the well-defined measures for R&D and entrepreneurial activities, the educational dimension of U-I collaborations requires closer examination. To fill this gap, the study focuses on exploring the experiences and perceptions of students participating in industry-sponsored capstone programs. These programs, situated within the engineering discipline, offer a unique context for investigating U-I collaborations in education due to their distinctive attributes, including "permeability,"

relevance to industry needs, and methodological advantages.

- 1. The role of the engineering discipline in U-I collaboration:** From the time of their conception, engineering schools were more “permeable” to industry needs than colleges of arts and sciences [109]. Their research and education missions could be more easily tailored to technology transfer from academia to industry, given the close connection engineering had with practical industry applications [73]. Further, engineering and design work is key to technological innovation as the discipline as a bridge between research and product development. Despite this centrality, the contribution of engineering and design to innovation systems remains underexplored, forming a crucial aspect of the knowledge gap addressed in this dissertation [158, 109, 73].
- 2. Relevance (to assessing educational value of U-I partnerships):** U-I partnerships provide a way for employers to collaborate with universities and develop a channel for talent to ensure a steady flow of adequately trained and educated graduates. As technology advances, there is growing demand for employees who excel at skills that machines cannot replicate. Therefore, future workers need a technical STEM education to be supplemented by “soft skills” such as design thinking, entrepreneurship, and creativity to flourish in the workforce [62]. In engineering, these skills are formalized in ABET’s undergraduate engineering program student outcomes, which emphasize applying “engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors” [38]. Industry sponsored capstone programs offer a way to deliver this design experience by providing students with the opportunity to work with industry mentors on designing solutions for relevant, real-world problems. A 2015 survey of 256 institutions from the US revealed that 70% of their engineering capstone programs were funded by external sponsors [91], indicating the prevalence of U-I capstones. Because of their popularity, the industry capstone makes an ideal context in which to study the educational outcomes of U-I collaborations.
- 3. Methodological Advantages (for identifying measures for educational value of U-I partnerships):** Direct U-I collaborations for education occur in the form of internships, joint

research projects, guest lectures and adjunct faculty appointments. However, these collaborations are often one-off, fragmented, context-specific, and difficult to measure. Essentially, their population is too small, too heterogeneous, and too distributed to be study systematically (small ‘N’). In contrast, industry sponsored capstone courses are very popular, host more homogeneous student populations (i.e., seniors in a specific engineering discipline) and consist of a sufficiently large student cohort for systematic study. For example, the capstone course considered in this consisted of an average of over 100 students and over 30 projects during the 3-year study period. Therefore, from a methodological perspective, capstone courses are a suitable unit of analysis due to (1) a relatively large student population which can be studied (relatively large ‘N’), (2) their iterative nature (usually offered every year) which allows for data collection over time and (3) a structured curriculum, which can be compared against other educational efforts (e.g., courses) and be affected by interventions to improve the educational value of these experiences.

#### *4.8.1 Existing Measures for Industry Sponsored Capstones*

Despite these methodological advantages and the prevalence of industry-sponsored capstone programs, existing measures specific to these programs primarily focus on assessing student learning outcomes in terms of the design process, teamwork, and communication. These include studies assessing different stages of the design cycle [160], faculty and industry panels scoring students design products [174, 173] and verbal protocol analysis, which assess students’ design process as they voice it out loud [7, 8]. In engineering design capstone literature, student outcome measures typically assess students’ design process, teamwork, and communications [47, 46]. There are some qualitative studies that address student, faculty, and industry sponsor reflections on their experience in capstone programs, but these, in large part, do not contain any measures [115, 129, 203, 150, 201]. While these outcomes provide valuable insights, there is a dearth of measures assessing student perceptions of their learning experiences. Measures of student experiences should not only account for what instructors think students learned but also students’ own perceptions of learning, because these perceptions inform students’ satisfaction with their education. Measuring the value students place on U-I capstones and the skills they gain from them can help inform interventions that can

make the capstone experience more relevant to student needs and eventually result in collaborations that are beneficial to all actors. Further, examining the relationship between student perceptions of their experience and relevant design outcomes emerging from their experience allows for understanding the critical link between perception and learning that can further inform interventions and continuous improvement of the industry capstone and other U-I collaborations from an educational perspective.

## **4.9 Methods**

With the overarching goal of addressing the knowledge gap concerning the educational value of university-industry (U-I) collaborations, specifically within the realm of engineering design education, this research endeavors to establish meaningful measures capturing students' perceptions of learning and innovation in industry-sponsored engineering capstones. Recognizing the lack of comprehensive measures tailored to educational outcomes within U-I collaborations, the study focuses on three research questions.

### *4.9.1 Research Questions*

1. *RQ1: How can we systematically measure students' perceptions of learning and innovation in industry-sponsored engineering capstones?* This question aims to address the absence of comprehensive measures specific to educational outcomes within U-I collaborations by conducting an Exploratory Factor Analysis (EFA) on Likert-type questions posed to students during the capstone period. The goal is to identify and validate measures that effectively capture students' perspectives, filling a crucial void in the literature.
2. *RQ2: How can we develop and validate measures to assess students' design performance, particularly in scoping their projects, within industry-sponsored engineering capstones?* This question seeks analyze students' final reports over multiple years, providing a foundation for quantifying, and validating measures that capture the nuances of student learning outcomes in U-I collaborative settings. This question was investigated by analyzing students' final reports from 2019, 2020 and 2021 to evaluate and measure students' design performance, specifically how students scoped their design projects. The measures were used to study two interventions

during COVID-19 to scaffold students' design scoping process.

3. *RQ3: What do the above measures indicate about generalizing the measurement of innovation?*  
By integrating findings from RQ1 and RQ2, this question aims to understand how innovation measures can be generalized beyond an industry-sponsored engineering design capstone setting.

Through this methodological approach, the study not only identifies but also validates measures designed to systematically assess the educational value derived from U-I collaborations in the context of innovation.

#### 4.9.2 Setting

Table 4.2: Study Setting for the ENGINE Capstone

Year	2019	2020	2021
Students	80	88	124
Projects	31	27	29
Instruction	In-person	Hybrid	Remote

Student perceptions and actual design outcomes from the industry capstone experience form the dataset for establishing suitable education-based measures of U-I collaborations. The data for this study was collected from an industry-sponsored capstone program (ENGINE) offered in electrical and computer engineering (ECE) at the University of Washington, Seattle. The capstone spans two quarters (i.e., 20 weeks), has typical enrollments of 120 students, and allows students to work in project teams of three to five. Design projects involve software, hardware, or hybrid software/hardware design projects. During the first quarter of the course, student teams develop and scope their project with their industry mentors. Once a scope and plan are established in consultation with both industry and faculty mentors, teams move forward to project realization, which continues until the end of the two-quarter program. The data for this study was collected from three iterations of the capstone program, offered in 2019, 2020 and 2021.

Three offerings of the industry-sponsored capstone were evaluated (Table 4.2): (a) a fully in-person offering in 2019; (b) a hybrid offering in 2020; and (c) a fully remote offering in 2021. In 2019, the entire design experience occurred in-person, whereas in 2020, the capstone shifted to a fully remote mode after the end of the first quarter when students had already developed their project scope. Students had no opportunity to anticipate nor plan for the sudden changes effectuated by the pandemic. In 2021, the cohort was subject to the same restrictions as the second quarter of the 2020 cohort. That is, the campus remained closed, and instruction continued remotely.

#### 4.9.3 Instruments and Approach

The goal of this study was to identify relevant measures for assessing student experiences along two dimensions: (1) measures of student perceptions of innovation in the capstone and learning in the capstone, *what do students think they need from U-I engineering design capstones?* and (2) measures of student learning, *what do students actually learn from U-I capstones?* To identify measures along these dimensions the following instruments were used:

#### **Instruments for Measuring Students' Perception of Innovation and Learning in the Capstone**

- Reflection survey administered at the end of the capstone:** The self-reflection survey contained a total of 41 questions. Questions about learning outcomes relevant to technical skills were developed based on Davis et al.'s conceptual model for capstone engineering design performance and assessment and ABET's student outcomes 3 [38]. Questions relating to non-technical outcomes were adapted from scales developed by Chandler et al. to study entrepreneurs' competencies [32] and scales developed by Keinänen et al. to measure innovation competencies of students in the applied sciences [95]. Items for industry mentor and teammate support were adapted from existing scales validated to measure faculty support [205]. A summary of the close-ended (Likert-type) questions associated with the self-reflection instrument is provided in Tables 4.3 and 4.4. All Likert-type items were measured on a 4-point scale from 1: Strongly Disagree to 4: Strongly Agree. In addition to Likert-type questions, the survey also contained several short-answer, open-ended questions. These questions are

Item	Label	Source
<i>Items adapted from Existing Scales</i>		
SE4: I learned how to analyze different designs and selected what we thought would be the most optimal	Systems Engineering	Chandler et al. [33]
A1: I learned how to develop a strategy to best take advantage of resources and capabilities available to us	Adaptability	
A2: I learned how to experiment with different approaches before settling on one		
A3: We learned how to adapt what we were doing to the resources we had		
A4: We learned how to be flexible and took advantage of opportunities as they arose.		
T1: I learned how to effectively collaborate in a team	Teamwork	Keinänen et al [102]
N1: I learned how to use my network to get the information/resources I need	Networking	
<i>Newly Developed Items</i>		
N2: I learned how to reach out to external sources to help me with a problem	Networking	N/A
SE1: I learned how the system development life cycle works- from requirement generation to system conception, design, and evaluation	Systems Engineering	
SE2: I learned to recognize the ethical, environmental and safety implications of our system		
SE3: I learned how to make informed design decisions, while being mindful of their real-world impact.		
A5: At the end of the capstone, I feel more comfortable handling uncertainty in a project	Adaptability	

Table 4.3: Likert-Scale Survey Items associated with Student Learning Outcomes

detailed in Table 4.5 and were designed to elicit information about how students pursued engineering design, made decisions, and adapted to changes along the way.

### Instruments for Measuring Design Learning in the Capstone

- Student Final Reports:** In the reports, student teams were required to describe and evaluate the extent to which they met design criteria they had drafted in the early stages of the project with guidance from industry mentors. These criteria were used to evaluate problem scoping performance and were operationalized based on the following measures: (a) the number of criteria each team generated; (b) number and percentage of criteria the team fully met; (c) number and percentage of criteria the team partially met; (d) number and percentage

<i>Description</i>	<i>Label</i>	<i>Source</i>
<i>Items adapted from Existing Scales</i>		
A6: We allowed the project to evolve as new information was made available	Adaptability	Chandler et al. [33]
G2: I was able to set realistic goals for my project	Goal Orientation	Keinänen et al. [102]
G3: I was able to satisfactorily meet the goals I had set		
C1: I was able to come up with new ideas to solve the problems at hand	Creative Problem Solving	Keinanen et al. [102]
C2: I was able to suggest practical solutions to reach a goal		
C3: I am good at coming up with new and imaginative ways to solve the problems I encountered		
P1: I had a clear and consistent vision for what we wanted to end up with, <u>early on in the project</u>	Planning	Chandler et al. [33]
P2: The product/deliverable we delivered is essentially the same one as we had originally conceptualized		
P3: The product/deliverable we delivered is substantially different from what we first imagined		
I1: My industry mentor was available when I needed help	Industry mentor support	Wilson et al. [199]
I2: My industry mentor was willing to spend time with me to discuss issues that are of interest and important to me		
I3: My industry mentor was interested in helping me learn		
I4: My industry mentor cared about how much I learned		
I5: My industry mentor was sufficiently involved in guiding me through all stages of the project		
I6: My industry mentor often asked me whether I had any questions		
I7: My industry mentor treated me with respect		
<i>Newly Developed Items</i>		
PK1: I was able to apply what I had learned in my previous courses to the project	Prior Knowledge	N/A
PK2: I was able to acquire new information that added to my understanding of what I already knew from previous classes		
PK3: I was able to apply the newly acquired information to my project		
G1: I was able to successfully plan tasks to achieve my goals	Goal Orientation	
T2: I was able to effectively communicate with my teammates	Teammate Support	N/A
T3: My team was responsive to my needs		
T4: I tried to ensure that all my teammates felt included		
T5: I felt included and a part of my team		

Table 4.4: Likert-Scale Survey Items related to Support, Self-Efficacy, and Preparedness

<i>Learning Outcome</i>	<i>Survey Text</i>
Engineering Design and Decision-Making	Additional comments on how you solved problems and/or how could you have better tackled problems you encountered
	Additional comments on what helped you achieve your goals and/or how you could have better achieved your goals
	Additional comments on what you learned or wish you had learned about the design process through this course
Adaptability	Additional comments on what you think helped you adapt and be flexible throughout the course
	Additional comments on what could have helped you adapt and be flexible throughout the course

Table 4.5: Open-Ended Student Survey Questions

of criteria the team did not met at all; and (e) the number and percentage of criteria that the team failed to address altogether. The total number of criteria determined the boundaries of the project scope, while the proportion of criteria met, partially met, not met and unaddressed offered an indication of how well students constrained the problem scope to the six-month project period.

#### 4.9.4 Data Analysis

##### *Closed-Ended Survey Data Analysis (RQ1)*

The quantitative data for this study consisted of close-ended (ordinal) Likert scale questions. Since all survey items were either adapted to or newly developed for this capstone setting, an exploratory factor analysis (EFA) was conducted to develop measures with construct validity and reliability. Likert-scale data were analyzed using R (version 4.0.2) and R studio (version 1.3). First, all items were assessed for suitability to an EFA by computing a correlation matrix and removing off-diagonal values greater than 0.9 to prevent redundancies. Next, Bartlett's test of sphericity was conducted to check whether the correlation matrix was an identity matrix. A small p-value for this test ( $p < .001$ ) would indicate that the variables are sufficiently correlated and suitable for an EFA. Further, a Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy was conducted as it signifies the proportion of an item's variance caused by underlying factors. Therefore, high KMO values are

usually desired. Items with KMO values less than 0.5 were removed [179].

To conduct the EFA, a principal component analysis (PCA) was performed on items which were not removed during preliminary tests. The number of factors for PCA was selected based on the number of eigenvalues greater than 1 and the percent variance explained by the factors, with 60% or more being desirable [68]. Items whose variance could not be justified by the factors were identified by computing the communalities. Items with communality less than 0.4 were removed [179]. PCA was repeated until all communalities were greater than 0.4. Once the number of factors was finalized, PCA was repeated with an oblique (“promax”) rotation, as items are assumed to be correlated and not orthogonal. Items that significantly loaded (loading  $\geq$  0.6) onto one factor were retained [54], whereas items that failed to load on any factor or had significant cross loadings were eliminated. The process was repeated until all items were clearly grouped into factors without significant cross-loadings. The internal reliability of the factors was measured using Cronbach’s alpha levels. Factors with Cronbach’s alpha level greater than 0.6 [68] were deemed suitable for further analysis. In cases where survey data was compared across multiple years linear regression and non-parametric tests of significance were applied to evaluate whether and how the measures changed over the three years studied.

#### *Open-ended Survey and Interview Data Analysis (RQ1)*

The qualitative data analysis was conducted using thematic qualitative analysis [122] of the open-ended survey and report data. The first round of coding for both sources of data was done individually and in an inductive manner to discover themes and patterns that were common among student experiences of the capstone. The next round of coding was based on the constant comparative approach, where themes emerging from the first round were compared across student teams to create categories, establish, and refine boundaries to those categories, and summarize the content of each category [116]. The categories were then compared across the different sources of data to leverage the discriminative power of the categories to identify patterns in the data that provide a more complete insight into the students’ experience as they navigated the capstone program.

*Final Report Data Analysis (RQ2)*

A two-phase screening process was used to filter out final reports for this study. A total of 31, 26, and 42 reports were submitted and analyzed for 2019, 2020 and 2021 respectively. The first phase of screening removed reports that were not focused on engineering design. Research/exploratory projects and feasibility studies were not retained for subsequent analysis. This phase resulted in the removal of 5, 3, and 9 of the final reports for 2019, 2020, and 2021 respectively. The second phase of screening evaluated the remaining reports to for completion and verified if they clearly articulated the design criteria that were set and ultimately met during the scoping process. Unfortunately, even though the final report guidelines required addressing criteria set and met, some design teams did not follow this guideline. This non-compliance resulted in the removal of 6, 3 and 12 of the reports from the analysis for 2019, 2020 and 2021 respectively. After both phases of screening, 61 total reports (20, 20, and 21 in 2019, 2020, and 2021 respectively) were retained for analysis. Non-compliant reports were removed to enhance the internal validity of the study by minimizing uncertainty and errors in measurement. The removal may have resulted in biasing the study towards “stronger” students with complete reports and may have underrepresented teams who truly had a hard time scoping their projects. However, the relatively small percentage of non-compliant reports removed instills confidence that the results of this study are likely to be reflective of overall student performance.

To control for differences in pre-capstone preparation, student GPAs from the quarter before they enrolled in the capstone were compared across the three cohorts. A one-way analysis of variance (ANOVA) revealed no significant differences between the three groups ( $p = 0.542$ ), thereby validating comparison of the three groups. Next, final reports were analyzed using a multi-phase, deductive coding process to identify scoping measures. First, a rubric was created that classified each original design criterion as one of the following: met, partially met, not met, or not addressed. In the second phase of coding, each criterion was evaluated and re-classified as necessary. Some criteria listed by students were found to be a combination of original design criteria and were separated so that they could be assessed individually. Other criteria were repeated, and duplicates were removed during the second pass. A third pass assessed the reliability of the coding process by having two raters independently recode a subset of the data based on a coding guide/rubric

developed by the original coder. Percentage agreement between the two raters was 85% (Cohen's  $k = 0.77$ ) suggesting substantial agreement between the raters [35].

Descriptive statistics were computed for scoping measures derived from the reports. The Shapiro-Wilk test for normality indicated that almost all the variables violated assumptions of normality and the Levene statistic indicated that the homogeneity of variance assumption was frequently violated. The small sample size in each of the groups made it difficult to visually validate assumptions about the data distribution. For these reasons, non-parametric, Mann Whitney U tests were chosen to make comparisons in the data [146].

#### 4.10 Results and Discussion

4.10.1 *RQ1: How can we systematically measure students' perceptions of learning and innovation in industry-sponsored engineering capstones?*

Items	Student Learning Outcome	Factor Loadings	
		Factor 1	Factor 2
SE1	Engineering Design and Decision-Making	0.0061	0.8376
SE2		-0.0759	0.9213
SE3		-0.0167	0.8615
A3	Adaptability	0.9622	-0.2043
A4		0.8702	-0.0333
N1		0.6630	0.2107
N2		0.8088	0.0492
A5		0.6619	0.1772
<b>% of Variance</b>		<b>40.3%</b>	<b>30.2%</b>
<b>Cronbach's Alpha</b>		<b>0.82</b>	<b>0.86</b>
<b>Eigenvalues</b>		<b>4.51</b>	<b>1.11</b>

Table 4.6: Exploratory factor analysis of survey items associated with student learning outcomes

EFA of items representing student learning outcomes yielded the results in Table 4.6. Only item T1 (Table 4.3) was eliminated from the preliminary analysis because it had communality less

than 0.4. In the subsequent factor analysis of the remaining eleven items, three items were removed because of significant cross loadings (SE4, A1 and A2 – see Table 4.3).

Two items positively loaded onto the first factor which was subsequently labelled "Engineering Design and Decision-Making" and included items associated with the systems engineering aspects of the capstone. The items focused on whether students felt like they learned more about systems engineering, ethical implications of design, and decision making. Notably, these skills are directly associated with technical competence [103]. The second factor contained four significantly loaded items associated with adapting to changes in the project scope, dealing with ambiguity, and obtaining information students needed to move forward. This factor was labelled "Adaptability" and refers to a student's ability to manage, remain flexible to and anticipate changes in the project. Unlike close-ended coursework, capstones can be effective tools in helping students become adaptable engineers by exposing them to open-ended real-world problems [103]. Both factors are attributes of top-quality engineers according to prior work [46]. These two factors related to student learning accounted for a total variance of 70.5%, which is above the desired threshold of 60% [68]. Reliability (Cronbach's alpha) for both constructs was above 0.7, which is considered adequate for further study [68].

EFA was repeated for items in Table 4.4. PCA analyses indicated that one item had communality less than 0.4 (P3 from Table 4.4) and subsequent PCA analysis with a fixed number of factors resulted in seven items being removed because of significant cross loadings. The remaining items loaded onto four factors: design self-efficacy, preparedness, teammate support, and industry mentor support. Individual loadings are summarized in Table 4.7. The factors represented a total variance of 72.1%, in the data which is above the desired threshold of 60% [68]. Reliability (Cronbach's alpha) for all constructs was above 0.7, which is sufficient for further study [68].

Based on the above analysis, the following types of measures emerged as measuring students' perceptions of learning and innovation and learning outcomes in ENGINE:

1. Measures of support: industry support and teammate support
2. Individual measures: design self-efficacy, and preparedness
3. Learning outcomes: engineering design and decision-making, adaptability

Items	Construct	Factor Loadings			
		Factor 1	Factor 2	Factor 3	Factor 4
C1	Design Self-Efficacy	0.0832	0.1200	0.8606	-0.1426
C2		0.0318	-0.0314	0.8905	0.0324
C3		-0.0618	0.1214	0.7625	0.1602
PK1	Preparedness	0.1308	-0.1781	0.2126	0.6832
P1		-0.0464	-0.0569	0.0133	0.8893
P2		-0.0517	0.2356	-0.1586	0.7643
T2	Teammate Support	-0.1423	0.8297	0.1187	0.0763
T3		0.0861	0.7950	-0.1413	0.1147
T4		-0.0642	0.8247	0.1300	-0.1493
T5		0.0957	0.8258	0.0663	-0.0503
I1	Industry Mentor Support	0.8347	-0.0273	0.0308	-0.0208
I2		0.9251	-0.0872	0.1076	0.0082
I3		0.9089	-0.0666	0.1020	-0.0179
I4		0.8607	0.1155	-0.1490	-0.0414
I5		0.9188	-0.0199	0.0143	0.0110
I6		0.6126	0.2133	-0.1457	0.0709
<b>% of Variance</b>		<b>27.6%</b>	<b>18.0%</b>	<b>14.4%</b>	<b>12.1%</b>
<b>Cronbach's Alpha</b>		<b>0.92</b>	<b>0.85</b>	<b>0.85</b>	<b>0.71</b>
<b>Eigenvalues</b>		<b>6.43</b>	<b>2.53</b>	<b>1.55</b>	<b>1.17</b>

Table 4.7: Exploratory factor analysis of survey items associated with students' perceptions of support and individual ability

Variable	Mean	Median	Std Dev	Skew	Kurtosis
Engineering Design and Decision-Making	4.22	4.33	0.72	-1.17	2.13
Adaptability	4.38	4.6	0.63	-1.21	1.75
Design Self-Efficacy	4.39	4.33	0.59	-0.84	0.94
Preparedness	3.87	4.00	0.84	-0.57	-0.29
Teammate Support	4.46	4.75	0.67	-1.45	-1.42
Industry Mentor Support	4.39	4.67	0.73	1.99	2.13

Table 4.8: Descriptive Statistics of Constructs

To further study the relationship between the student learning outcomes, measures of support and individual measures, a linear regression model was developed. First, descriptive statistics were

computed for each of the independent and dependent variables (Table 4.8). The kurtosis and skewness of all variables fell within the acceptable range of a normal distribution between -7 and +7 and -2 and +2 respectively for all variables [81].

To ensure that none of the assumptions of multiple linear regression were violated, model residuals versus independent variables were plotted to check for any violation against linearity and heteroscedasticity. Normal Q-Q plots were examined to check for violation of normality [68]. None of the above-mentioned assumptions—linearity, heteroscedasticity, and normality were violated. The results of the two regression models (one for engineering design and decision-making and one for adaptability) are summarized in Table 4.9.

Predictors	Estimates	Standard Error
<b>Student Learning Outcome #1: Engineering Design and Decision-Making</b>		
(Intercept)	-2.0439	1.069
Industry Mentor Support	-0.006	0.065
Preparedness	1.025	0.300***
Teammate Support	0.781	0.242**
Design Self-Efficacy	0.352	0.079***
Preparedness*Teammate Support	-0.155	0.065*
R <sup>2</sup> /Adjusted R <sup>2</sup>	0.517/0.502	
<b>Student Learning Outcome #2: Adaptability</b>		
(Intercept)	-1.059	1.069
Industry Mentor Support	0.505	0.171**
Preparedness	0.644	0.22**
Teammate Support	0.248	0.062***
Design Self-Efficacy	0.312	0.066***
Preparedness*Industry Mentor Support	-0.101	0.049*
R <sup>2</sup> /Adjusted R <sup>2</sup>	0.564/0.549	

\* p < .05, \*\* p < .01, \*\*\* p < .001.

Table 4.9: Linear Regression Results

The final model for engineering design and decision-making had an adjusted R<sup>2</sup> of 0.50, indicating that the independent variables and interactions between them collectively explained 50%

of the variance in the data. All independent variables were significantly and positively linked to engineering design and decision-making except for industry mentor support.

The final model for adaptability had an adjusted R<sup>2</sup> of 0.55 indicating that the independent variables and interactions between them collectively explained 55% of the variance in the data. All independent variables were significantly and positively linked to adaptability.

Two significant interaction effects between the independent variables were observed. In the first model (for engineering design and decision making), interactions between preparedness and teammate support were significant, indicating that for students who did not feel well-prepared for the project, teammate support played a larger role in their engineering design and decision-making skills. Similarly, in the second model (for adaptability), the interaction between preparedness and industry support was significant, indicating that industry mentor support has a stronger impact on adaptability skills when students felt less prepared for their projects.

Deductive coding in the thematic analysis of the qualitative data was done according to four themes corresponding to the four independent variables in the regression analysis. Frequencies of the four themes are summarized in Table 4.10 as they related to the two themes associated with student learning outcomes used in the quantitative analysis. Teammate support and preparedness were the most cited factors that helped students through engineering design and decision-making, while for adaptability, design self-efficacy and industry mentor support led the way.

Theme	Frequency	
	Engineering Design and Decision Making	Adaptability
Industry Mentor Support	31	14
Design Self-Efficacy	39	14
Teammate Support	48	11
Preparedness	42	13

Table 4.10: Frequency Analysis of Qualitative Themes

*Student Perceptions of Industry Support*

Two aspects of industry mentor support emerged as being prominent to students' perceptions of adaptability: the mentors' (1) technical feedback, and (2) flexibility to changes. Students stated that being able to frequently ask technical questions and have access to expert advice helped them adapt to different changes, and effectively solve problems: "Having an industry mentor that was so involved and was able to actively give us feedback helped a lot when it came to flexibility. When we wanted to try something out of the box our industry mentor could quickly approve and give feedback on those ideas that weren't originally planned."

Flexibility on the mentor's part made students feel more comfortable in exploring the problem space and altering aspects of the project that students deemed infeasible. Negative aspects of industry mentor support also forced students to adapt, for instance: "We got used to having to adapt in the project because our industry mentors would often have to take time giving us access to various things and it forced us to change our focus for the week." However, delayed industry mentor support was not a learning experience for all students: "We in a sense lost upwards of 7-8 weeks of time due to a bunch of delays and miscommunications and internal issues on the company end that caused our project to be in much worse shape than anticipated."

Therefore, there is a fine line between when an industry mentor's lack of timely support can be a learning experience versus when it may result in inferior project outcomes. While not statistically significant, examples of industry mentor support impacting students' perceptions of engineering design and decision-making emerged in the qualitative responses. Students looked to industry mentors for "high-level" support instead of details on solving technical problems and expressed how well-defined expectations from the mentor allowed them to design with more clarity:

"The company came into the project with a fairly set idea for what they wanted to see so we didn't make many big picture decisions about what our device would do, however we had lots of implementation decisions for how exactly to accomplish the overall goals."

For engineering design and decision-making, mentor support was not as influential in solving technical problems or making detailed design decisions, which is likely why it was not significantly linked to perceptions of engineering design and decision-making skills in RQ2. However, early support from the mentors in defining a clear vision of the project goals can aid students in making

technical decisions more easily. This calls for the development of best practices to help mentors support student learning so that students can take ownership of their design experience without getting lost in the process.

### *Student Perceptions of Teammate Support*

Two aspects of engineering design and decision-making prominently emerged as needing teammate support: solving technical problems and achieving goals. Students emphasized the value of a strong organizational structure, effective project management, and communication among team members, as exemplified here: “I think I helped our team achieve our goals by being an effective team manager and keeping the team organized and suggesting practical goals.”

Technical problem solving also benefitted from strong teammate support. For instance: “I was stuck with the appropriate deep learning model for my end of things. Upon discussing with everyone within the team, we came up with different models to try out like fast rcnn, d2go, yolo. Also, we had problems with setting up Bluetooth in Arduino. All of us went together in the lab and resolved the problem.”

In addition to problem solving, students also looked to their teammates for brainstorming ideas, balancing pros and cons of different designs and planning for engineering tasks: “I learned a lot about how design process works, such as initial brainstorming, working with the team to determine what design is best (pros and cons of each and how to fix them down the line after we get a working rough prototype out), etc.”

Although mentioned less frequently, students also relied on teammate support to improve adaptability. Students emphasized the value of having good communication with their teammates in making the design journey easier, especially when facing and adapting to challenges. In short: “Effective communication made it easier to adapt and be flexible. Trusting my teammates helped me take challenges head on rather than getting frustrated when things were not going my way.”

Clearly, during the design process, a student’s team was their best resource to solve technical problems, come up with new ideas, ensure that goals are being achieved on time, and navigate unforeseen changes in their project scope. This result is a clear call for capstone instructors to pursue additional and improved strategies to build team support.

### *Students' Perceptions of Preparedness*

Two aspects of preparedness emerged as being important to students' perceptions of engineering-design and decision-making and adaptability: (1) technical preparedness, and (2) project plan preparedness. Students who felt more prepared for their project were also able to organize their team's direction more effectively. This demonstrates how preparedness mediates the relationship between teammate support and engineering design and decision-making. For example: "As I had worked on similar problem of robot collaboration before, I was aware of the challenges and had the Birdseye view of the problem/modules. This helped in ensuring stable overall progress of the project and more profound brainstorming/scope discussion."

In the case of adaptability, one student remarked how prior technical experience with student engineering clubs helped them better adapt to uncertainties in the project. Additionally, students seemed more comfortable adapting to changes later in the project if they had clarity about the project goals earlier on. Industry mentor support emerged as being vital to preparing students to adapt to unforeseen changes by providing a concrete vision of the project goals. From both quantitative and qualitative results, it is evident that preparedness is important to students' perceptions of both engineering design and decision-making and adaptability skills. Capstone instructors can better prepare students by providing appropriate educational resources during the capstone and developing best practices for industry mentors to help students appropriately scope project goals.

### *Students' Perceptions of Design Self-Efficacy*

Students' ability to self-learn and apply new knowledge to solve problems emerged as being key to positive perceptions of what they learned about engineering design, as exemplified by one student: "I feel like initially the project scared me and I questioned my ability to handle it, but eventually I realized that even if I don't know some of the software and concepts that we need to use, I can learn them and contribute to the progress of the project."

Students mentioned how they pivoted their problem framing and/or accessed different online resources to achieve project goals and overcome technical challenges and were appreciative of what they learned about executing an open-ended, real-world engineering project.

"I learned how to create system architecture, conceptual models, simulation to better design

experiments that help progress goals under hardware, environment constraints.”

A prominent aspect of design self-efficacy that impacted students’ perceptions about adaptability was information and resource gathering. When students did not receive support or expertise within their own teams, they adapted by actively seeking information outside their immediate reach (forums, other capstone groups, open-source communities) to find solutions. However, some students expressed frustration at self-learning and a lack of teammate or industry mentor support. The burden of self-learning led students to feel stressed and worry that they might not be able to deliver on their project goals.

Given the importance of design self-efficacy in enhancing students’ belief that they can be successful in their capstones, instructors should consider devising strategies to boost students’ design self-efficacy. This may include helping students scope tasks that are challenging yet attainable and can bolster students’ sense of mastery, facilitate peer learning, and create frequent feedback loops with teammates and industry mentors [166].

### *Implications*

These measures provide a nuanced understanding of students’ perspectives and experiences within industry-sponsored engineering capstones, addressing a previously overlooked aspect in the evaluation literature. They serve as a foundational framework for comprehensive measures, bridging the existing gap in evaluating the impact of university-industry collaborations on students’ learning and innovation outcomes in engineering education. The uncovered factors, such as “Engineering Design and Decision-Making” and “Adaptability,” transcend traditional measures by delving into essential aspects of systems engineering, ethical considerations, decision-making skills, and adaptability—components often neglected in standard evaluations. This comprehensive approach provides a holistic view of the educational impact of university-industry collaborations on students’ learning outcomes.

The identified factors, including design self-efficacy, preparedness, teammate support, and industry mentor support, shed light on individual and interpersonal dimensions of students’ experiences, going beyond conventional measures. This deeper understanding allows for insights into how students perceive their own abilities, their preparedness for real-world challenges, and the influence of

supportive networks. Such insights are vital for evaluating the broader impact of collaborations on individual growth and professional development.

Equipped with these measures, educators and industry partners gain the ability to tailor interventions to enhance specific aspects of students' learning and innovation experiences. For instance, if there's a notable gap in perceived teammate support or industry mentor support, interventions can be designed to strengthen these collaborative dynamics, thereby positively influencing learning outcomes. Importantly, the measures explicitly connect students' perceptions to tangible learning outcomes in terms of engineering design and decision-making skills, assessing the practical impact of university-industry collaborations on students' ability to apply theoretical knowledge to real-world scenarios, fostering innovation and creativity.

The identified measures contribute to a more comprehensive and accurate evaluation of industry-sponsored engineering capstones. While traditional evaluations often focus on quantitative outputs, these measures provide a qualitative understanding of the educational journey, filling the existing gap and offering a richer narrative of the collaborative impact on students. This, in turn, empowers actors to make informed decisions, implement targeted improvements, and contribute to the continuous enhancement of collaborative programs.

#### *4.10.2 RQ2: What measures of student learning in industry sponsored engineering capstones?*

While RQ1 explored students' perceptions of learning and innovation, RQ2 extends the investigation to concrete measures of student learning derived from the detailed analysis of final reports and team performances. The capstone experience is a unique educational setting where students, guided by industry mentors, translate theoretical knowledge into real-world solutions. This transition necessitates a meticulous examination of their problem scoping capabilities, providing invaluable insights into the practical outcomes of university-industry collaborations. These problem scoping capabilities were assessed by establishing and evaluating scoping criteria derived from students' final reports [202]. In the final reports, teams were tasked with detailing and assessing their adherence to design criteria established in the project's early stages, guided by industry mentors. These criteria, essential for evaluating problem scoping performance, were measured using the following measures: (a) the count of criteria generated by each team; (b) the count and percentage of criteria fully met

by the team; (c) the count and percentage of criteria partially met by the team; (d) the count and percentage of criteria not met at all; and (e) the count and percentage of criteria that the team did not address. The overall number of criteria defined the project scope boundaries, while the proportions of criteria fully met, partially met, not met, and unaddressed provided insights into how effectively students constrained the problem scope within the six-month project timeframe.

The five problem scoping measures (number of criteria, number and percentage of criteria met, not met, partially met, and not addressed) were analyzed from the 61 team reports. Additionally, the scoping criteria were used to compare students' performance across three offerings of the capstone traditional (2019) and remote (2020 and 2021). From the total number of criteria identified to the nuanced breakdown of criteria met, partially met, not met, and unaddressed, these measures offer a granular understanding of how students navigate and define the boundaries of their engineering projects. Importantly, they provide a bridge between RQ1, which focused on students' perceptions, and the tangible outcomes manifesting in their project scoping efforts.

*Scoping Measure 1 (Total Number of Criteria)*

Measure	Year	Mean	Median	Std Dev	Skew	Kurtosis
Total Number of Criteria	Total	24.80	21.00	18.24	1.97	4.69
	2019	19.80	18.00	11.42	0.72	0.18
	2020	24.25	22.50	13.31	0.87	0.93
	2021	30.10	21.00	25.51	1.44	1.01
No statistically significant, year-to-year differences were identified						

Table 4.11: Initial Scoping of Capstone Design Projects

Student teams scoped anywhere between 5 and 102 total criteria with an overall mean (M) of 24.80 criteria and a standard deviation (SD) of 18.24 (Table 4.11). The total number of criteria appeared to rise from 2019 (M = 19.80, SD = 11.42) to 2020 (M = 24.25, SD = 13.31) and again to 2021 (M = 30.10, SD = 25.52). However, a Mann-Whitney U Test indicated that there were no statistically significant differences between the total criteria students identified in 2019 vs. 2020

( $W = 208.5$ ,  $p = 0.979$ ) and 2020 vs. 2021 ( $W = 138$ ,  $p = 0.966$ ). Further, high positive skew and high kurtosis in the 2020 data indicated that the distribution was skewed to the left (i.e., had a long right tail) and had a steeper peak than normal.

However, upon further analysis, it was observed that a single outlier was the cause of both high skew and high kurtosis. Once the outlier was removed, the 2020 distribution returned skew and kurtosis values to the range -2 to +2, thereby indicating sufficient normality to proceed [48]. Although not statistically significant, the mean of total criteria in 2021 ( $M = 30.10$ ) remained higher than in 2020 ( $M = 24.25$ ) and the mean of total criteria in 2020 remained higher than in 2019 ( $M = 19.80$ ).

#### *Scoping Measure 2 (Criteria Met)*

Measure	Year	Mean	Median	Std Dev	Skew	Kurtosis
# of Criteria Met	Total	13.80	9.00	16.49	3.19	12.63
	2019	11.45	10.50	9.21	1.14	0.88
	2020	11.30	9.50	8.32	0.36	-1.18
	2021	18.43	7.00	25.19	2.07	3.54
% of Criteria Met	Total	52.38	51.43	29.78	0.00	-0.99
	2019	54.43	54.73	26.98	-0.06	-0.75
	2020	46.30	41.29	31.76	0.17	-1.16
	2021	56.21	59.72	30.89	-0.07	-1.30
No statistically significant, year-to-year differences were identified						

Table 4.12: Team Performance (Criteria Met)

Student design teams met a mean ( $M$ ) of 13.80 (52.38%) criteria in their team efforts ( $SD = 16.49$ ) (Table 4.12). A Mann-Whitney U Test indicated that there were no statistically significant differences between the number of criteria met in student design projects in 2019 versus 2020 ( $W = 197.5$ ,  $p = 0.957$ ) and in 2020 versus 2021 ( $W = 206$ ,  $p = 0.927$ ). Similarly, there were no significant differences in the percentage of criteria met either in 2019 versus 2020 ( $W = 234.5$ ,  $p = 0.357$ ). or in 2020 vs. 2021 ( $W = 171$ ,  $p = 0.073$ ).

Measure	Year	Mean	Median	Std Dev	Skew	Kurtosis
# of Criteria Not Met	Total	3.52	2.00	5.44	2.97	9.91
	2019	2.75	1.50	3.16	1.06	0.10
	2020	1.95	1.00	2.74	1.91	3.35
	2021*	5.76	2.00	7.99	1.88	2.40
% of Criteria Not Met	Total	16.53	9.68	20.22	1.63	2.15
	2019	19.00	9.90	20.79	0.72	-0.95
	2020	8.47	6.46	12.43	2.55	6.93
	2021*	21.85	12.50	23.83	1.51	1.33

\* Differences from previous year were statistically significant

Table 4.13: Team Performance (Criteria Not Met)

*Scoping Measure 3 (Criteria Not Met)*

An analysis of the number and percentage of criteria that student teams did not meet revealed some statistically significant differences (Table 4.13). Both the number of criteria not met in 2021 ( $W = 120$ ,  $p = 0.017$ ) and the percentage of criteria not met in 2021 ( $W = 118$ ,  $p = 0.016$ ) were significantly higher than in 2020.

*Scoping Measure 4 (Criteria Partially Met)*

Measure	Year	Mean	Median	Std Dev	Skew	Kurtosis
# of Criteria Partially Met	Total	1.89	1.00	2.82	3.35	15.34
	2019	0.90	0.00	1.29	1.01	-0.44
	2020*	3.10	2.50	4.13	2.32	5.69
	2021	1.67	1.00	1.88	1.49	1.64
% of Criteria Partially Met	Total	8.08	4.35	11.00	2.04	4.99
	2019	4.38	0.00	6.43	1.19	0.21
	2020*	12.53	7.28	14.93	1.39	1.41
	2021	7.36	4.35	8.81	1.47	1.34

\* Differences from previous year were statistically significant

Table 4.14: Team Performance (Criteria Partially Met)

Not all criteria that student teams identified at the start of their projects were met or not met; some were partially met (Table 4.14). Mann-Whitney U tests showed that the number of criteria

partially met ( $W = 112$ ,  $p = 0.013$ ) and the percentages of criteria partially met ( $W = 126.5$ ,  $p = 0.039$ ) in 2020 were significantly higher than criteria partially met in 2019.

*Scoping Measure 5 (Criteria Not Addressed)*

Measure	Year	Mean	Median	Std Dev	Skew	Kurtosis
# of Criteria Not Addressed	Total	5.54	4.00	6.03	1.27	0.92
	2019	4.7	3.50	4.97	0.92	-0.39
	2020	7.75	7.00	6.62	0.66	-0.42
	2021*	4.24	3.00	6.07	1.99	3.12
% of Criteria Not Addressed	Total	22.85	20.00	19.76	0.60	-0.30
	2019	22.19	22.50	19.24	0.25	-1.30
	2020	32.21	28.57	22.95	0.19	-0.95
	2021*	14.57	17.39	12.63	0.20	-1.43
* Differences from previous year were statistically significant						

Table 4.15: Team Performance (Criteria Not Addressed)

A surprisingly large number of criteria (overall mean of 5.54) and percentage of criteria (overall mean of 22.85%) were not addressed at all in the final design reports (Table 4.15). In comparing the three cohorts, Mann-Whitney U tests indicated that the number ( $W = 288$ ,  $p = 0.042$ ) and percentage ( $W = 305$ ,  $p = 0.013$ ) of unaddressed criteria in 2021 was significantly lower than in 2020. All other differences were not significant.

*Deciphering Adaptive Responses: Unveiling Innovation Through Scoping Measures*

This study empirically examined students' problem-scoping capabilities during the COVID-19 pandemic, utilizing scoping measures to analyze various aspects of their engineering design problem-scoping skills. The measures revealed a nuanced narrative of adaptability and innovation amid the pandemic. The examination of scoping measures yielded mixed outcomes, with specific measures, such as the proportion of unaddressed, partially met, or unmet design criteria, showing dynamic shifts during the pandemic. However, other indicators, including the total number of criteria and the proportion of criteria met, remained remarkably stable.

The study focused on the overall breadth of problem scoping, using the total number of design criteria set by students. Importantly, no significant differences emerged across academic years (2019, 2020, and 2021), indicating a consistent distribution of project scope. This finding mitigates potential confounding effects, allowing for a deeper investigation into the dynamics of students' adaptive responses. The examination of the proportion of design criteria met revealed interesting patterns. Despite pandemic-induced disruptions, there were no significant changes between 2019 and 2020. The study attributed this resilience to a mid-capstone mitigation plan in 2020, fostering adaptability and enabling students to maintain pre-pandemic levels of meeting criteria. However, the lack of significant changes from 2020 to 2021 raised questions about the efficacy of a scaffolded intervention in the latter year to encourage reflective design and problem-scoping.

The analysis of partially met criteria showed a substantial increase in 2020 compared to 2019, reflecting a significant rescoping process due to the pandemic. Due to the pandemic, many criteria students initially set became infeasible. As one 2020 student aptly said: "Many previously required deliverables became stretch goals for the project". Students addressed stretch goals in their final reports via different forms of partially met criteria. For instance, some students managed to complete prototypes but were unable to test them due to closed labs, resulting only in partial fulfillment of their initial design criteria. Other students came up with alternative ways to circumvent restrictions in access to testing facilities. For example, one student team was unable to field test their prototype due to the closure of their sponsor's lab and adopted the following solution: "Since it wasn't possible to test it in the actual ocean, I ran tests in a container of saltwater to verify that the fully integrated light trap would properly work and take accurate readings in a saltwater solution". While these creative solutions show students' adaptability to an uncertain crisis, they were not a substitute for rigorous testing and were categorized as partially fulfilled requirements. Hardware-heavy projects faced greater challenges, leading teams to pivot to simulations. Despite an additional scaffolded intervention in 2021, no significant changes were observed in fully met and partially met criteria. However, the intervention significantly reduced the number of unaddressed requirements in 2021 compared to 2020, indicating heightened awareness and a more deliberate approach.

The proportion of criteria failed to address emerged as a crucial measure of neglect. There was a significant decrease in criteria not addressed from 2020 to 2021, aligning with the intervention's

impact. This decrease indicated increased intentionality and a structured approach in reporting the status of original design criteria in 2021. Despite not meeting more criteria, the intervention enhanced students' attentiveness, intentionality, and reflective skills. This shift is crucial, as intentional prioritization, balance, and evaluation are traits of expert and reflective engineers.

The use of scoping measures proved to be a nuanced approach in assessing students' design capabilities amid the challenges of the pandemic. Traditional assessments often fall short in capturing the complexities of adaptability and innovation exhibited by students in real-world design settings. The constancy in the total number of design criteria set showcased students' adaptability, and the inconsistent stability in fully met and partially met criteria underscored the impact of additional interventions. Scoping measures acted not just as quantitative gauges but as instruments to explore the qualitative dimensions of students' adeptness, intentionality, and resilience in the design process, providing a robust foundation for future interventions and assessments.

The implementation of scoping measures not only demonstrated students' design capabilities but also highlighted the broader significance of university-industry (U-I) partnerships in fostering skills contributing to innovation systems. By capturing adaptive and innovative responses to challenges, these measures offer a lens through which the value of U-I collaborations can be underscored and how change in students' design process can be assessed. The scoping measures provide a robust framework for articulating students' adeptness in navigating real-world constraints, emphasizing the invaluable role of U-I collaborations in shaping the next generation of innovative engineers. This perspective enriches the understanding of student learning outcomes and contributes to the dialogue on the instrumental role of industry partnerships in cultivating adaptability and innovation within education.

#### *4.10.3 RQ3: What do the above measures indicate about generalizing the measurement innovation?*

The industry sponsored engineering capstone design program presents a specific setting where knowledge development (in the form of students' skills) and exchange (between industry mentors and students) occurs to build engineering design competence among students. Knowledge development and exchange form the first two activities of a Technological Innovation System (See Chapter 2, section 2.3). The previous research questions focused on developing and validating measures

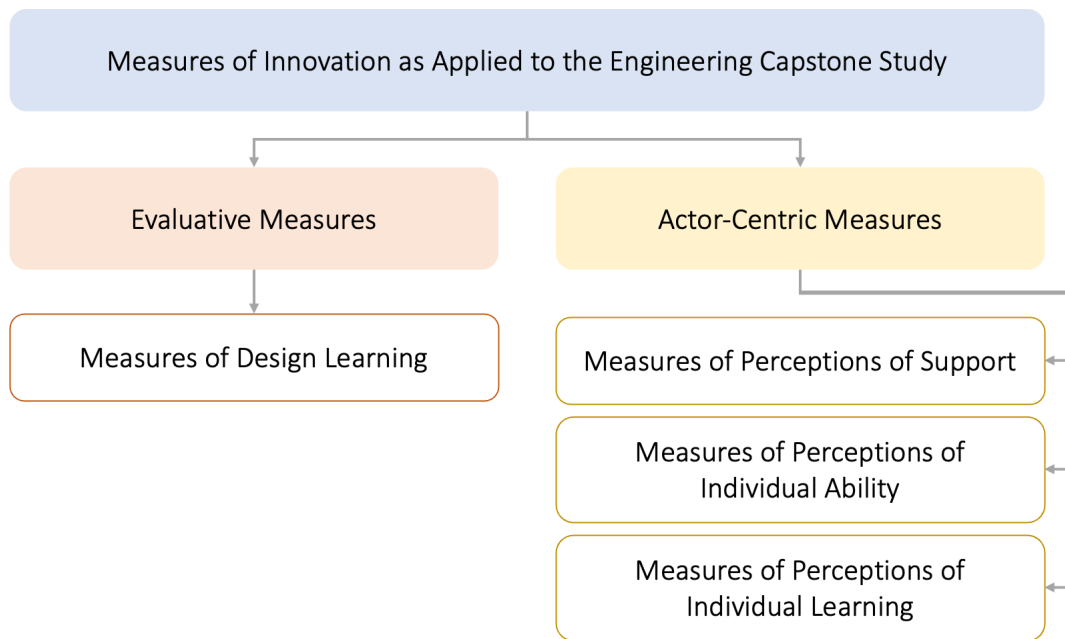


Figure 4.4: Actor Centric Framework of Innovation Measurement

that assess students' perceptions and learning outcomes in this setting. Notably, RQ1 establishes a correlation between students' perceptions of support and individual ability with their perceived learning outcomes. The industry sponsored engineering design capstone is an example of the micro-interactions that occur at a small-scale that contribute to the functioning of the larger innovation system. Measures that characterize these micro-interactions provides a glimpse into how innovation measures can be organized and generalized.

Findings from RQ1 and RQ2 underscore that there are two types of measures: measures that assess the actors' (in this case students) needs and perceptions and measures that evaluate the outcome of the system or activity (the capstone) (Table 4.4). Students' perceptions of the capstone program hold particular significance, as they directly influence students' performance, consequently shaping the learning outcomes of the capstone. This framing of measures can be generalized to other functions of an innovation system. As extensively discussed in Chapter 2, an innovation system not only consists of the novel products and processes that emerge from it, but it also consists of

the actors and organizations that interact to bring novel ideas to fruition. The effectiveness of those actor activities and interactions directly determines the effectiveness of an innovation system. Therefore, it is imperative to not only measure the outputs or outcomes of an innovation system, but also measure the activities and perceptions of individual actor groups.

In the context of the industry sponsored engineering design capstone study, measures that assessed the outcome of the program are termed as evaluative measures. These measures include the scoping measures that assess students' problem scoping skills in the capstone. Another example of an evaluative measure in this setting would be the final grade of the student as an indicator of their performance. On the other hand, measures that assessed students' perceptions about support, ability and learning can be termed as actor-centric measures. In this case, students are the "actors" doing innovative activities in the capstone. These measures assess what they need to "do" their projects successfully. Within these actor-centric measures, measures of support (from industry mentors and other peers) evaluate aspects of knowledge exchange between different actor groups. Whereas measures of perceptions of individual ability and learning evaluate aspects of actors' knowledge and skill development. Given below is an illustration of the two types of measures in the capstone context.

#### **4.11 Conclusion**

This study examined the knowledge development and exchange functions of a technological innovation system (TIS) in the context of university-industry collaborations for education and competence building. Particularly, an industry sponsored engineering design capstone program was selected as a setting to study the interactions that occur at a small scale in an innovation system. This setting was selected because: (1) measures for university-industry collaborations for education are lacking in literature, (2) measures that assess the contribution of engineering and design are lacking from innovation literature, and (3) the setting presented a methodological advantage for data collection and rigorous statistical analysis.

The study examined three research questions. The first research question examined measures of students' perceptions in the capstone. This inquiry resulted in three measures of perceptions: measures of support, measures of individual ability and measures of learning. The second research question gave rise to measures of skill, in particular measures of students' problem scoping skills

during the capstone. The significance of students' perceptions in influencing their performance underscores the importance of considering the human dimension in innovation evaluations. Tailoring interventions and improvements based on these perceptions can enhance the overall learning and innovation experiences. The framework outlined in this study serves as a valuable contribution to the discourse on evaluating university-industry collaborations, providing insights that extend beyond quantitative outputs to encompass the qualitative aspects of students' educational journeys and their collaborative impact. Ultimately, this approach empowers actors to make informed decisions, implement targeted improvements, and contribute to the continuous enhancement of collaborative educational programs.

The third research question expanded the focus to examine how these measures could inform innovation measurement more broadly, transcending the specific capstone and educational setting. The study concluded that an effective evaluation framework for innovation necessitates a dual perspective. Integrating both actor-centric measures, which delve into the perceptions and needs of actors within innovation systems, and evaluative measures, which assess the tangible outcomes and performance of the innovation system, yields a more comprehensive understanding of the innovation process. This dual-perspective framework provides a valuable tool for assessing and enhancing innovation at various scales, guiding actors in making informed decisions to foster continuous improvement in collaborative educational programs and innovation initiatives.

The next chapter broadens the focus of this dissertation by applying this dual framework to understand the perspectives of innovation measurement held by various actors within an innovation system. While there is considerable literature on evaluative measures, actor-centric measures warrant deeper exploration. Going beyond the educational realm, this study delves into innovation measurement within the domains of research and entrepreneurship, aiming to understand the specific measures required by actors to effectively engage in innovation activities within their respective contexts.

## Chapter 5

### EXPLORING ACTORS' PERSPECTIVE ON INNOVATION MEASURES

#### 5.1 *Introduction*

Innovation systems are complex and multi-actor environments whose scale, emergent dynamics and path-dependent nature make them challenging to study and model. Despite these challenges, scholars have developed measures and frameworks aimed at characterizing the complex interactions among actors that underlie these systems [65, 76]. However, while these theories and empirical measures offer valuable insights, they often fall short in capturing the real-world unfolding of actor dynamics within innovation systems. There are two main reasons for why this discrepancy arises. Firstly, many of the existing measures and theories were originally developed by researchers and economists predominantly targeting audiences within their respective fields [36, 73, 161]. Therefore, while these measures are effective at evaluating the state of an innovation system, they often fail to adequately address the unique needs, experiences and perspectives of various actors and practitioners within the innovation system. Secondly, the theories that attempt to describe specific actor dynamics are scattered across multiple academic disciplines such as innovation studies, economics, business management and entrepreneurship. This fragmentation leads to a lack of a cohesive narrative regarding how actors “do” innovation in innovation systems. To address this gap between theory and practice, the objective of this study was to delve into how diverse actors assess and evaluate opportunities and their involvement in an innovation system. Additionally, the study was used to validate the actor-centric framework that emerged in Study 1, by broadening the investigation to contexts beyond education. This was achieved by conducting a comprehensive analysis of perspectives, information requirements and practices exhibited by the actors.

To facilitate this investigation, an interactive data dashboard was designed to visually represent commonly accepted evaluative measures used to assess the performance of an innovation system. This dashboard was then used in a three-part semi-structured interview study designed to elicit meaningful discussion with actors and address the research questions. The study comprised of 13

participants hailing from six actor groups identified from relevant literature [27]: university actors, corporate actors, entrepreneurs, government actor and a miscellaneous “other” category. Part 1 of the interview focused on understanding actors’ perspectives, activities, and decision-making practices in their current capacities. Part 2 involved using the data dashboard in a “think aloud” activity, where participants provided real-time reactions and insights while interacting with the tool. In the final part of the interview, participants reflected on the think aloud activity and offered suggestions regarding the relevance of specific measures in their respective contexts, as well as identified any gaps that existed.

Findings underscored the diversity of actors’ interests in different measures, advocating for actor-specific measures to complement evaluative ones in capturing the varied activities within an innovation system. One of the key findings was the emergence of an innovation measurement framework based on the availability of measures versus their influence on actors’ decision-making. The interview study emphasized that most of the commonly used evaluative measures from the innovation systems literature are readily available but do not have very high influence on actor’s decision-making. On the other hand, relationship-based measures that are typically harder to come by have a much stronger influence on actors’ decision-making. Another main finding of the study revealed that actors want measures that are specific to a specific industry. The structure of the industry provides essential context around institutional norms that govern innovation activities in that industry. The study also showed that quantitative measures are not sufficient to capture the complex dynamics of innovation systems. Though quantitative measures provide important insight into the intensity of innovative activity within an innovation system, they do not help assess the quality of activities that different actors are engaged in. Therefore, qualitative measures and constructs are required to obtain an understanding of actors’ perceptions of the opportunities and barriers to their role in an innovation system.

Overall, this multi-actor approach sought to bridge the divide between theoretical frameworks and the practical realities faced by actors operating within innovation systems. The aim was to gain a deeper understanding of the diverse perspectives, decision-making practices, and information needs of actors, as well as to shed light on how measures of innovation can be influential for actor’s decision-making and which measures are overlooked or absent.

## 5.2 Sources of Innovation Data

To explore the actors' perspectives on prevailing measures of innovation, an initial step involved evaluating the accessibility of these measures. The landscape of innovation data comprises of two main categories: quantitative (structured) and qualitative (unstructured). Structured innovation data predominantly originated from publicly available sources such as patents, research publications and funding, and business activity, which is hosted within online government databases. Notably, the digital era has ushered in a new dimension of innovation data with online platforms such as LinkedIn, press releases and other online databases, offering unprecedented access to social and organizational data in qualitative, unstructured formats. However, an innovation system is not characterized by a single source of data, but relies on the interplay between multiple disjointed, misaligned, and heterogeneous sources [12]. This amalgamation of data sources presents a challenge in weaving them together into meaningful insights. Existing analytical tools encompass various business intelligence platforms [11, 89], open-source visualization tools developed by various government organizations and scholars [74, 138, 176], as well as proprietary databases such as Pitchbook and Crunchbase. While these tools serve as initial resources, they tend to focus on specific aspects of the innovation system. For instance, the National Science Foundation's S&E indicators provide a suite of separate state-levels maps for visualizing various research and business indicators, yet they lack the means to interconnect these indicators into a holistic system-level analysis. Similarly, maps focused on entrepreneurial and business activity [138, 176] often disregard research activity, ignoring a vital aspect of the innovation system.

Basole et al (2018) underscore the inadequacy of current innovation system analysis tools in capturing the interdependencies within innovation systems [12]. Similarly, Smith highlights a need for web-based mapping tools that simplify socio-economic data analysis, enabling cross-comparisons of innovation indicators across different geographical locations [172]. Moreover, as detailed in Chapter 2, existing measures of innovation predominantly evaluate and emphasize quantifying R&D expenditure, patents, publications, and investment. While these measures offer insights into the early-stage invention activities, they omit a multitude of other critical actions that occur within innovations systems including design, engineering, education, and market research, which are often not measured by existing measurement frameworks for innovation.

This study involves the validation of existing measures while concurrently identifying their limitations. By employing established innovation measures, the study seeks to discern actors' perceptions concerning the utility of these measures in shaping their decision-making processes. Subsequently, the study's focus shifts to pinpointing measures that bear limited relevance, identifying the ones that are absent, and acknowledging those that extend beyond the scope of conventional measurement and approach innovation measurement by validating what exists and identifying what is missing. The central aim of this study is to gain an insightful understanding of innovation measures through the diverse lenses of actors within an innovation system.

### ***5.3 Visualization of Innovation Data***

To delve into the relevance of established innovation measures for diverse actor groups, a vital aspect was to first develop a method for eliciting and framing discussions around these measures. For this purpose, an interactive data dashboard tool was developed, intended to serve as an interview probe to guide in-depth conversations with the study participants. The adoption of interactive data visualization as the methodological approach for this study was rooted in its novel nature, lacking preexisting equivalents, and its inherent alignment with the core objects of data visualization: discovery, decision making and explanation. As Card et al define it, information visualization encompasses “the use of computer-supported, interactive, visual representations of abstract data to amplify cognition” [29]. The advent of computational technology has revolutionized the creation of graphics capable of displaying large amounts of data in real-time and at minimal cost. The cognitive benefits of information visualization are multifaceted. Card et al propose six major ways in which effective visualizations can amplify cognition: (1) by increasing the memory and processing resources of the user, (2) by reducing search for information, (3) by enhancing pattern detection through visual aids, (4) by enabling perceptual inference through the effective organization of information, (5) by encoding information in an interactive medium that can allow users to “play” with various parameters and explore the space of parameter values, and (6) by enhancing perceptual monitoring of relevant data by using motion or appearance characteristics [18]. Consequently, interactive information visualization serves as a well-established tool for enhancing data processing, facilitating pattern recognition, enabling inquiry, and information decision-making. Research has shown that visualizations significantly reduce cognitive load compared to numerical and textual

formats, particularly when it comes to pattern discovery and exploratory data analysis [113]. The intricacies of innovation system dynamics span across many different actors, sectoral and geographical boundaries. Given these complexities, information visualization emerges as an apt methodology to probe the complex interactions within innovation systems, leveraging its potential to bolster cognitive abilities and inference-making.

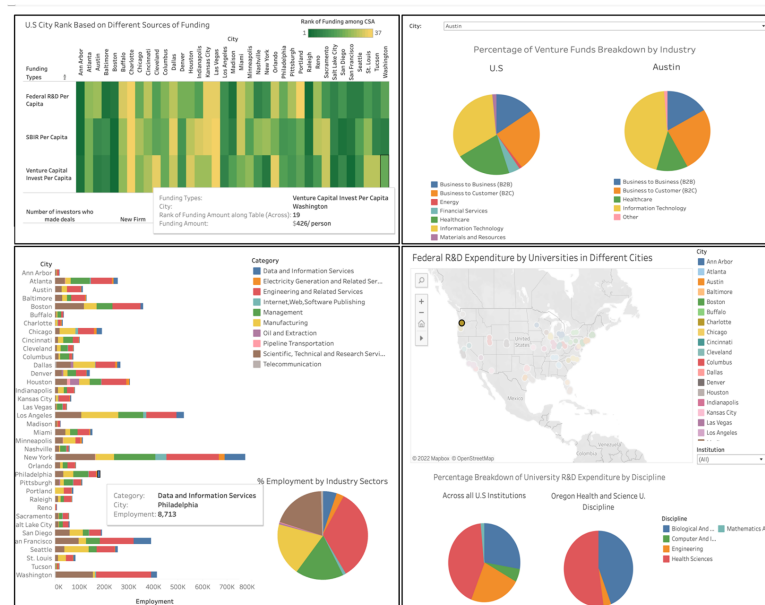
The selection of measures for this study was based on relevant literature that specified how innovation activities are commonly measured [76, 27]. The visualization tool took form of a Tableau dashboard prototype, with metropolitan statistical areas (MSA) chosen as the unit of analysis. The selection of MSAs was driven by the urban-centered nature of innovation systems, often situated in metropolitan regions. The dashboard provided a snapshot of diverse measures for the year 2019, focusing on cross-sectional data to manage scope. Table 5.1 outline the types of data and sources visualized for each MSA for the year 2019.

Data Type (unit)	Source	Activity Type
Federal R&D Funding (\$)	Grants.gov	Indicator for research activity
Small Business Innovation (SBIR)/Small Business Technology Transfer (STTR) grant funding (\$)	Grants.gov	Indicator for research commercialization from universities to industry
Total venture capital funding (\$)	Pitchbook	Indicator for entrepreneurship
Number of new investors who made deals	Pitchbook	Indicator for entrepreneurship
Number of new firms that emerged by industry sector	Business Census Data (Bureau of Labor Statistics)	Indicator for economic development
Venture Capital Funding by sector (%)	Pitchbook	Indicator for entrepreneurship
Venture Capital Funding by technology (%)	Pitchbook	Indicator for entrepreneurship
Employment created by industry sector	Bureau of Labor Statistics	Indicator for economic development
University research grant funding by institution and discipline	National Science Foundation	Indicator for research activity

Table 5.1: Data types, sources, and description for the dashboard tool

In designing the dashboard, foundational principles of data visualization were adhered to [29, 168]. Following Shneiderman’s mantra of ”overview first, zoom and filter, then details-on-demand” [168], the dashboard aimed to cater to actors’ varying modes of analysis. Different chart types, such as pie charts, heatmaps, stacked bar charts, and map-based visualizations, were strategically employed to address these diverse analytical preferences. Stacked bar charts offered a ”top-down” analytical approach, while pie charts presented a ”bottom-up” perspective. Map-based visualization

gauged actors' interest in geographical context, and heatmaps facilitated comparison of funding types across US metropolitan cities, thereby assessing preferences for ranking innovation systems. The result was the development of eight visualizations spanning four distinct chart types (Figure 5.1).



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Figure 5.1: Interactive data visualization panels for the the think aloud study

By combining actor perspectives with innovative visualization techniques, this study aimed to initiate insightful discussions around the applicability and gaps in existing innovation measures, revealing how the measures align with the cognitive needs and decision-making processes of actors within an innovation system.

## 5.4 Methods

### 5.4.1 Research Questions

The study was guided by one key research question:

How do actors within an innovation system perceive and prioritize different measures of innovation?

The inquiry guided by the above question was broken into three sub-questions:

1. RQ1: What types of activities do different actors perform in an innovation system?
2. RQ2: What type of measures and information tools do actors prioritize to conduct their activities?
3. RQ3: What are actors' perceptions of existing measures of innovation?

### **5.5 Conceptual Model: Technological Innovation Systems**

The Technological Innovation Systems (TIS) framework is used to scaffold the findings of this study. This framework provides a conceptual lens through which actor's function and activities within an innovation system are interpreted and understood. Chapter 2 provided a comprehensive exploration of Technological Innovation Systems (TIS), offering a detailed understanding of its core principles and components. A brief review of the TIS framework is presented here. Technological Innovation Systems are defined as:

*'A dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilization of technology.'* (Carlsson and Stankiewicz, 1991)

The essence of TIS lies in its approach to studying the structure and functions of different technological innovations. Rather than focusing solely on the technology itself, the TIS framework emphasizes the broader set of actor interactions and environments within which technological innovations emerge and develop. The structural elements of the system encompass a range of actors, institutions, organizations, and the networks between them. These actors can include universities, research organizations, government entities, companies, business, and various other actors. Institutions refer to the established rules, norms, and regulations that dictate the interactions within the system. Meanwhile, organizations play a role in orchestrating innovation-related activities and networks are the connections and collaborations that foster information and resource exchange among

different entities of the system. In addition to the structural elements, the TIS framework also consists of seven fundamental functions that are crucial to the working of an innovation system. These functions provide a comprehensive view of how innovations are fostered, developed, and diffused within a given context. While the specifics might vary, these functions generally include.

1. **Knowledge Development:** Development of new technologies, markets, networks, users etc. typically through research and development activities.
2. **Knowledge Exchange/Diffusion:** Exchange of knowledge between actors, institutions and organizations in an innovation network typically through the formation of networks.
3. **Entrepreneurial Activities:** Commercial experimentation classically undertaken by entrepreneurs to translate knowledge into business opportunities and eventually transition an invention to an innovation.
4. **Guidance of Search:** Activities that shape the needs and requirements of actors with respect to their support of emerging technologies. Examples of this function include policy targets, technology specific competitions etc.
5. **Resource Mobilization:** Mobilization of financial, human, network-based and physical resources required to support the innovation of a technology. Typical activities include investments and subsidies. This can also include education and the development of large R&D facilities etc.
6. **Market Formation:** The creation of demand for a particular technology and thereby creating markets to help new technologies compete with incumbent technologies.
7. **Legitimation:** Support and advocacy from existing groups that enables competitiveness within the existing system.

In order to assess the performance of an innovation system, measures should be designed to assess the seven TIS functions. To assess the seven functions, it is imperative to understand

how the structure of the TIS (namely, the actors) support the functionalities of a TIS. It is the activities and interactions of these actors and institutions that can enhance or hinder the function and thereby the performance of a TIS. Therefore, the TIS framework, specifically its functions were used to categorize the activities of the different actors in this study to understand what measures actors used and needed to gauge their performance when conducting these activities.

### 5.5.1 *Participants*

A total of 13 participants were recruited for the study across six actor groups working in Knowledge-Intensive Industries (KTI) as defined by the National Science Foundation [23], which primarily includes science, technology, and healthcare sectors. These actors collectively provided a comprehensive representation of the innovation system's diverse actors. The specific actors and their corresponding roles were as follows:

1. **Entrepreneurs (4):** These were individuals who founded early-stage (0-5 years old) technology companies.
2. **University stakeholders (5):** This group included individuals responsible for technical and business education programs within universities, as well as those engaged in facilitating technology transfer activities.
3. **Government (economic development) stakeholders (2):** Members of this group worked with government organizations contributing to organized economic development efforts.
4. **Risk capital (investors) stakeholder (1):** This individual invested capital in technology companies either as an individual or as part of a venture capital firm.
5. **Corporate (analysts) stakeholders (3):** Participants in this category were analysts or managers working for private corporations. They were engaged in expanding the corporation's customer or partner portfolio.
6. **Other stakeholders (2):** These two participants managed accelerator programs that supported startups during their scaling phase, offering them access to mentors. They fall in the

“Other” category of the stakeholder framework [11].

In order to maintain consistency and prevent city-based differences from confounding the study, all participants were based in the Seattle Metropolitan Area. All interviews were conducted remotely on Zoom. The careful selection of participants ensured that a diverse array of perspectives and insights were represented. The participants’ roles and affiliations aligned with the actor groups central to the innovation system, ensuring a thorough exploration of the themes and questions posed in the study. This participant selection process laid the foundation for fruitful discussions, generating nuanced understandings of how different actors perceived, utilized, and assessed existing innovation measures within their respective contexts. The subsequent sections build upon this foundation to provide a thorough narrative of the study’s outcomes and insights. Table 5.2 provides an overview of all the participants, their roles, and affiliations.

Participant #	Group <sup>a</sup>	Role	Notes
1	O & U	Accelerator Founder, Faculty	Also has experience in investing
2	C	Financial Business Partner	
3	C	Analyst	
4	O & C	Accelerator Associate Director, Sales Manager	
5	U	Program Director	University College of Engineering
6	ED	Program Manager	Economic Development Non-Profit
7	E	Startup Founder	
8	U	Innovation Manager	University Technology Transfer
9	U	Assistant Director	University Business School
10	ED & E	Startup Founder, Consultant	
11	E	Startup Founder	
12	E & R	Startup Founder, Senior Venture Partner	
13	U	Senior Technology Manager	University Technology Transfer

<sup>a</sup>C=corporate actors, E= entrepreneurs, ED= economic development, O=other (accelerator actors), R=risk capital actors, U=university actors

Table 5.2: Overview of study participants, their roles and affiliations

### 5.5.2 *The Interview Study*

A three-part interview study was conducted with the dashboard tool created in Tableau. Participants were provided with a website link where the tool was hosted and were requested to share their screens, offering a real-time glimpse as they navigated through it. Each interview session lasted for around 1 hour during which the audio, video and screens of the participants were recorded. Appropriate IRB approval was obtained prior to recruiting for the interview. Each interview consisted of three parts:

1. **Part 1: Actor Activities in Innovation Systems:** The goal of this initial part was to understand the types of innovation activities participants conducted in their region's innovation system. Questions explored participants' roles, responsibilities, and practices as part of their job. Insights were obtained regarding the local innovation landscape and participants' motivations for engagement. Part 1 also laid the foundation for the subsequent exploration of the digital dashboard tool.
2. **Part 2: Think Aloud Activity with the Data Visualization Probe:** This part of the interview sought to understand participants' interactions with the dashboard tool and explore the information on the dashboard tool were of most interest to the participant. Participants were introduced to the dashboard's general premise and data content, after which they were encouraged to explore the tool at their pace, voicing their thoughts and questions aloud. Particular attention was paid to the order in which participants visited the tabs, the duration of time they spent on each tab, and whether they visited all the tabs.
3. **Part 3: Reflections:** To conclude the interview session, participants were prompted to reflect on their engagement with the visualization tool. This part of the interview sought to identify (a) additional information of interest to the participant; (b) suggestions for enhancing the presentation of existing data, and (c) the overall utility of the tool in the participants' quest for information and contributions to the innovation system.

The structured interview methodology was not only driven by an understanding of the actor experiences but also grounded in the tool's capacity to facilitate nuanced insights. These interview

phases established a narrative, capturing actor perspectives and shedding light on the alignment between the dashboard tool and their cognitive needs.

### *5.5.3 Data Analysis*

The data analysis for this study was driven by the process of thematic analysis, a methodology chosen to analyze actor perspectives for underlying thematic commonalities. The analysis unfolded in a systematic manner, deriving insights from the wealth of data gathered through interviews and participants' interactions with the visualization tool. Additionally, the analysis was guided by the technological innovation systems (TIS) framework [30]. To add granularity and structure into the analysis, the study employed deductive coding, using labels provided by the TIS functions. This involved categorizing actor activities and interactions based on these pre-defined functions. The primary goal was to recognize alignment or divergence between actor actions and the functions within the TIS framework. This approach not only facilitated a streamlined analysis but also enabled insights into how actors' real-world activities resonated with the conceptual framework.

The first step of the analysis involved transcribing the interview recordings, capturing both audio and screenshare interactions. This transcription process served as an immersion into the data corpus, facilitating familiarity with the data. Subsequently, a preliminary set of codes was generated. Codes, acting as concise labels, drew attention to meaningful segments within the data that held potential relevance for the study. These codes conveyed the underlying themes of the corresponding text. A unique aspect of thematic analysis is its capacity to accommodate variety. The same piece of data could be coded with multiple codes if it represented more than one theme. This flexibility allowed for the development of initial codes as the analysis proceeded, allowing for further subdivisions or combinations to suit the emerging insights.

The coding process was conducted inductively, discovering patterns and themes common or distinct among actors within each group. This preliminary round of coding set the stage for finding the overarching themes that represented the shared perspectives across actor categories. Next, the analysis transitioned into a constant comparative approach. Themes that arose from the first round were systematically compared across different actor groups. This process resulted in the creation of categories, refining the boundaries of these categories, and capturing the essence of each

through concise summaries. The outcome resulted in three main themes: tasks, information tools and information needs. These themes reflected the perspectives and practices articulated by actors, depicting the diversity of their roles within the innovation system.

The thematic analysis provided a cohesive account of participants' narratives and interactions with the visualization tool. It not only captured actors' viewpoints but also explored their activities within the context of a conceptual framework, building a connection between theory and practice. The subsequent section consolidates the emergent themes, summarizing the richness and diversity of actor perspectives within the innovation system.

## **5.6 Result**

### *5.6.1 Actor Tasks and Activities*

The Tables (Tables A.1 and 5.3 below briefly describes what each participant does at their organization and where their role fits within an innovation system. From the table it is evident that diverse actor groups were engaged in a multitude of activities collectively shaping the innovation landscape. Consequently, the measures they use are also likely to be varied and not sufficiently covered by those that are widely used today. The tasks and responsibilities of different actors can be categorized into 7 key functions based on the functions of technology innovation systems (TIS) in Chapter 3

Based on the above table, actor activities within an innovation system can be categorized into functions of an innovation system as described in the TIS framework.

1. **Knowledge Development:** Among the participants, four individuals were involved in knowledge development activities. While three entrepreneurs worked actively on developing novel products, a participant from a consulting company redirected their efforts toward supporting innovation. This participant supported the innovation system by producing market reports, contributing artifacts that augment the innovation process. This pivotal function underscores the inception of innovation, where knowledge is developed as a foundation for further advancements.
2. **Knowledge Exchange:** Knowledge exchange activities were performed by 4 participants in

Innovation Function	Frequency
Knowledge Development	4
Knowledge Exchange	4
Entrepreneurial Experimentation	3
Guidance of Search	5
Resource Mobilization	8
Market Formation	2
Legitimation	4

Table 5.3: Frequency of TIS Functions Across all Participants

this study. An accelerator program participant worked towards directly supporting innovation by fostering connections between entrepreneurs and mentors, bolstering commercialization efforts. Simultaneously, an entrepreneurial program specialist at a university orchestrated the exchange of insights and experiences between budding innovators and seasoned mentors, through coursework and business plan competitions, invigorating the innovation landscape. Furthermore, the foundation for future innovation was set as participants managed collaborations between industry sponsors and university students for project-based educational experiences. These projects were often novel ideas that industry sponsors did not have the bandwidth to explore in their companies and therefore partnered with a university to have students work on them. This act of harnessing intellectual capital and channeling it into innovative projects underscores the capacity-building aspect of Knowledge Exchange activities. Lastly, a program director at an economic development agency facilitated knowledge exchange through conferences and workshops, enriching the innovation discourse.

3. **Entrepreneurial Experimentation:** Three of the 13 participants were entrepreneurs and hence engaged in entrepreneurial experimentation by performing technological and market experiments to increase adoption of their novel products. Their endeavors align with the heart of innovation, embodying the experimentation and the resilience to adapt, characteristic of

entrepreneurship.

4. **Guidance of Search:** Within the innovation system, Guidance of Search takes center stage as actors strategically navigate the innovation landscape. Two participants, operating within mission-oriented accelerators, meticulously focused on driving innovation in specific domains. Their efforts in computational health and emerging manufacturing technologies exemplify the conscious guidance of search, steering technology advancements to address targeted challenges. Additionally, a healthcare innovation competition organizer at a university directed search efforts by identifying promising innovations that could alleviate pressing healthcare concerns. This role, akin to a compass for innovation, underscores the guidance that shapes the trajectory of progress. Moreover, a participant, who doubles as an investor, allocates resources strategically to propel certain technologies, thus exemplifying the guidance of search through resource allocation.
5. **Resource Mobilization:** Resource Mobilization emerges as a pivotal function, exhibited by over half of the study's participants. Entrepreneurs and accelerator personnel, driven by a need for funding, actively raised funds to propel their innovative ventures. Simultaneously, university participants channeled their efforts towards mobilizing human capital, contributing to the talent pool that drives future innovation. An economic development agency participant showcased the mobilization of resources through grant funding, fostering a monetary and human capital inflow to fuel innovation in designated domains. This function resonates as the lifeblood of innovation, sustaining and propelling its momentum.
6. **Market Formation:** Two participants were involved in market formation activities. A large technology company representative strategically navigated market dynamics, competing for customers and solidifying market presence. Concurrently, an individual facilitated international startups' integration into the US market, a critical step in fostering competitive markets for emerging technologies. This function, symbolic of creating fertile ground for innovation, entails shaping the marketplace to accommodate diverse and novel technologies.
7. **Legitimation:** The legitimation function was embodied by two participants working within

university technology transfer offices, coordinating the commercialization of emerging technologies. A participant from an economic development agency championed the enhancement of the travel and tourism industry post-COVID-19 through the establishment of an accelerator, while simultaneously advocating structural changes to bolster innovation. Lastly, a director at an accelerator spearheaded the development of a computational health accelerator, enhancing innovation in this domain through both academic and practical pursuits. The legitimation function underscores the instrumental role of these actors in legitimizing and supporting innovative endeavors.

The activities of the participants, categorized into the seven key functions derived from the Technological Innovation Systems (TIS) framework, offer valuable insights into how different actors contribute to the innovation system through different activities. Key findings reveal that while certain participants actively contribute to the early stages of innovation through knowledge development and entrepreneurial experimentation, others play pivotal roles in later stages, focusing on market formation, legitimation, and resource mobilization. Moreover, the guidance of search and knowledge exchange emerges as critical functions shaping the trajectory of innovation. Additionally, one participant is often involved in multiple TIS functions and will just require a diverse suite of measures to assess his/her activities across different functions.

### *5.6.2 Information Tools*

The study's focus on actor tasks and activities reveals the details of information seeking and utilization within innovation systems. Table 5.4 shows how information tools that actors employ to conduct innovations activities map to TIS functions.

1. **Online Databases/Data Services:** Online databases/data services emerge as a pivotal tool, catering to tasks such as resource mobilization, guidance of search, market formation, entrepreneurial experimentation, and knowledge exchange. These digital repositories serve as a springboard for actors to explore financial information, scout potential collaborators, and access economic development measures. These tools provide information about different companies in a sector or technological area of interest. Examples include Pitchbook, Crunchbase,

Tools & Resources	Activities	Function
Online Databases	Look up financial information about other companies, find other companies to contact, economic development measures, relevant statistics	Resource mobilization, guidance of search, market formation and entrepreneurial experimentation, knowledge exchange
Industry and Market reports	Get general “high-level” information about market trends and predictions	Market formation
Academic Articles	Get information on emerging technological or economic trends	Knowledge development, legitimation
Social Media and Networks	Outreach (scout for companies to be part of a program), look for key thought leaders, advisors, and mentors to connect with.	Resource mobilization, knowledge exchange
Personal/Professional networks	Look for key thought leaders, advisors, and mentors to connect with, getting advice and mentorship	Resource mobilization, guidance of search, knowledge exchange, knowledge development
Experts	Get information on topics that require technical, business, or other expertise	Knowledge development, knowledge exchange, resource mobilization
Alumni	Look for key thought leaders, advisors, and mentors to connect with, getting advice and mentorship, scouting for donors and project/program sponsors.	Knowledge development, knowledge exchange, resource mobilization

Table 5.4: Tools actors use to obtain information while conducting their innovation activities

Statista etc. Pitchbook emerged as the most prominent online data service that participants used to look up startups and their financial information. Participants used Pitchbook to get an idea of how much money was flowing into markets or technologies of interest and who were the key players. It was primarily used by participants who were entrepreneurs, investors, and worked in accelerators or corporations (resource mobilization, guidance of search, market formation and entrepreneurial experimentation). Additionally, participants also used these databases to find organizations and individuals of interest (knowledge exchange). Other databases included federal databases such as the US Census Data and data by the Department of Labor Statistics, which were mainly used by participants undertaking economic development activities (usually government actors.)

- 2. Industry and Market Reports:** A few actors, mainly entrepreneurs, investors and corporate actors used online market reports from firms such as BCC, Gartner, Markets and Markets etc. to obtain the current “lay of the land” of the market they were interested in. These are

high-level reports that describe global market trends such as market growth prediction, key barriers and drivers of growth and market size information (Knowledge development, guidance of search).

3. **Academic Articles:** Some actors also used digital databases to access scientific and academic articles to gain knowledge in their area of interest. Entrepreneurs used this for further product development (knowledge development). Government actors used academic articles primarily in economics to obtain measures of interest (for example GDP, housing prices etc.) or keep up with economic trends. Some university actors such as technology transfer managers use scientific academic articles to compare an innovation disclosure (lab technology) with existing technologies (legitimation).
4. **Social Media/Networks:** These digital platforms include LinkedIn, Instagram, technology magazines (such as TechCrunch and Geekwire) and blogs. Actors used these tools primarily to find people of interest, market to target audiences and find partnerships (resource mobilization and knowledge exchange). In the context of innovation systems, these tools were primarily used by participants who were entrepreneurs, investors, and worked in accelerators or corporations.
5. **Personal/Professional Network:** These are individuals in the participants' immediate network who they rely on for advice and strategy, partnerships/recruiting or funding.
6. **Experts:** Most actors rely on experts in their fields (such as scientists, researchers, clinicians etc.) to provide information on the novelty of a technology, inform business strategy, disclose new inventions at the university or solicit advice on partnerships and funding. Experts are also sought after by entrepreneurs, government, and university actors to serve on advisory boards.
7. **Alumni:** University actors and entrepreneurs who spin out of the university heavily rely on the university's alumni network to find people who can help inform business/program strategy, build, or help solicit partnerships/ and most importantly provide funds and donations. Actors who run university programs, especially educational programs for innovation

and entrepreneurship seemed to heavily rely on alumni for funding. Alumni are also on advisory committees in universities, government and corporate and startup boards that steer the direction of these organizations.

8. **Other:** Some actors also mentioned organizations such as accelerators, incubators, consulting organizations or trade associations as being an important source of information, specifically in the context of business and entrepreneurship.

Trust and experience emerge as cornerstones of information value within the innovation system. Actors' reliance on personal/professional networks, experts, alumni, and other resources underscores the significance of trusted relationships and credible insights. The act of seeking advice, strategy, partnerships, and funding is inherently tied to the trust built over years of engagement. This is underpinned by the idea that trust bolsters the authenticity and reliability of the obtained information. Information obtained from human sources (personal/professional networks, experts, alumni etc.) was deemed to be more valuable than information obtained from digital tools. Almost all participants emphasized that no digital tool could compare with the power of personal and professional networks. As one of the actors commented:

“One of the values of an in-person network is the ability to iterate on your knowledge-seeking via conversation. It's the kind of thing that even email isn't as good at about. When you ask someone a question, they say something that makes you think about something else. It's like doing follow up questions in an interview. You can't plan for every question you will ask because it depends on what the interviewee is going to say. Same with learning something new. When learning something new, you often don't even know what the questions are that you need to ask. That's the advantage of a real-time interaction.”

Furthermore, the concept of experience adds an additional layer of depth to the information's value. Actors gravitate towards information sources that possess a wealth of experience in successfully navigating similar activities. This experience extends beyond technical or business realms to encompass a nuanced understanding of the broader social, political, cultural, and economic intricacies of the innovation system. Such insights, embedded within a context, offer actors a holistic perspective that guides their decisions.

Two key reasons emerged as to why information from networks was valued over digital tools: trust and experience.

1. **Trust:** Actors relied on their personal/professional networks, experts, alumni, or other resources because they trusted the information they were obtaining. Actors had often spent years building relationships with individuals in their network. For example, one actor mentioned that he prefers to leverage his network that he had “painstakingly built over 15 years” to get the information he needs. In the case of experts, trust emerged from the experts’ credibility in their field of expertise. For alumni, trust is brokered by a sense of belonging to the same institution. In the context of innovation and business, the role of close social ties and resultant increase in trustworthiness has been previously established in literature [191, 194].
2. **Experience:** Actors placed a lot of value on the experience their network had in successfully conducting similar activities in the past. Actors valued experience because it was often not just limited to a technical or business area but also extended to the experience an individual had in navigating the social, political, cultural, and economic aspects of a particular innovation system. Therefore, the information obtained from such a resource was deemed to be more nuanced and accurate as it was in the right context. As one entrepreneur said:

“The advisors have decades of experience, so not only are they well-versed in the technical ins and outs, but also the politics between institutions, interpersonal situations etc. Sometimes the advisors might not know the answer themselves but might know someone else in their network who can help and so the advisors can connect us to that resource.”

All actors implicitly or explicitly stated that the contextual nature of the knowledge they are seeking tends to come with experience and cannot be easily replicated digitally. Therefore, they rely on other people who have experience in the desirable context to obtain relevant information. The findings from this study reinforce prior work, which emphasizes the importance of networks of actors with diverse experiences and expertise in innovation systems [151]. Therefore, the reason actors value information from people more than digital tools is because they trust the information they obtain from people in their network and believe that the experience people have provides better contextual information than any digital tool.

The participants used digital tools to obtain “high-level” information that provided a starting point for whatever task they wanted to embark upon in an innovation system. Digitally available information provided an initial filter/lens through which participants viewed information to start making decisions. For example, one of the participants who worked for an accelerator used Pitchbook to find companies for the accelerator based on technology, sector, and location. The participant would then vet the company by evaluating the company’s financial information also provided by Pitchbook and the company website to get a sense of the traction that a company had. This quantitative information, encompassing financial measures and website data, facilitated an initial screening, allowing for a quick assessment of a company’s viability. The participant would then reach out to qualified entrepreneurs to then decide whether the entrepreneur is truly a good fit for the accelerator.

Yet, what emerged resoundingly from the experiences of all participants was a unanimous reliance on personal networks when confronted with pivotal decisions. The people in their network provide the contextual information needed to drive action. Beyond the quantitative measures easily accessible through digital sources and reports, it is within these networks where important information resides, such as details on market dynamics, partner credibility, and other nuanced factors that steer decision-making. This shift in perspective implies that while certain measures may be readily available through digital databases, their influence on the actual decision-making processes within innovation systems is comparably weak. Conversely, the real potency lies in measures concealed within interpersonal relationships and networks, which might be challenging to quantify but emerge as more robust, reliable, and actionable. In essence, the reliance on networks for critical decision-making underscores the potential of qualitative, network-oriented measures that elevate the discourse of innovation measurement beyond readily quantitative measures.

### *5.6.3 Actors’ Information Needs and Perceptions on Measures of Innovation*

This segment explores how participants interacted with a data visualization tool, thereby uncovering their information preferences. The following discussion, as shown in Table 5.5, underlines the data types that piqued different actor groups’ interests and the dimensions of granularity, analysis modes, people/organizations of interest, industry specificity, and personalization that emerged as crucial

<b>Actor Groups</b>	<b>Data Types of Interest</b>	<b>Data Types Not of Interest</b>
Entrepreneurs	Federal R&D, Venture Capital Funding by sector and technology, total venture capital funding	Employment, Establishments data SBIR
University Actors	Federal R&D, SBIR, Employment, Venture Capital Funding by sector, total venture capital funding (mild interest)	Venture Capital Data (for around half the actors), Establishments
Government Actors	Employment Data	Venture Capital Data, Federal R&D Data
Risk Capital Actors	Federal R&D Data, SBIR, Venture Capital Funding by sector and technology, total venture capital funding	Employment (for around half the actors), Establishments
Corporate Actors	Federal R&D, SBIR (mild interest), Venture Capital Funding by sector and technology, total venture capital funding, Employment (mild interest)	Establishments Data

Table 5.5: Breakdown of evaluative measures of innovation based on actor type

contextual facets. The data visualization tool provided a unique opportunity for actors to articulate their information needs. This process involved participants "thinking out loud" while interacting with the tool's quantitative measures. Note the mapping in Table 5.4 is not absolute. Some actors might be using measures that are generally not of interest to the rest of the group and vice versa. The mappings assume that the data types that actors spent most time on or commented the most on were of most interest and vice versa.

The above categorization underscores the divergent information needs dictated by the roles of different actor groups. University and government actors exhibit a heightened interest in employment trends, driven by educational and workforce perspectives. Entrepreneurs, risk capital, corporate actors, and accelerators prioritize funding information for region-specific technology verticals, facilitating strategic decisions aligned with industry trends. In contrast, most university and government actors were not as interested in how much funding was allocated to different technology

verticals (FinTech, Clean Energy etc.). On the other hand, entrepreneurs, risk capital, corporate and accelerator actors found this information to be useful. Entrepreneurs wanted to know this information to see which regions are better funded for the technology vertical that aligns with their enterprise. Corporate actors were interested in this information to see the technological profile of different cities for further investments and partnerships. Risk capital actors were interested in this data as it could provide them with a regional analysis of where venture funds are concentrated for technologies that they are interested in funding. Actors who managed accelerators were interested to see what other streams of technology they could add to their program.

Most actors (N = 11) either did not comment on the benefit of knowing the breakdown of companies in a city by sector or explicitly stated that they did not find this measure to be useful. Only around a third of the actors navigated to this page (N= 4). Out of those who did, only two of them verbalized interesting insights they gained from the information presented on this page. Almost all actors (N = 11) said that currently, the information they need to make decisions around their tasks is scattered across different digital tools and human resources. example, one of the actors exclaimed that:

“Pitchbook (a platform that keeps track of company’s early-stage financing) doesn’t capture Federal R&D funding or SBIR funding”.

While most actors demonstrated interest in these typical evaluative measures of innovation, they were clear about the limited decision-making power of these measures. All of the above measures were “nice-to-knows” and did not by themselves steer decision-making. Thus, the evaluation of participants’ interactions with a data visualization tool not only reveals distinct information preferences but also unveils critical gaps in the array of available innovation measures.

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1. **Granularity:** Nine out of 13 actors explicitly stated that for the tool to be useful to them, they would like to see more granular information, or “details-on-demand” [168] but in context. Examples of granularity included additional data on breaking down the federal R&D funding further by funding agency (NASA, NIH, NSF etc.) or breaking the industry segments further into its constituents. This underscores a key inadequacy in the availability of innovation measures to provide detailed breakdowns of funding and information about other actors in the system. For instance, one participant remarked, “In a perfect world, it would break it down to the level of detail where it showed company names that run into some of these

categories,” emphasizing the need for a more refined understanding at the company level.

2. **Support Multiple Modes of Analyses:** Participants uniformly expressed the need for innovation measures to support both comparative analyses across different cities and in-depth information about a single city. This requirement transcends the binary nature of existing measures, calling for a more versatile approach that accommodates diverse analytical needs. This inadequacy lies in the limited flexibility of current measures to cater to the dynamic information requirements of actors. The lack of support for multiple modes of analyses underscores a dynamic where existing measures, while available, are not sufficiently influential in accommodating the varied information requirements of actors engaged in innovation activities.
3. **People/organizations of interest:** Seven of the 13 actors emphasized the inability of current innovation measures to comprehensively identify and provide insights into relevant people and organizations. The existing measures fall short in providing comprehensive insights into the network of actors within the innovation landscape. For example, one university actor commented, “For us just knowing where the entrepreneurship centers are you know, give us an idea of who might be good partners to learn from, rather than having to go through websites and searching.”, underscoring the necessity for innovation measures that facilitate networking opportunities and aid in the identification of key collaborators. The restricted availability of measures that facilitate networking opportunities hinders participants from leveraging their social capital effectively.
4. **Industry Specific Information:** Six out of 13 actors expressed the need for the data to be more specific to their industry of interest. For example, one of the actors working in health-care technologies wanted more information about a region’s strengths in different medical fields as determined by the number of clinicians in that field. In this case, the context is provided by the industry of interest. This was aptly summarized by one actor:

“How valuable is knowing about basic research funding, knowing about SBIR funding, and

then knowing about VC funding? Because those are different kinds of activities we're talking about. If we're talking about life sciences, it matters. If you're talking about B2C (business-to-customer) tech tools, they don't really care about the basic research funding as much. They might much more care about the employment pieces. The utility of all that information (measures on the dashboard) is sector specific.”

5. **Personalization:** The desire for innovation measures to be more personalized and customizable, as expressed by five out of 13 participants, reveals a shortfall in availability. Current tools lack the features necessary to allow users to sort, filter, select, and export measures aligned with their specific contexts. The unmet need for personalization features highlights the limited influence of existing measures in adapting to the unique use cases of actors. This lack of adaptability restricts the effectiveness of available measures in providing context-specific insights. Participants desire tools that adapt to their unique use cases, providing a tailored and exportable format. The absence of personalization features in existing measures impedes their utility for actors who seek more nuanced and context-specific insights.

In summary, the discussion on information needs of actors in an innovation system reveals the limited power and inadequacies of existing innovation measures. The granularity, analytical versatility, networking capabilities, industry specificity, and personalization features emerge as critical dimensions where current measures fall short in their availability and influence on actors' decision-making. Addressing these gaps requires a reevaluation of the design and implementation of innovation measures that are not only specific to actors' needs but are available and have sufficient influence on their decisions to be useful.

#### *5.6.4 Availability and Influence of Measures*

The analyses of actor roles, responsibilities and perceptions of innovation measures revealed another framework of innovation measurement based on the influence different measures have on actors' decision-making and their availability. Figure 5.2 provides an illustration of the framework. Note that the list of measures in the figure is not exhaustive but is representative of the types of measures that may fall into the different categories.



cess and number of sponsors who return. Additional measures that highly influence actor decisions and are readily available include regulatory measures. Regulatory measures are dependent on the sector or technological field and are usually publicly available.

The key gap in innovation measurement lies in measures that have a high influence on actor decisions but are not easily available. These measures typically fall into two types, namely, relationship measures and measures that are confidential and hence unavailable. The study emphasizes the paramount importance of relationships in the innovation landscape, with successful connections offering access to invaluable expertise, advice, and mentorship. Yet, measures evaluating the success of forming and utilizing these relationships are notably absent. Additionally, confidential measures, such as financial details of non-public companies or venture funds, represent another dimension of unavailability that restricts their influence despite their significance in decision-making.

The study also highlighted actors' interest in industry-specific measures, such as employment trends in healthcare, technology breakdowns, and funding distribution, highlights the significance of measures that align with the sectors in which actors operate. The structure of a sector or an industry forms the environment and institutions within which actors operate. Thus, tailoring measures to the specific industries and technologies of interest enhances the relevance and applicability of the measures and allows for developing more precise and actionable measures that can move the needle on innovation in that specific sector and/or technology. Another finding of this study emphasized the inadequacy of relying solely on quantitative measures due to their inherent availability bias. While quantitative measures are often perceived as objective, their selection may overlook the broader spectrum of innovative activities. The study advocates for the development and availability of qualitative measures, encompassing elements like trust, experience, and mentorship. These qualitative measures are crucial for capturing the multifaceted nature of innovation that transcends quantifiable dimensions, offering a more holistic understanding of the innovation landscape.

In summary, the availability and influence framework of innovation measurement highlights the interplay between the accessibility and impact of diverse measures within the innovation ecosystem. This framework not only informs the current state of innovation measurement but also serves as a catalyst for future developments, advocating for measures that are not only available but wield significant influence in shaping the dynamics of innovation.

### **5.7 Methodological Limitations**

Despite the valuable insights garnered from this study, it is essential to acknowledge certain methodological limitations that may influence the generalizability and robustness of the findings. Firstly, the study's reliance on a qualitative approach, while conducive to in-depth exploration, may limit the broader application of the results to more extensive and diverse populations. The small sample size of participants, although rich in diversity, might not fully encapsulate the heterogeneity present in the broader innovation landscape. Additionally, the study's cross-sectional design captures a specific moment in time, potentially overlooking dynamic changes in actors' perceptions and practices over time. The research's focus on self-reported data introduces the possibility of social desirability bias, as participants may shape their responses to align with perceived expectations. Furthermore, the study primarily centers on actors within the innovation ecosystem in a specific geographical context, potentially constraining the transferability of findings to different regional or cultural settings. Moreover, some participants had overlapping roles, which affected how they used and interpreted the digital dashboard and made it difficult to disentangle which categorical perspective (entrepreneur vs. investor etc.) they spoke from. An innovation system consists of many actors with

Despite these limitations, this research contributes valuable qualitative insights that offer an understanding of innovation measurement dynamics within a specific context, laying a foundation for further exploration and refinement of measurement frameworks in diverse and dynamic innovation systems.

### **5.8 Conclusion**

This study was conducted to explore actors' perceptions of commonly used evaluative measures of innovation. Through a three-part interview study with 13 participants from six actor groups and digital dashboard tool, the study detailed (1) the various tasks, responsibilities, and functions of different actors in an innovation system, (2) the tools and technologies they used to obtain different types of information pertaining to innovation measures and (3) actors' perceptions on existing measures of innovation, especially regarding what is missing. The study adopted the Technological Innovation Systems (TIS) framework to frame the tasks and responsibilities of different actors as they pertained to the various TIS functions. The same framework was used to study what types

of information/data different actors require to conduct their tasks.

The study reinforced the idea that different actors are interested in measuring different aspects of innovation, that is, general evaluative measures need to be supplemented with actor-specific measures to capture the full spectrum of activities occurring in an innovation system. The study unveiled a pivotal framework that characterizes innovation measures based on their availability and influence on actors' decision-making, shedding light on the inadequacies of commonly used evaluative measures. This paradigm shift emphasizes the importance of actor-specific measures and the contextual nature of innovation activities. Additionally, the study underscored the significance of industry-specific measures, recognizing their varying relevance across different use cases and contexts. The significance of industry-specific measures varies with the use-case and context. In certain cases, such as education, the structure of the industry may not be as essential as it does not pertain to direct knowledge development. However, when studying the measurement of research and entrepreneurship functions for innovation, industry-specificity is of much significance as it provides essential context and institutional norms within which the innovation is occurring.

Ultimately, the study provides a foundational concept—the availability-influence paradigm for innovation measurement, in addition to the evaluative and actor-centric characterization of measures from the previous study (Chapter 4). This set the stage for its application in a subsequent case study within specific industries and technologies, namely clean energy, and long duration energy storage (LDES) respectively (Chapters 6 and 7).

## Chapter 6

**INTRODUCTION TO LONG DURATION ENERGY STORAGE  
INNOVATION SYSTEM****6.1 *Setting the Stage***

The findings from interviews of actors in an innovation system emphasized the importance of delving into a specific technology and sector to identify and develop more actionable and actor-centric measures of innovation. Consequently, the scope of further research in innovation measurement was narrowed to the context of long duration energy storage technologies within the energy sector. The selection of this domain was guided by strategic criteria:

1. **Relevance:** Relevance to electrical and computer engineering (ECE) because ECE is the home department for this dissertation.
2. **Maturity:** Focused on technologies within the Technology Readiness Level (TRL) range of 4-6, ensuring substantial growth potential and active transition from research to practical implementation.
3. **Literature and data availability:** Chosen based on a well-documented history within the innovation context and the availability of publicly accessible data for comprehensive quantitative analyses.
4. **Impact:** Closely associated with addressing global challenges, adhering to frameworks such as the National Academy of Engineering Grand Challenges and the United Nations Sustainable Development Goals. Clean energy, a pressing challenge, was chosen under this criterion.

This strategic selection enables the exploration of an innovation landscape with academic relevance, technical maturity, data availability and global sustainability implications. The study aims

to advance innovation measurement practices within a context characterized by evolving technologies and interdisciplinary collaboration. The deliberate focus on clean energy and long-duration energy storage technologies, specifically electrochemical and thermal variants, aligns with global impact criteria, poised to significantly influence the transition to cleaner energy sources. These emerging technologies, currently in the pilot and demonstration stages, offer substantial potential for growth, fulfilling the maturity criterion. Moreover, their direct relevance to the field of electrical and computer engineering underscores their importance within the academic context, thereby meeting the relevance criterion. As a result, this study is positioned to advance the understanding of innovation dynamics in a rapidly evolving landscape, promoting interdisciplinary collaboration and sustainable solutions for the future.

This chapter is dedicated to establishing the background for long-duration energy storage technologies. It serves to introduce the context, research questions and methodologies employed to analyze innovation measurement within this specific domain. Subsequently, Chapter 7 will delve into the outcomes of the analyses and present conclusions.

### *6.1.1 Introduction*

The decarbonization of the power sector is imperative to address the pressing climate crisis and achieve ambitious targets like those set by the Biden administration: 100% carbon-pollution free electricity by 2035 and achieving Net Zero emissions by 2050. Presently, the power sector accounts for approximately one-third of domestic greenhouse gas emissions in the U.S. Decarbonization involves transitioning away from fossil fuel-based power generation, which is a major source of these emissions, and moving toward cleaner and more sustainable energy sources. This transition primarily involves the adoption of renewable energy sources like wind and solar, which has seen historical growth rates in the United States and globally [4]. However, integrating renewable energy sources into the grid presents unique challenges due to their intermittent nature. Unlike fossil fuel power plants, which can be dispatched on-demand, renewable energy sources are dependent on weather conditions and time of day. This intermittency creates variability in energy generation, making it essential to balance supply and demand effectively in real-time to ensure grid stability and reliability. This is where Long Duration Energy Storage (LDES) technologies come into play.

LDES systems are designed to store surplus energy during periods of high generation and release it when demand is high, or generation is low. These technologies can provide grid operators with the flexibility needed to manage and smooth out the variability of renewable energy sources.

A Department of Energy's (DoE) analysis suggests that that the U.S. may require substantial LDES capacity ranging from 225 to 460 gigawatts (GW) for applications within the power sector to achieve a net-zero economy by 2050 [52]. The deployment of LDES technologies on this scale represents a significant capital investment of approximately \$330 billion, highlighting the need for substantial financial commitment from various actors, including government agencies, utilities, and private investors, to fund the development and deployment of LDES infrastructure. Despite the substantial upfront investment required, the analysis underscores the long-term economic benefits of deploying LDES. Net-zero pathways that include LDES technologies are projected to yield annualized savings ranging from \$10 to \$20 billion compared to pathways that do not utilize LDES. These savings result from improved grid flexibility, reduced reliance on fossil fuels, and enhanced energy system efficiency.

Long Duration Energy Storage (LDES) holds substantial promise as a key player in the decarbonization of the U.S. power system. However, while LDES has the potential to decarbonize various power sector use cases, it competes with other energy storage technologies, notably lithium-ion battery storage. To maximize its impact, LDES must distinguish itself within this competitive landscape. Further, to realize its full potential in a net-zero grid, LDES needs to scale to a point where it becomes self-sustaining. In other words, it should not rely heavily on public capital but should instead attract private investment. Achieving self-sustainability is essential for long-term viability and widespread adoption. To achieve self-sustainability, LDES must make significant advancements in three core areas [52] (1) LDES technologies must continually improve in terms of cost-effectiveness and performance efficiency. Lowering the cost per unit of energy stored and enhancing the overall performance parameters, such as roundtrip efficiency (RTE) and cycle life, are critical. Round-trip efficiency is a key performance measure for battery storage systems. It quantifies the energy losses that occur during the charging and discharging processes, (2) energy markets must develop mechanisms that accurately reflect the value of long duration storage capabilities. This includes recognizing the role of LDES in mitigating intermittency issues associated with renewable energy sources and valuing the reliability it provides to the grid, and (3) scaling up

manufacturing and deployment capabilities is essential for reducing production costs and increasing the availability of LDES solutions. Widespread deployment can drive economies of scale, making LDES more accessible and cost competitive.

To effectively drive commercialization efforts in the Long Duration Energy Storage (LDES) sector, understanding the ongoing innovation dynamics within the domain is paramount. The application of the Technological Innovation System (TIS) Analysis serves as a structured framework, aiding in the comprehensive evaluation of innovation systems across various sectors. Leveraged by the Copernicus Institute for Sustainable Development and Innovation, this approach has proven instrumental in identifying gaps and informing effective sustainable innovation policies and strategies in different regions, including the UK, the Netherlands, Norway, and Asia. [182, 97, 197, 92]. For the success of LDES in supporting the decarbonization of the U.S. power system, key factors such as competitiveness, self-sustainability, cost and performance advancements, and adaptation to evolving market mechanisms are critical. Employing established analytical frameworks like TIS analysis can facilitate a systematic examination of LDES innovation, enabling actors to address ecosystem gaps and devise concrete measures for enhancing competitiveness. By strategically addressing these aspects, LDES can significantly contribute to shaping a sustainable energy future.

### 6.1.2 Background

Duration (Hours)	Citation Count (number of cites followed by references)							Total
	U.S. Dept. of Energy	Journal (technology focus)	National Lab Report	Journal (grid focus)	Media	Utility/ Trade/ Consultant	Other	
>2	1 (2)							1
≥4		3 (5–7)	2 (8, 9)	2 (10, 11)	3 (12–14)	2 (15, 16)	1 (17)	13
≥6	1 (18)							1
≥8						1 (19)	1 (20)	2
≥10	2 (21, 22)	2 (23, 24)		7 (4, 25–30)	1 (31)		3 (32–34)	15
Beyond diurnal <sup>a</sup>		1 (35)	1 (36)	5 (3, 37–40)				7
<b>Total</b>	<b>4</b>	<b>6</b>	<b>3</b>	<b>14</b>	<b>4</b>	<b>3</b>	<b>5</b>	<b>39</b>

<sup>a</sup>Typically multiday to seasonal

Figure 6.1: Various sources defining long duration energy sources [48]

Long duration energy storage (LDES) technologies refer to technologies that are expected to store energy efficiently for many hours, days and even over weeks. Different organizations and scholars have different definitions of what long duration stands for. A study done by the National Renewable Energy Laboratory (NREL) found different definitions of what long duration meant (See Table 6.1) [48].

From the table, it is evident that there are different threshold values for what can be classified as long-duration energy: greater than 4 hours, greater than 10 hours and multiday to seasonal. Recent documentation from the Department of Energy (DoE) defines LDES as systems that can store energy for more than 10 hours, a definition also consistent with that of ARPA-E [48]. According to the NREL report, there appears to be some justification as to why a duration of 10 or more hours is a valid threshold. First, this threshold had the largest number of citations in the NREL study. And second, it has been accepted by the DoE and ARPA-E (which defines LDES as 10-100 hours). A recent DoE report considers two segments of LDES: inter-day and multi day/week LDES. Inter-day LDES assumes a storage duration between 10–36 hours. It includes almost all mechanical storage technologies and some electrochemical technologies. On the other hand, multi-day/week LDES is defined as storage for duration between 36–160+ hours and includes thermal and electrochemical technologies [52]. LDES technologies have the potential to offer a diverse range of energy storage services, categorized into four primary groups, each serving a distinct role in modernizing and enhancing the reliability of the electrical grid [52]:

- **Energy arbitrage:** These services involve the process of storing electricity during periods of low demand or low energy prices and then discharging it during high-demand or high-price periods and is deemed to be the fundamental role of energy storage in today’s grid. This strategy optimizes the value of electricity by shifting it from times when it is less valuable to times when it can command a higher price. The integration of renewable energy sources, such as solar and wind, further enhances this opportunity. As these renewable resources exhibit fluctuations over time, LDES can store surplus energy when generation is high and deliver it when renewables are not producing enough power to meet demand. This aligns with the goal of maximizing the utilization of clean energy sources.
- **Ancillary Services:** These services include frequency regulation services, voltage support

services and black start capability. Frequency regulation services involves the use of storage to mitigate fluctuations caused by short-lived differences between power generation and load demand. LDES technologies can provide valuable support by quickly injecting or withdrawing electricity from the grid to maintain the desired frequency. Voltage support services involve using energy storage to absorb or produce power to stabilize voltage levels between the transmission and distribution systems. This is vital for ensuring the quality and reliability of electricity delivery. On the other hand, black start capability refers to a power station's ability to restart in the event of a power system collapse without relying on the rest of the power system.

- **Transmission and distribution infrastructure services:** LDES can defer or even eliminate the need for costly upgrades to the transmission and distribution infrastructure. By acting as a buffer during periods of congestion or overloads, energy storage systems can optimize the utilization of existing infrastructure, reducing the immediate capital expenditures required for expansion and enhancing the overall efficiency of the grid.
- **Customer energy management services:** Smaller-scale LDES systems can provide benefits directly to energy consumers. These systems enhance the reliability of power supply during peak demand periods, reduce electricity costs, and offer greater control over energy consumption for residential, commercial, and industrial customers.

In addition to technical, grid-scale benefits, LDES technologies can also provide the following key market-related benefits [52]:

- **Support the expansion of renewable energy sources:** LDES technologies address the intermittency challenge associated with renewable energy sources. As the grid accommodates a greater share of renewables, LDES can enhance grid reliability by ensuring a continuous and balanced energy supply. This support is crucial for achieving net-zero goals that prioritize clean and sustainable energy sources.
- **Enhance grid resiliency:** Currently, most of the grid's reliability and resiliency services are provided by fossil fuels and hydro power. Natural gas peaker plants, for example, are

commonly used to handle peak demand. Peaker plants are not only “unclean” sources of energy but can also cause various respiratory health problems and two-thirds of these plants are located in low-income areas which exacerbates existing environmental exposure disparities for the poor [183]. LDES technologies have the potential to replace or complement these peaker plants by offering grid adaptability, thus reducing reliance on fossil fuels, reducing environmental exposures in low-income areas, and improving grid resiliency.

- **Diversification of energy storage supply chain:** In 2022, China accounted for over \$9.3 billion in lithium-ion battery exports to the US [156]. This results in the U.S being reliant on other countries for their lithium-ion battery supply, which makes the US’s net-zero goals be contingent on the security of imports from other nations. Reducing dependence on specific energy storage technologies, like lithium-ion batteries, is essential for energy security. By diversifying the types of storage technologies, the energy sector can become less reliant on imports, particularly from other countries. This enhances a nation’s energy security by establishing domestic supply chains for energy storage, ultimately contributing to long-term sustainability and self-reliance.

These technical and market-related benefits highlight the significant potential of LDES technologies in modernizing and optimizing the electrical grid. A well-functioning LDES innovation system, supported by strong research, development, and investment, is essential for realizing these benefits and driving the transition toward a cleaner, more resilient, and sustainable energy future.

### 6.1.3 Technological Landscape

LDES technology can be categorized into three groups based on their physical characteristics and chemistries and are briefly discussed below (also See Table 6.1):

- **Mechanical LDES:** Mechanical technologies are generally the most mature, and some are already at the commercial and demonstration stage. Mechanical storage involves converting and storing electrical into various types of mechanical energy such as gravitational potential energy and kinetic energy. Mechanical energy storage technologies have a much lower energy density when compared to other LDES technologies, due to which they tend to have large

Duration	Storage Type	Technology	Nominal Duration (hrs)	TRL
Inter-Day LDES	Mechanical	Traditional Pumped Hydro	0-15	9
		Novel Pumped Hydro	0-15	5-8
		Gravity-Based	0-15	6-8
		Compressed Air (CAES)	6-24	7-9
		Liquid Air (LAES)	10-25	6-9
		Liquid CO <sub>2</sub>	4-24	4-6
Multi-Day LDES	Thermal	Latent Heat (ex. aluminum alloy)	25-100	3-5
		Sensible Heat (ex. molten salts, concrete)	10-200	6-9
Both inter-day and multi-day LDES	Electrochemical	Hybrid Flow Battery with liquid electrolyte and metal anode	8-50	4-9
		Metal Anode Batteries	50-200	4-9
Multi-Day LDES		Aqueous electrolyte flow batteries	25-100	4-9

Table 6.1: Types of Long Duration Energy Storage Technology, adapted from the Department of Energy [52]

physical footprints (i.e., 50–100 MW costing \$100M+) and are dependent on geologically favorable locations. Pumped storage hydropower (PSH) is one of the most mature mechanical storage technologies that accounts for over 90% of the current functional grid-scale energy storage capacity that currently exists in the U.S. However, PSH projects and mechanical storage projects in general require large capital investments, are geographically limited due to sizing and siting requirements and are prone to major cost overruns.

- Thermal LDES:** Thermal energy storage work by storing heat effectively in low-cost materials making them suitable for multi-day/week use cases. Thermal storage solutions can also provide additional benefits if waste heat from various industrial processes can be leveraged for applications beyond energy dispatch. One advantage of thermal storage technologies is that they can be added to existing infrastructure in addition to steam turbines at existing power plants and thus replace fossil-fuel boilers. Thermal technologies vary widely in their round-trip efficiency, which can be anywhere between 20% to 90% [52]. In terms of commercialization, thermal technologies are moving into commercial demonstrations. However, they require large demonstration projects and hence large capital investments to scale.

- **Electrochemical LDES:** Electrochemical storage systems encompass different types of battery technologies. In this context, round-trip efficiency can vary significantly among different electrochemical storage technologies. While Li-ion batteries can achieve round-trip efficiencies of around 95%, some metal-air chemistries exhibit lower efficiencies, sometimes as low as 40%. This range underscores the importance of selecting the right technology for specific applications, as efficiency directly impacts the economics of energy storage [4]. A notable advantage of electrochemical storage systems is their scalability and versatility. Unlike some other LDES technologies (e.g., pumped hydro), electrochemical systems tend to have a smaller physical footprint and are not reliant on specific geographical features. This inherent flexibility makes them suitable for a wide range of deployment scenarios, from residential and commercial applications to utility-scale energy storage projects. In terms of where these technologies are in the process of commercialization, electrochemical technologies are mostly in lab or in the pilot phase (greater than 10MW). Electrochemical storage's ability to be deployed and tested in smaller projects offers several advantages. Firstly, it facilitates faster iterations, as multiple smaller projects can collectively generate more data and insights than a single large-scale endeavor. For example, 10 projects at 10 MW may produce more learning than one project of 100 MW in another technology type. Additionally, smaller projects are often less financially risky, making them attractive for investors and organizations exploring new technologies.

Despite their longstanding presence, the commercialization of mechanical storage has faced significant hurdles, primarily attributed to geographical limitations and the substantial initial capital expenditure (capex) requirements. Therefore, this dissertation focuses on studying thermal and electrochemical technologies within the Long Duration Energy Storage (LDES) sector. The rationale for this emphasis stems from the fact that these technologies represent the latest advancements in the field of LDES. In contrast, traditional forms of mechanical storage, such as pumped storage, have existed since the 19th century.

## **6.2 Research Objectives**

This case study aims to operationalize and validate the innovation measurement frameworks derived in studies 1 and 2 within the specific context of long-duration energy storage (LDES) technologies

in the United States. The primary objective is to offer a comprehensive description of the LDES landscape and critically evaluate the effectiveness of the innovation system in advancing LDES technologies using the integrated innovation measurement framework. The study begins with a Technological Innovation System (TIS) analysis using evaluative measures of innovation outlined in Chapter 2. This analysis leads to the characterization of key actors involved in LDES innovation, an assessment of the strength of diverse activities within the LDES TIS, and the identification of inducement and blocking mechanisms influencing the pace of LDES innovation. Subsequently, the introduction of actor-centric measures involves the analysis of six use cases of long-duration energy storage technologies, detailing the involved actors and the measures pertinent to each use-case context. This investigation includes an evaluation of the availability and influence of these measures on decision-making, contributing to a coherent narrative on measuring innovation within the framework developed in this dissertation.

### 6.2.1 Research Questions

The key research question this study aims to answer is:

*How can innovation measurement frameworks derived in this dissertation be applied to measure the effectiveness of the LDES innovation system?*

Inquiry into the above research question is guided by the following sub-questions:

1. How can evaluative measures be applied to assess the structure and functions of the LDES TIS?
2. How can actor-centric measures be applied to assess the functions of the LDES TIS?
3. Where do the measures in RQ1 and RQ2 sit in the availability-influence framework of innovation measurement?

Addressing these research questions directly contributes to understanding and enhancing the effectiveness of the innovation system in an emerging battery storage sector. This is relevant for policymakers, industry actors, and researchers involved in advancing sustainable energy solutions. The novelty of this research lies in the application of novel innovation measurement frameworks

specifically to the LDES context. Additionally, an analysis of the LDES TIS is novel to innovation literature, as it has not been conducted before. The TIS analysis furthers the understanding of the various actors and activities that contribute to and hinder the progress of novel LDES technologies, which in turn can fuel the decarbonization of the US's power grid. Therefore, the impact of work lies in the potential to inform strategic decision-making within the LDES innovation system. By applying the developed innovation measurement frameworks, the study can offer a comprehensive analysis of the innovation landscape, identifying key actors, assessing the strengths and weaknesses of various activities, and uncovering factors that induce or impede innovation. The findings have the potential to guide investments, policy interventions, and collaborative efforts to accelerate the development and deployment of LDES technologies, thereby influencing the trajectory of sustainable energy solutions.

### **6.3 Analytical Framework and Methodology**

To gain a comprehensive understanding of innovation within the Long Duration Energy Storage (LDES) technology landscape and to answer the four research questions, a Technology Innovation System (TIS) analytical framework was first adopted. This perspective outlines the actors, institutions, networks, and the interactions between them [88] involved in the innovation of LDES technology and their function within the innovation system. By considering the structural and functional components of the LDES innovation system, as emphasized in the works of [88], the analysis aims to unravel the dynamics and interdependencies shaping the evolution of LDES technologies. The systemic perspective is then followed by an analysis of measures used to characterize innovation in this space. The focus of the analysis of measures will be on the use of existing measures and where these measures fall short in spring boarding the adoption of LDES technologies.

The analytical steps for this draw from Bergek et al.'s "scheme of analysis" which describe the "steps" that an analyst can take to study a TIS. The first step of the analysis involves defining the technological innovation system (TIS) in focus [16]. In the context of this study, the technological innovation system in focus is the Long Duration Energy Storage (LDES) technological innovation system, with a primary focus on the United States. The next step involves identifying the structural components of the TIS (actors, networks, and institutions), which enables the following step of a functional analysis. A functional analysis entails describing the activities in a TIS in terms of the

seven key functions and an illustration of how each function manifests itself in the system. The next step involves assessing the effectiveness of the functional pattern followed by identifying mechanisms that either drivers or blockers of the desired functional pattern. The final step involves outlining the key issues related to these driving/blocking mechanisms and devising recommendations for how to bolster driving mechanisms and suppressing blocking mechanisms. After a TIS analysis, actor-centric measures are then derived by examining 6 different use cases of LDES technologies, the actors involved in those use cases and how the blocking and inducement mechanisms that emerged from the TIS analyses may impact the actors. The evaluative and actor-centric steps may often not be sequential and are often iterative in nature. Once both the evaluative and actor-centric measures are analyzed, they are placed on an availability-influence spectrum to determine which of the existing measures relevant and measures are missing.

The following section describes the key steps in a TIS analysis highlighted above. The section also details the scope of the work, data sources, methods, and limitations for the study.

### *6.3.1 Structural Analysis*

A structural analysis maps the innovation system and the associated knowledge infrastructures of the long duration energy storage technologies over time. To conduct a structural analysis, the first component of interest are actors in a TIS. These may include firms, universities, and research institutes, along with public organizations, industry associations, venture capitalists, organizations deciding on standards, etc. Actors in a TIS can be identified using several methods. Quantitative methods of identifying actors can include (1) Bibliometric analysis which can provide a list of the most active academic and research organizations, (2) Patent analysis which can reveal the volume and direction of technological activity in different organizations can be used to identify actors with a specific technological profile, (3) Financial information database surveys from Pitchbook, Bloomberg and government funding databases such as USASpending.gov to help identify organizations that fund activities in a specific sector and can thus help identify additional actors, and (4) Interviews with technology or industry experts can help further actors. This can “snowball” into each actor pointing to additional participants.

The second component of a structural analysis of interest is networks. Many different types

of networks may exist in a TIS including formal and informal networks. Formal networks can be easily recognized, whereas informal networks are harder to identify and may require input from industry experts or other actors, or analysis of co-patenting, co-publishing, or collaboration. The third component of interest in a TIS is institutions such as regulations, laws, norms, and routines [130]. For new innovations to scale, institutions need to be aligned to enable the development of the new technology. For emerging TISs there are intrinsic uncertainties, which make structural analysis challenging. Relevant actors can be difficult to identify when industry associations are scarce or if the actors are not even aware of belonging to a certain TIS. Additionally, in the early phases of a TIS, networks tend to be undeveloped or may not exist yet. Regardless, conducting a structural analysis is essential to characterize a TIS. Further, recognizing the structural aspects of the system provides a basis for the next step: a functional analysis of the TIS.

### *6.3.2 Functional Analysis*

A functional analysis of a TIS involves determining how the TIS is behaving in terms of a crucial set of processes. Functional patterns differ across different TISs and across time. A functional analysis typically requires a mixed-method approach which integrates quantitative and qualitative methodologies. Quantitative data provides a high-level overview of “what is going on”, whereas qualitative data can help evaluate “how” the innovation system is performing, which involves consulting experts within the system to assess its efficacy [16]. This analysis measures the effectiveness of innovation by measuring the performance of seven TIS functions [88, 14], . These include: 1) knowledge development, 2) knowledge exchange, 3) entrepreneurial experimentation, 4) guidance of the search, 5) resource mobilization, 6) market formation, and 7) legitimation. This quantitative and qualitative analysis assesses the barriers and challenges to innovation in the sector [88, 118]. Each of the seven functions is explained in further detail in the following sections of the analysis.

## **6.4 Methods**

The empirical scope of this analysis is electrochemical and thermal long duration energy storage technologies in the US context. The two technologies were selected because they have a high commercialization potential and have been identified as appropriate technologies for LDES. Additionally, the two technologies have the potential to be applicable to different storage needs; thermal

storage has been gaining ground for decarbonizing industrial heat and electrochemical storage has been gaining traction with utilities. Even though technological innovation systems in principle can be global [31], the study is limited to the US context because of the nation's unique grid structure, research and development infrastructure and nation-specific actors. Furthermore, the increasing penetration of variable renewable energy sources (like wind and solar), the increasing cost of Li-on battery systems for supporting longer duration grid storage, the promise of cheaper longer duration storage with these emerging technologies, and complexity of the grid storage sector make long duration energy storage a highly relevant subject for a technological innovation systems analysis. Conducting this TIS analysis requires an exploration of both the structural and functional dimensions of the innovation system that is integral to thermal and electrochemical storage.

A mixed-methods approach was applied to generate the necessary data to conduct such an analysis. The quantitative analyses consisted of bibliometric analysis, patent analysis [87], and analysis of data on LDES startups and venture capital support for LDES technologies. The qualitative approach consisted of analyzing (1) relevant literature on LDES technologies and TIS frameworks, (2) documents published by government, consulting firms (mainly McKinsey and Company), and reputed news outlets and (3) 10 semi-structured interviews with representatives of various firms, public agencies, and other organizations. All these methods shed light on both TIS structural and functional dimensions. When judging the status of the different TIS functions, data from different sources was combined to score each function on a three-point scale (non-existent-emerging-developed). Researching emerging innovation and development processes is a complex endeavor [177]. However, the study was designed to increase the credibility of the research by triangulation of interview data (several organizations within different organization types), and by using different qualitative and quantitative methods.

#### *6.4.1 Bibliometric and Company Financial Analyses*

Bibliometric analyses are a set of quantitative methods used to analyze and explore large volumes of scientific publication data. These analyses are used for a variety of reasons, such as exploring emerging trends in literature, collaboration patterns between researchers and organizations, funding patterns and the general intellectual structure of a specific domain. The analyses rely on both

quantitative (ex. number of citations) and qualitative (ex. thematic analysis) evaluations to interpret trends in literature. Bibliometric studies can enable researchers to (1) gain an overview of a specific domain, (2) identify knowledge gaps, (3) inform further research directions, and (4) identify key actors, organizations and sources of funding that support research in a specific domain [55]. In the context of this work, a bibliometric analysis was used to analyze the scientific and research structure of novel electrochemical and thermal energy storage technologies.

In addition to a bibliometric analysis, a financial analysis of LDES startups was conducted to understand the trajectory of different LDES startups, their financial history, sources of capital and current state. This analysis helped (1) provide an insight into the current health of the ecosystem and (2) identify key investors and venture capital actors in the LDES ecosystem.

1. Web of Science database was used as the data source for a bibliometric analysis of scientific literature pertaining to electrochemical and thermal LDES technologies. Web of Science was selected because (1) it is freely available through the University of Washington libraries and (2) because it is one of the most comprehensive databases used for quantitative analysis of scientific research. Web of Science offers access to over 171 million records across its platform, which include articles, reviews, editorials, abstracts, proceedings, and technical papers since 1900. The platform's multidisciplinary coverage encompasses 12,000 high impact journals and 160,000 conference proceedings.
2. USPTO and Google Scholar databases to obtain technology patents.
3. Pitchbook was used as a data source for the company financial analysis. Pitchbook was selected as an academic license for the platform is freely available through the University of Washington libraries.

The following general filtering parameters were used to construct the corpus of relevant data:

1. Publication year/Patent granted year: To narrow down the scope of analysis, a fifteen-year span between 2008 and 2022 was considered for this analysis. Data outside this data range was filtered out.

2. Language: Only English language data was considered
3. Country/Location of organizations: This research focuses mainly on the United States. Therefore, the country where these articles were published was restricted to the US.

The resulting corpus of data included:

1. Publications: 5,576
2. Patents: 10,541
3. Companies: 39

#### *6.4.2 Interviews*

Interviews were carried out in 2023. The interviews were conducted face-to-face or via telephone/video conference, and typically lasted 45 minutes. For all interviews, a semi-structured interview format was followed, in which the protocol was adapted from guides based on the TIS framework. The interview protocol was tailored to different actor types. Transcribed interviews were coded according to TIS functions (See Chapter 2). This made it possible to connect and analyze each specific technology according to the TIS framework.

### **6.5 Limitations**

#### *6.5.1 Limitations of Bibliometric Analysis*

One of the key limitations of a bibliometric analysis is its reliance on the quality of good search terms. It is impossible to perfectly include/exclude relevant/irrelevant articles. Many articles may have overlapping themes which may get included/excluded based on the search terms. While every effort was made to ensure that no relevant data was excluded, the dataset should be considered as representative instead of extensive. There were two key challenges when conducting the bibliometric analysis, both were resolved as best as possible:

1. **Inclusion of technologies that were either lithium-ion and/or not long duration storage:** The term “long duration storage” is relatively new, therefore it could not be used

explicitly in the search terms, as that would limit the search and discard potentially relevant articles. Therefore, the data corpus may contain articles that are not explicitly about long duration energy storage (LDES) but describe technologies that are relevant to long duration storage. A similar argument applies to lithium-ion chemistries. One of the key arguments for the need to develop new LDES technologies is the fact that lithium-ion chemistries become too expensive as duration increases. Therefore, ideally the bibliometric analysis should include explicitly lithium-ion chemistries. Even though this was enforced explicitly in the search terms, there may be some potential “leakage” such that the data corpus may contain some articles that mention lithium-ion chemistries. This challenge was even more prominent with thermal storage technologies. There are many different types of thermal storage technologies that use different materials and span different disciplines. This made it very challenging to slice and dice the domain and construct complex search terms. In this case, the search terms were kept simple to err on the side of inclusion instead of exclusion.

2. **Exclusion of technologies that were long duration storage:** Even though the strategy with the bibliometric analysis was to err on the side of inclusion, it is almost certain that some relevant articles may fall through the cracks and may end up being excluded from the search. To remedy this as best as possible, the search query was kept as simple as possible for the greatest flexibility. The queries were adapted from queries used in literature to search for relevant technologies to ensure that as many relevant technologies are being considered as possible.

### *6.5.2 Limitations of Financial Analysis*

The company financial analysis had its own set of limitations. The first one being companies to include in the analysis. A list of companies was constructed by triangulating data from trusted sources such as the ARPA-E database to obtain companies in the LDES domain that had been funded previously, Canary Media and Utility Dive (trusted publications covering clean energy), the LDES Council website to look for member companies and Pitchbook. However, given how rapidly the field is changing, it is possible that some very early-stage companies might have not been missed and not included in the analysis. Further, very early-stage companies often do not have publicly

available information about their funding status. Therefore, including them may not have been beneficial to the study. Another challenge is that the data from Pitchbook becomes less reliable the earlier the company is. This is because Pitchbook often scrapes SEC filings of investment firms to get accurate numbers on funding rounds. However, early-stage investment is often done through SAFEs and convertible notes which are not subject to SEC and hence may not appear on Pitchbook. Another challenge with Pitchbook is that it uses self-reported data from investors and companies. Therefore, the veracity of the data depends on whether the self-reporting is done truthful, which may sometimes not be the case because investors may or may not want to reveal certain investments for strategic and confidentiality purposes. Therefore, Pitchbook data was used and triangulated with data from Crunchbase (when available).

### *6.5.3 Limitations of Expert Interviews*

One of the main limitations of the qualitative interviews in this study is that the analysis and interpretation are based on the subjectivity of the researcher, who is also the main instrument of the research [122]. But the multiplicity of data sources served as a form of triangulation to render credibility to the findings of the study. Another limitation is that due to the competitive nature of the LDES domain, many interviewees were hesitant to provide details and breach confidentiality. Therefore, some of the thoughts expressed in the interviews might not have represented the complete picture of an interviewee's opinions. Despite these limitations, the results of this study offer rich insight into the structure of the LDES innovation system and how it is evolving.

## **6.6 Conclusion**

This chapter was focused on presenting the background and context for long duration energy storage (LDES) technologies. The LDES innovation system was selected as a case study to validate the innovation measurement frameworks developed in studies 1 and 2 (Chapters 4 and 5 respectively). The sector was selected based on its relevance to the electrical engineering discipline, maturity level of the technology, global impact and availability of data and literature. The chapter is a primer for understanding what LDES technologies are, and how may they benefit the decarbonization and clean energy goals of the US. The chapter then introduced the research objectives for the case

study, and an explanation of the methodology used and its limitations. The next chapter delves focuses on addressing the research objectives and discussing the results of the case study.

## Chapter 7

# LONG DURATION ENERGY STORAGE INNOVATION SYSTEM ANALYSIS

### 7.1 *Introduction*

The previous chapter provided a brief background of long duration energy storage (LDES) and its potential advantages for decarbonizing the energy grid. The previous chapter also provided details on the analytical framework and methodology that will be employed to undertake the case study on the LDES innovation system analysis. The key research question this study aims to answer is:

How can innovation measurement frameworks derived in this dissertation be applied to measure the effectiveness of the LDES innovation system?

This question is guided by the following sub-questions:

1. How can evaluative measures be applied to assess the structure and functions of the LDES TIS?
2. How can actor-centric measures be applied to assess the functions of the LDES TIS?
3. Where do the measures in RQ1 and RQ2 sit in the availability-influence framework of innovation measurement?

This chapter presents a deeper dive into each of these research questions leveraging the technological innovation system (TIS) framework for analysis. RQ1 consists of a typical TIS analysis as explained in Chapter 6, Section 6.5. RQ2 will be assessed using a qualitative analysis of six use cases derived from reports generated by the Department of Energy to understand which actors are involved in the various use cases and which measures do they use to assess their activities and success. Finally, the availability-influence framework as developed in Study 2 will be used to analyze the evaluative and actor-centric measures used discussed in RQ1 and RQ2 to then provide recommendations for strategic interventions that can enhance the functioning of the LDES TIS.

## 7.2 RQ1: Structure of Long Duration Energy Storage Innovation System

The structure of an LDES Technological Innovation System (TIS) consists of the relevant actors, organizations, institutions, and networks that are involved in developing, commercializing, and supporting innovation in LDES technologies. Table 7.1 provides an overview of the structure of the LDES TIS.

Type	Actors
Government	Department of Energy (DoE) Office of Energy Efficiency & Renewable Energy (Energy Earth shots), ARPA-E (DAYS Program), DoE Office of Clean Energy Demonstrations, DoE Office of Electricity, DoE Office of Technology Transitions, DoE Energy Storage Grand Challenge, National Science Foundation, Department of Defense, DARPA, DoE National Laboratories, State governments
Knowledge actors	Universities, Colleges, Technical Schools, Joint Center for Energy Storage Research (JCESR)
Industrial Actors	Utilities, Large Energy Companies, ESG Companies, Local Power Authorities, Microgrid Developers, and Tribal Organizations
Entrepreneurs/Developers	These are typically early-stage companies developing new LDES technologies, examples include Form Energy (electrochemical), Antora Energy (thermal) and many others
Investors/Risk Capital	Federal Government, Investment organizations such as Breakthrough Energy, E8, Chevron Ventures
Other Organizations	LDES Council, Accelerators, incubators like Activate and Greentown Labs

Table 7.1: Structure of the Long Duration Energy Technological Innovation System

### 7.2.1 Government

Government is one of the key actors in the long duration energy storage (LDES) innovation ecosystem. Government funding has played a critical role in de-risking the development and commercialization of LDES technologies.

[Add table]

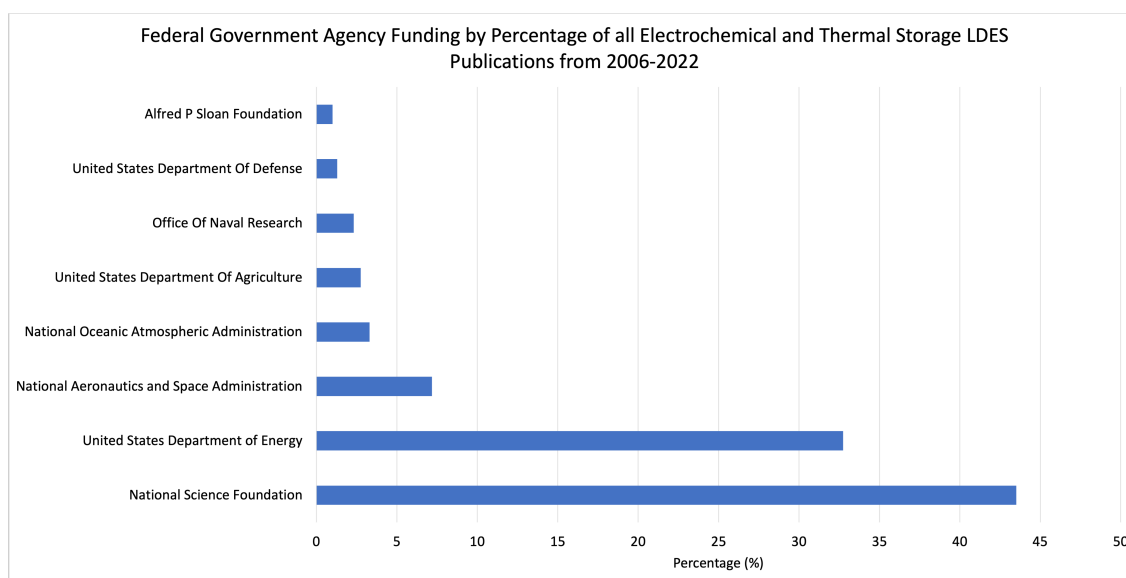


Figure 7.1: Federal government funding by percentage of all LDES publications from 2008-2022

### *Federal Government*

The National Science Foundation (NSF) and the Department of Energy (DoE) along with National Aeronautics and Space Administration (NASA), National Oceanic Atmospheric Association (NOAA), United States Department Agriculture (USDA), and the Department of Defense have funded most of the basic research and development of LDES technologies (See Figure 7.1). While the NSF has sponsored mostly basic R&D, the DoE has sponsored basic and applied R&D along with efforts to commercialize LDES technologies and scale them outside the lab. In 2018, ARPA-E commenced the Duration Addition to ElectricitY Storage (DAYS) program to support the commercialization of LDES technologies. The main goal of the program was the development of LDES systems that deliver electricity at a levelized cost of storage (LCOS) of 5 cents/kWh-cycle across the full range of storage durations (i.e. 10 to approximately 100 hours) [5]. Since its inception, the DAYS program has spent \$39.45 million and funded 11 LDES projects across various companies and universities. The awardees include 6 early-stage startups, 3 universities, 1 national laboratory and 1 large corporation. From its early days, ARPA-E has supported the development of LDES technologies. An early ARPA-E program called Grid-Scale Rampable Intermittent Dispatchable

Storage (GRIDS) focused on low-cost grid scale storage technologies. The program funded many electrochemical storage companies such as Energy Storage Systems (ESS), Primus Power, ITN Energy Systems, General Atomics etc.

In 2020, the DoE announced the Energy Storage Grand Challenge, which outlines the department's energy storage strategy. The program aims to create and sustain the US's leadership in energy storage [117]. The program roadmap proposes various activities such as building a diverse portfolio of LDES technologies, supporting the development of innovations that lower manufacturing costs, and enhancing exchange of knowledge between labs and external partners etc.

In 2021, the US Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) announced the Long Duration Storage Shot as the second Energy Earthshot initiative. The Energy Earthshots are created to drive integrated program development across the U.S, which aim to accelerate the development, commercialization and manufacturing of emerging technologies needed to achieve the Biden-Harris Administration's NetZero carbon emission goals by 2050. The Long Duration Storage Shot focuses on reducing storage costs by 90% for storage systems that deliver 10+ hours of storage in one decade [135]. In addition to coordinating various LDES programs across the DoE, this initiative also hosts an annual summit to engage various actors involved in accelerating LDES technologies. Also in 2021, the DoE established the Office of Clean Energy Demonstrations (OCED) to help scale emerging technologies that will help achieve the U. S's NetZero goals by 2050. As part of the Bipartisan Infrastructure Law, the OCED can allocate \$505 million for the development of LDES demonstrations to validate emerging technologies and enable customers and communities to integrate grid storage more effectively.

In 2023, the DoE's Office of Technology Transfer in partnership with the Edison Electric Institute for Energy Transition, Electric Power Research Institute (EPRI), and the Long Duration Energy Storage Council (LDES Council) signed a Memorandum of Understanding (MOU) to further accelerate the commercialization of long-duration energy storage (LDES) [137]. The signed MOU establishes three primary strategies for collaboration, which will support the development manufacturing of energy storage technologies. The first strategy focuses on facilitating the understanding and dissemination of the technological and economic benefits of LDES. The second strategy focuses on enhancing collaboration by providing access to DoE national laboratories' core competencies in energy storage and infrastructure integration for accelerating R&D and deployment. The last

strategy focuses on leveraging the knowledge provided individually by regulators, electric companies, and technological vendors to understand the pain points of and potential solutions to the deployment of LDES technologies at the grid scale.

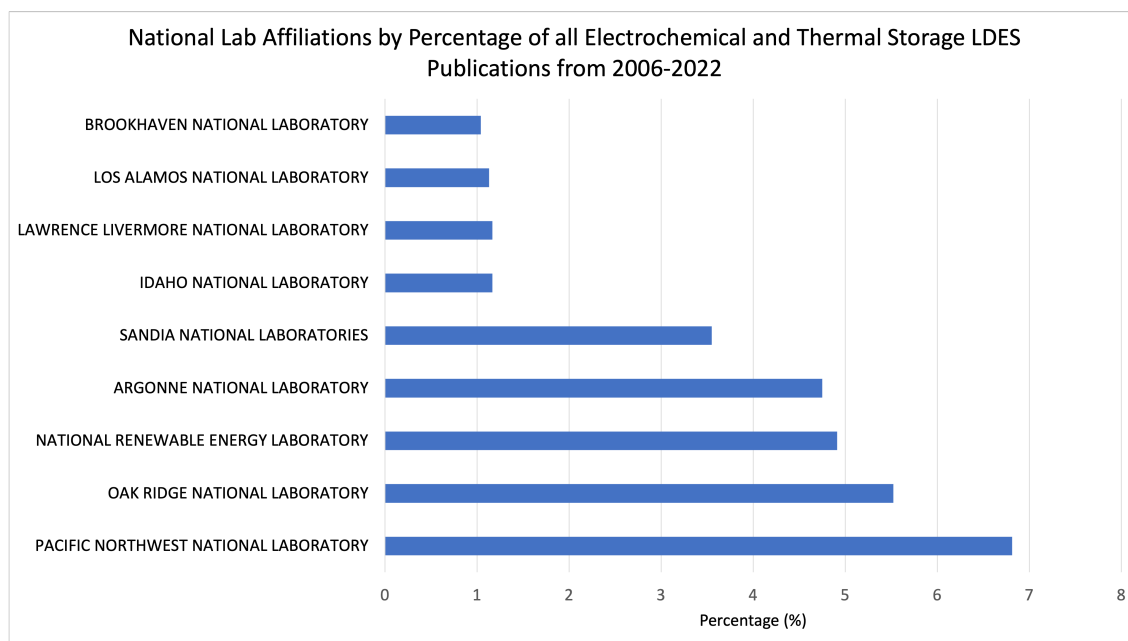


Figure 7.2: National laboratory affiliations by percentage of LDES publications between 2008-2022

Another set of key government players in the LDES innovation system are the Department of Energy National Laboratories, particularly the Pacific Northwest National Laboratory (PNNL), Oakridge National Laboratory (ORNL), National Renewable Energy Laboratory (NREL), Argonne National Laboratory (ANL) and Sandia National Laboratory (See Figure) 7.2. These labs are at the forefront of conducting basic research in novel LDES technologies. Additionally, the labs are also where commercial traction starts for early-stage LDES technologies. The national laboratories provide space for emerging technologies to be tested at scale. They often work with technology developers and other actors to assess storage installations under local and market conditions and support field deployments. For example, in 2022, PNNL was selected as the site for a national grid energy storage research facility (also known as the grid storage “launchpad”), with investments from the State of Washington, Battelle and PNNL. The goal of the facility is to (1) conduct independent

testing and validation of emerging energy storage technologies (less than 100kW) under realistic grid operation conditions and hence de-risking technological developing to some degree, (2) foster collaboration between other national labs, universities, and actors to solve crosscutting challenges, and (3) train the next generation of grid safety officials, utility planners and regulators.

### *State Governments*

In addition to the federal government, state governments and entities also play an important role in the LDES innovation system. State governments design policy incentives for the use of certain technologies that can create market mechanisms that can accelerate the adoption of novel technologies. In 2021, the states of California and Texas collectively accounted for around 75% of installed grid-level battery storage in the U.S [49]. California has been particularly active in incentivizing long duration storage on the grid. This is exemplified by the fact that as of July 2023 the state had 5.6GW of battery storage capacity online, which is 11.2 times increase from 2020 (500 MW) [94]. In addition to designing policy that reward long duration storage, states also provide funding to support the development of LDES technologies. For example, in 2023, the state of New York provided \$15 million to four LDES demonstration projects in the state [155]. Many states also support testbeds, incubators, and accelerator programs which in turn support the development of long duration storage. Examples of such organizations include, Center for Evaluation of Clean Energy Technology supported by New York state, OregonBest (now VertueLabs) and Los Angeles Cleantech Incubator.

### *7.2.2 Knowledge Actors*

There are multiple public and private universities in the US that have contributed to different types of LDES technologies over the years. Figure 7.3 depicts the contribution of different universities and university system to basic LDES research. Note that this is not an exhaustive list of knowledge actors and universities involved in LDES research, but a snippet of some of the key players.

According to the figure, the University of Michigan system leads basic research in LDES. This can be explained by the fact the Michigan being an automotive hub is also home to a large amount of battery technology research. In 2022, the University of Michigan received \$10.5 million from

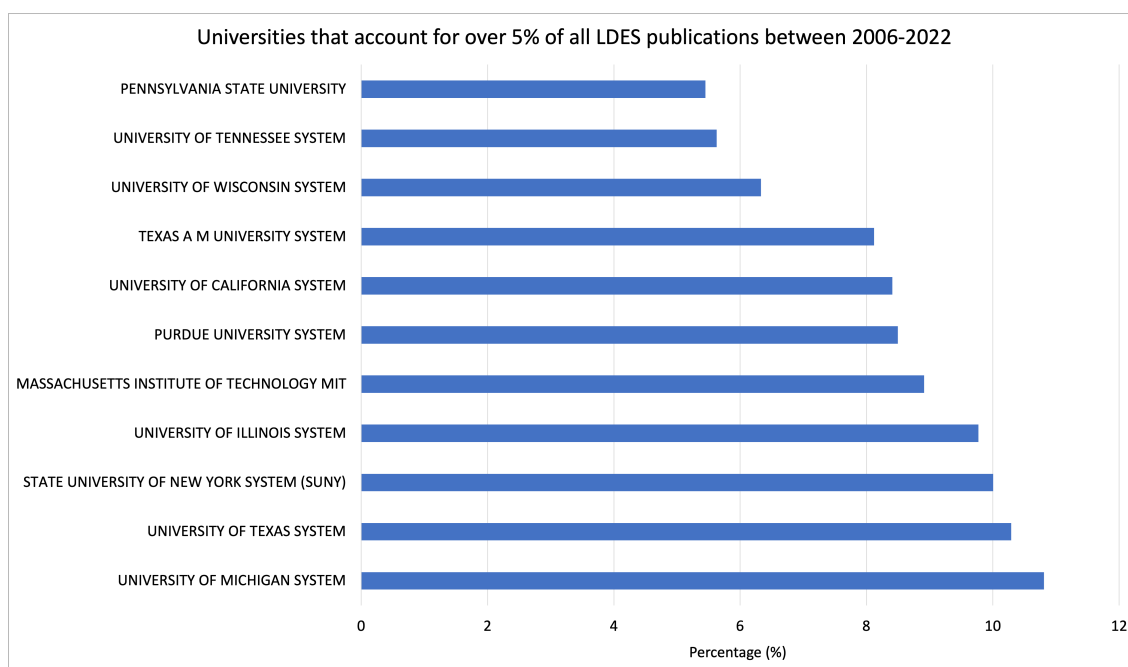


Figure 7.3: Universities that account for over 5% of LDES publications between 2008-2022

the Department of Energy to build a research center to explore the use of ceramic ion conductors as replacements for electrolytes commonly used in lithium-ion batteries for electric vehicles and in flow batteries for grid storage [139]. The University of Texas system is also a key knowledge player in the LDES ecosystem. Texas is second in place after California for having the largest amount of grid scale battery storage in the US. The University of Texas (home to the lithium-ion battery pioneer John Goodenough) and Texas A&M University systems play an important role in driving energy research to support the oil, gas, and electricity industry in the state. The State University of New York (SUNY) system also tops the list primarily because the state of New York has been investing heavily in long duration energy storage projects. For example, in 2023, the New York State Energy Research and Development Authority (NYSERDA) announced a nearly \$15 million in awards to four long duration energy storage projects in the state [155]. Different SUNY campuses focus on different aspects of energy and energy storage research. For instance, Stony Brook University's Advanced Energy Research and Technology Center has partnered with Brookhaven National Laboratory to develop, characterize, and demonstrate vanadium flow batteries

and flywheel energy storage systems [193]. All the organizations in Figure 7.3 focus on different aspects of LDES technologies. Different knowledge actors focus on multiple LDES technologies, and so it is hard to categorize them by technology. In addition to being knowledge actors, universities can also act as a facilitator for commercializing new technologies for spinning out companies. The most successful example in the LDES context would be the MIT spinout Form Energy, which has raised a total of \$935.8 million (until mid-2023) in investments to commercialize their iron-air long duration battery technology. Some universities, such as the University of Washington have testbeds, which subsize the lab to market scaling process for novel battery technologies by offering them the manufacturing equipment and infrastructure needed to scale their technology from the lab to a pilot scale.

Universities also partner with industry and national laboratories to conduct research and commercialize new technologies. The Joint Center for Energy Storage Research (JCESR) is one example of such a collaboration. The center consists of over 150 researchers across 18 organizations (universities, industry, and national laboratories) to work together on fundamental material science, chemistry, and engineering problems in energy storage [72].

There are diverse knowledge actors operating in the LDES innovation system, with different capacities, expertise, and contributions. Some universities may have a single researcher who may become involved in an LDES related project as a principal investigator (PI) or a Co-PI. On the other hand, some universities have dedicated battery research centers and labs, where multiple researchers work together. Some universities have access to large-scale testing infrastructure and sophisticated grid modeling software while others may not. Therefore, different knowledge actors in the LDES innovation system bring with them different needs and capabilities and should not be viewed as a monolithic group of organizations conducting research on the same topic.

### *7.2.3 Industrial Actors*

Industrial actors consist of actors that are potential customers of LDES technologies at various stages of commercialization.

### *Large Energy Consumers*

In 2022, the industrial sector was responsible for 33% of the total US energy consumption [2]. Four main types of industries fall under this category (by % consumption): manufacturing (76%), mining (12%), construction (7%), and agriculture (4%). Other players in this space include large hospitals, distribution centers and data centers who constantly require large amounts of energy. These group of actors can be promising early-adopters for LDES technologies and can use these technologies to manage weekend, week, or seasonal demand changes.

### *Local Power Authorities, Microgrid Developers, and Tribal Organizations*

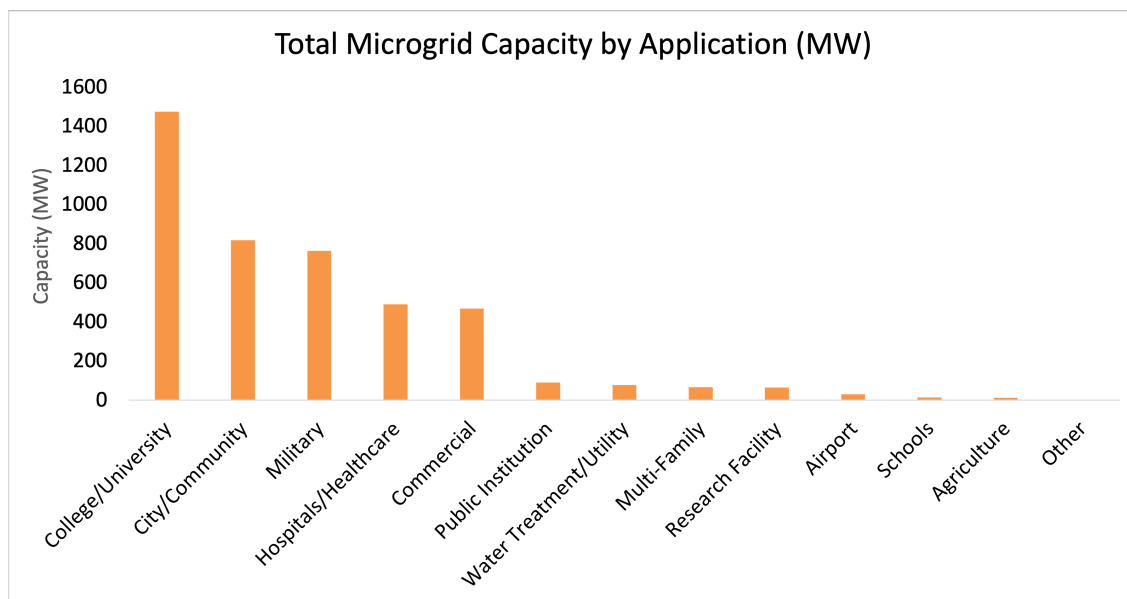


Figure 7.4: Total installed microgrid capacity (in MW) in the U.S as of 2023

Microgrids are a group of interconnected and distributed energy resources that are part of a single controllable entity with respect to the grid. They can connect or disconnect from the grid to operate in grid-connected or islands modes respectively [105]. As of 2023, the U.S has a 691 microgrids installed, with a total capacity of 4.4GW [134]. As 7.4 shows, most microgrid capacity resides in college and university campuses followed by city/community applications and military

applications. These actors can be potential customers for LDES technologies to help them make increase the reliability and resilience of their microgrids.

### *ESG Customers*

ESG is an acronym that stands for ‘environmental, social and governance’ standards that investors use to select investments that are environmentally and socially conscious. ESG criteria measure how companies impact the environment and society, and the corporate governance structures that drive high standards [127]. ESG scores are produced by ESG research firms such as Bloomberg, S&P Dow Jones Indices, MSCI etc. Leading ESG companies often put out corporate renewable power purchase agreements (PPAs) to reduce their environmental footprint and increase their energy savings. These companies can be a potential early-stage customer for emerging LDES technologies to help them ensure that their business has energy all around the clock.

### *Utilities*

Utilities are one of the main industrial actors in the LDES innovation system and a primary customer of many LDES technology developers. Utilities are organizations that deliver electricity to customers by (1) obtaining power from resources just as coal, gas, solar etc., (2) distributing the generated electric power, and (3) selling the power to customers. In the U.S, there are two different types of grid structures:

1. **Vertically Integrated Grids:** Traditionally, state electricity markets have been vertically integrated, where the utility may own or oversee all aspects of the electricity delivery process from generation to transmission, distribution, and sales. This structure evolved when electricity was a novel commodity and was seen as a natural monopoly. Under this structure, utilities own generation assets, and transmission and distribution lines. These utilities are overseen by state commissions (public utility commissions) that monitor the rate of return on investments and ensure that electricity is affordable to customers. In the context of LDES, vertically integrated utilities maybe more open to try unproven grid storage technologies, as they do not have to compete in a deregulated energy market. This gives them the flexibility to take some risk to test and validate newer storage technologies.

**2. Restructured Electricity Markets:** In the late 1990s and early 2000s, some states began restructuring their energy markets to increase competition. These states required utilities to sell their generation assets while still owning the transmission and distribution systems. In this case, wholesale energy prices are set by Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs). Most restructured states provide their customers the option to choose their electricity supplier. Therefore, there is a decentralization of the electricity distribution process in these states. From the LDES perspective, selling to utilities in deregulated markets maybe harder because utilities are often competing to buy and sell electricity. So, if a utility has an LDES system installed that holds energy for 4 hours, the utility may see a net loss as the price may have fluctuated within those 4 hours.

Both vertically integrated utilities and transmission and distribution utilities can support the adoption of LDES by including LDES as an energy resource in long-term energy planning to meet load balancing needs. Long duration storage technologies have been gaining traction with utilities. For example, utilities such as Great River Energy, Xcel Energy and Georgia Power have all signed up to conduct demonstration projects with Form Energy’s iron-air batteries [60].

#### *7.2.4 Developers*

Developers comprise of organizations and companies that are actively engaged in developing and deploying cutting-edge LDES technologies. Within this ecosystem, there exists a diverse mix of companies. They are the primary “vehicle” through which LDES technologies will reach market penetration and hence are one of the most important players in the LDES ecosystem. Developers encompass both sizable enterprises and earlier stage startups. Some of the prominent industry players include Siemens and Sumitomo Electric, who function as original equipment manufacturers (OEMs). Additionally, notable oil and gas companies such as Schlumberger, industrial contractors like Raytheon, and vanadium suppliers like Largo Resources.

It is worth noting that a substantial portion of early-stage developers in the electrochemical and thermal LDES technology sphere have emerged relatively recently. On average, these companies are approximately 10 years old, highlighting the nascent nature of this field. Out of the 40 total large and small sized companies active in this area, 20 of them are based in the United States while

the other 19 are based in Canada, Europe, Japan, and Australia. While only the US ecosystem is being considered in this dissertation, non-US companies were retained for this analysis as they also operate in the US market and receive US incentives and investments. Among electrochemical LDES companies, the promising early stage LDES companies has been Form Energy, which has raised a total of \$816 million to commercialize its iron-air batteries. So far, Form Energy has announced 4 pilot and demonstration projects with different utilities and has gained a great amount of traction.

However, while the novel LDES technology landscape is rapidly evolving and expanding, early-stage companies have a challenging road ahead of them to commercialize and scale their technology. This was exemplified by the apparently surprising bankruptcy of a prominent thermal LDES company, Azelio in 2023 [204]. Azelio was a Swedish company, whose thermal energy storage technology stored in an aluminum alloy material, which would then be converted to electricity using a Stirling engine. In 2023, Azelio declared bankruptcy by announcing that it was unable to secure enough financing to complete negotiations with a potential strategic partner [9]. Up until its bankruptcy, Azelio had raised a total of \$126.2 million indicating a good amount of traction. Therefore, even in 2023, when the need for LDES technologies has been accepted by different actors in the domain, early-stage companies are having a hard time raising capital to demonstrate their technologies and move them along on the path to commercialization.

### *7.2.5 Investors/Risk Capital*

Private investment and risk capital plays a pivotal role in helping LDES technologies scale and commercialize. The federal government is the main source of funding at the research and development stage. However, as technologies move from lab to market, additional capital is needed to fund pilots and demonstrations of novel technologies. In 2016, Gaddy et al. argued that venture capital (VC) is the wrong model for energy innovation [78]. Their argument was that clean energy startups that were involved in developing new materials, hardware, and processes were ill-suited for investment from VCs because they required a large capital investment, had long development timelines, were too risky (as they had not been proved at scale) and were unable to compete or attract corporate acquirers. Gaddy et al. advocated for having other types of investors who did not have the same time or capital constraints of traditional VC, which maybe better suited to clean energy innovation.

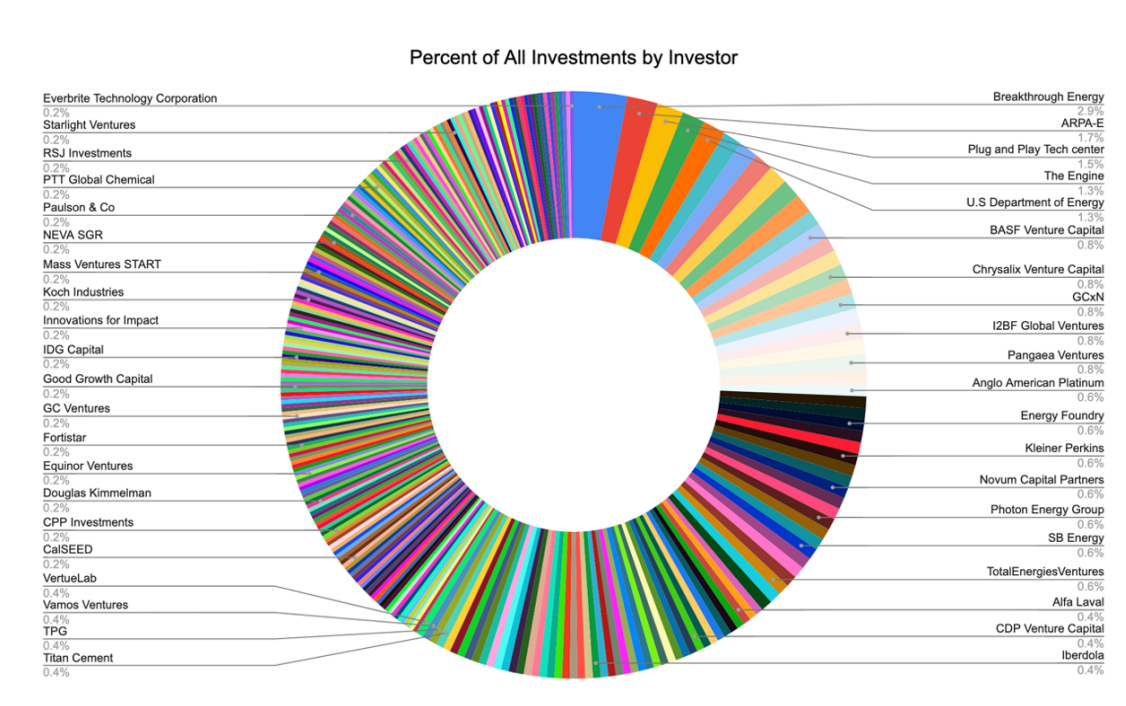


Figure 7.5: Percent of investment in LDES companies by different investors between 2008-2022

Since Gaddy's article, a major type of investing has emerged in the clean energy and LDES space, known as impact investing. Impact investing is driven by the dual goals of making a profit and creating a positive socio-environmental impact.

In the LDES space, one of the main impact and philanthropic investors is the Breakthrough Energy Coalition. Breakthrough Energy is an organization founded by Bill Gates in 2015 that aims to accelerate innovation in sustainable energy through impact and philanthropic investing. The Coalition was formed via a commitment from 28 high net-worth investors from across the world. Breakthrough Energy has been a key investor in Form Energy (a prominent metal-air battery storage company), ESS (a flow battery company), Antora Energy (thermal storage) and many other prominent startups in the field. In addition to impact investors and conventional VCs, LDES investors also include the venture arm of established corporations such as Aramco Ventures, Shell Ventures, and Chevron Ventures. Other corporations such as Siemens, Sumitomo Electric, and Schlumberger (vanadium supplier, relevant to flow batteries) are also investors in early stage

LDES technologies. State government organizations such as the California Energy Commission and the New York State Energy Research and Development Authorities have also invested in LDES companies by granting them capital to conduct pilot and demonstration projects.

7.5 depicts the rich landscape of investors investing in early stage LDES companies. While Breakthrough Energy makes up the largest share of investments in LDES companies, it is not necessarily the most dominant investor. Multiple one-off investments make up the bulk of the landscape. Additionally, many of these investors are part of the same deals, with one investor leading the round. Therefore, even though there are 286 unique investors participating in the LDES ecosystem, many of these cluster into communities that invest together on the same deals.

#### *7.2.6 Other organizations*

In addition to the actors discussed above, there are other critical organizations that support the growth of the LDES ecosystem. One such key organization is a non-profit known as the LDES Council, which brings together developers, industry, investor, and government actors who work on the commercialization of LDES technologies globally. The council was launched in 2021 at COP26 with the goal to accelerate the decarbonization of the energy system at the lowest costs to society through the deployment and development of long duration energy storage [121]. The council provides education and advocacy services to help with the adoption of LDES technologies by leveraging the experience of the council members [41]. Members of the council include emerging LDES startups, service providers (such as Vermont Electric Power Company), and industry leaders such as Breakthrough Energy, Microsoft, Google, Siemens Energy, Shell, Sumitomo etc. To date, the council has released 4 reports on various aspects of scaling LDES. Organizations such as the LDES council support the ecosystem by convening different actors of the ecosystem and spurring collaboration among them.

Other supporting organizations include accelerators and incubators that assist very early-stage companies develop a business plan and access resources and expertise required to help them scale their technology. Two prominent incubators in the LDES ecosystem are Greentown Labs and Activate. Greentown Labs is the largest climate tech incubator in the U.S. The incubator started out as a community of MIT graduates who worked at four climate tech startups and were looking

for a new prototyping laboratory space. By 2021, the incubator had grown to support over 200 startups in the Somerville, MA and Houston, TX areas. Greentown Labs provides its members with expertise, resources, introductions to strategic partners, equipment, and community to emerging climate tech startups. In terms of the LDES ecosystem, Greentown Labs has supported Form Energy and e-Zinc, both of which are long duration battery storage companies. Like Greentown Labs, Activate Global also supports emerging startups in LDES, but further upstream by helping researchers and scientist spin their technologies out. Every year, Activate works with some US institutions to select a cohort of fellows who work on commercializing their clean energy technology. The organization provides fellows with entrepreneurial education, access to funders, experts and facilities required to turn their research into a product. So far, Activate has supported 188 fellows and 145 startups which have generated \$1.3 billion in follow-on public and private funding. Past Activate fellows have included LDES companies such as Noon Energy, Innate Energy and Flux XII.

Therefore, while not a direct actor in the LDES ecosystem, these organization play a vital role in helping accelerate LDES innovation by provide emerging LDES companies with access to networks, resources and expertise that can enable them to successfully commercialize their technology and hence move the needle on innovation in LDES technologies.

### *7.2.7 Institutions*

In an innovation system, institutions are the norms, formal and informal rules such as policies, laws, standards, and regulations. Institutions can either bolster or hinder the development and diffusion of innovation and hence need to be aligned in order for a technology to scale [16]. All the interviews and supporting research were unequivocal about the fact that two key institutional aspects have spurred innovation in LDES technologies, these are the Infrastructure Investment and Jobs Act (also known as the Bipartisan Infrastructure Deal, abbreviated as IIJA) and the Inflation Reduction Act (IRA). A direct impact of the IIJA was the establishment of a new Office of Clean Energy Demonstrations (OCED) for the purpose of accelerating the pace of deployment of low-carbon technologies. The IIJA has appropriated \$505 million for the development of LDES demonstrations to validate new technologies [136]. The funding will be managed by OCED for up to 11 demonstration projects that can help cut costs of grid scale storage by 2030.

From the document analysis and actor interviews it was clear that further institutional measures are needed to spur the commercialization of LDES technologies. Over half of the interviewees stressed that state government organizations need to design specific policies that would support the adoption of non-lithium ion LDES technologies, especially in utilities. An example of this is that ISOs when rolling out RFPs for new types of storage can explicitly ask for long duration storage that is not lithium ion. Two of the actors referenced California's first long duration RFP as an example of how the industry is still leaning towards lithium-ion for long duration storage and needs to move away from it in order to support the development of other LDES technologies.

### *7.2.8 Networks*

Networks participating in an innovation system can either be initiated formally or informally. In the Long Duration Energy storage innovation system, formal networks are typically initiated through governmental efforts such as the Joint Center for Energy Storage Research (JCESR), which brings together over 150 researchers across 18 organizations (universities, industry, and national laboratories) to work together on fundamental material science, chemistry, and engineering problems in energy storage [72]. JCESR was initiated as a Department of Energy Innovation Hub developed to advance research to the point of commercialization. Another key formal network in the LDES innovation system is the LDES Council. The LDES Council was established in 2021 as a global non-profit that works to accelerate innovation in long duration energy storage. The Council consists of 70 members, including LDES developers and industry-leading organizations with a strong interest in Long Duration Energy Storage either as an end-user or a capital provider. The LDES Council is an industry organization that publishes reports and conducts events that bring different actors in industry together to accelerate the adoption of LDES technologies.

Other informal networks consist of university and national laboratory collaborations for research grants such as DoE's Long Duration Energy Storage Shot grant funding, and the ARPA-E program. Further, many LDES technology developers such as Form Energy (spinout from Massachusetts Institute of Technology) and Redoxblox (spinout from Michigan State University) are spinout from universities and therefore form bridges between university research, entrepreneurship, and commercialization.

### *7.2.9 Summary of the LDES Innovation System Structure*

The structure of the Long Duration Energy Storage (LDES) innovation system for electrochemical and thermal technologies involves various key actors, including the government, knowledge actors, industrial actors, entrepreneurs/developers, investors/risk capital, and other supporting organizations. The government, particularly the Federal Government, has been instrumental in funding and promoting LDES technologies. Entities such as the National Science Foundation (NSF), Department of Energy (DoE), NASA, NOAA, USDA, and the Department of Defense have supported research and development initiatives. The DoE has launched programs like the Energy Storage Grand Challenge and the Long Duration Storage Shot. Additionally, the DoE National Laboratories, including PNNL, ORNL, NREL, ANL, and Sandia National Laboratory, have been at the forefront of basic research and testing of emerging LDES technologies. State governments, such as those of California and New York, have also contributed by designing policies, providing funding, and supporting incubators and testbeds for LDES technologies.

Knowledge actors, including universities and research institutions, have actively participated in the development of LDES technologies. Examples of prominent contributors include the University of Michigan, the University of Texas system, and the State University of New York system. Collaboration between universities, industry, and national laboratories is facilitated through initiatives like the Joint Center for Energy Storage Research (JCESR).

Industrial actors, such as large energy consumers, local power authorities, microgrid developers, tribal organizations, ESG customers, and utilities, play a crucial role as potential customers for LDES technologies. Large-scale industrial consumers, including manufacturing, mining, and healthcare sectors, are exploring LDES for managing fluctuations in energy demand. Microgrid developers and local power authorities are interested in enhancing the reliability and resilience of their energy systems. ESG customers are looking to reduce their environmental footprint, while utilities are actively exploring LDES technologies to balance their energy supply.

Entrepreneurs and developers are driving the commercialization of LDES technologies, with companies such as Form Energy and Antora Energy leading the way. However, the path to commercialization remains challenging, as evidenced by the bankruptcy of Azelio, a prominent thermal LDES company, in 2023. Investors and risk capital providers, including impact investors like Break-

through Energy Coalition, venture capitalists, and corporate venture arms, are crucial in supporting the scaling and commercialization of LDES technologies. These entities provide essential funding for pilot projects, demonstrations, and commercialization efforts.

Other supporting organizations, such as the LDES Council, accelerators like Greentown Labs and Activate, and research institutions like JCESR, contribute to the growth and development of the LDES ecosystem. These organizations facilitate collaboration, provide resources, and promote knowledge sharing among actors. Institutional support, such as the Infrastructure Investment and Jobs Act (IIJA) and the Inflation Reduction Act (IRA), has provided crucial funding and policy frameworks to accelerate the deployment of LDES technologies. Further, networks, both formal (e.g., JCESR and the LDES Council) and informal (e.g., university collaborations and research grants), have fostered collaborations and knowledge sharing within the LDES innovation system.

The Long Duration Energy Storage (LDES) innovation system is a complex and dynamic system involving various key actors and supporting organizations. Collaborative efforts among these actors have led to significant advancements in LDES technologies, with notable progress in both electrochemical and thermal storage solutions. However, challenges persist, as seen in the struggles faced by some early-stage companies in securing funding and achieving commercialization.

The next section, which delves into the functional analysis of the LDES innovation system, further elucidates the interdependencies and roles of these various actors. By understanding the functional dynamics and interactions within the system, it becomes clearer how each actor contributes to the overall development, deployment, and adoption of LDES technologies. Through this lens, the network of relationships and contributions will come into sharper focus, highlighting the essential functions and collaborations necessary for the sustained growth and advancement of the LDES ecosystem.

### **7.3 RQ1: Functional Analysis of Long Duration Energy Storage Innovation System**

This section describes the functional patterns of the LDES technological innovation system (TIS) focusing primarily on the US. The aim of the functional analysis is to determine how key innovation processes are occurring in the innovation system. The functional patterns of a TIS help uncover the dynamics of the innovation system contingent upon the structure of the TIS. The functional analysis does not have any normative features. This means that the functional patterns are likely

to differ over different types of TIS and are also likely to change over time. There is no optimal or general pattern of TIS functions, that is, no one type of functional behavior is better than the other. There are seven key functions of a TIS and are outlined in Table 7.2. In the following subsections, each function is qualitatively and quantitative described based on the available data.

Function Number	Function Name	Description
F1	Knowledge Development	Captures the depth and the breadth of the current knowledge base of the TIS and how it has changed over time.
F2	Knowledge Diffusion	Exchange of knowledge between actors occurring through networks
F3	Entrepreneurial Experimentation	Captures the reduction in uncertainty in an innovation system through success and failures of entrepreneurial experiments
F4	Guidance of Search	Incentives and pressures that result in actors conducting innovative activities that drive the direction of innovation.
F5	Market Formation	Existence and creation of niche markets that enable new technologies to compete with incumbent technologies
F6	Resource Mobilization	Allocation of financial, human, and physical capital to support innovation in the TIS
F7	Legitimation	Support from existing institutions that enable competition within the existing system.

Table 7.2: Brief description of the functions of technological innovation systems

### 7.3.1 F1 Knowledge Development

A key measure in gauging the progress of knowledge development in the early stages of LDES technologies is the number of scientific publications. These publications serve as a tangible product of the research and development endeavors within this domain. Figure 7.6 shows a graphical representation of the number of scientific publications concerning electrochemical and thermal LDES technologies spanning from 2008 to 2022, provides valuable insights. The graph indicates a clear trend that there has been a consistent and substantial increase in the number of publications over this timeframe. This upward trajectory, culminating in a peak in 2022, signifies a robust surge in research activity within the LDES landscape. It is evident that the scientific community is actively engaged in exploring and advancing these technologies, underlining their growing significance on

the innovation frontier.

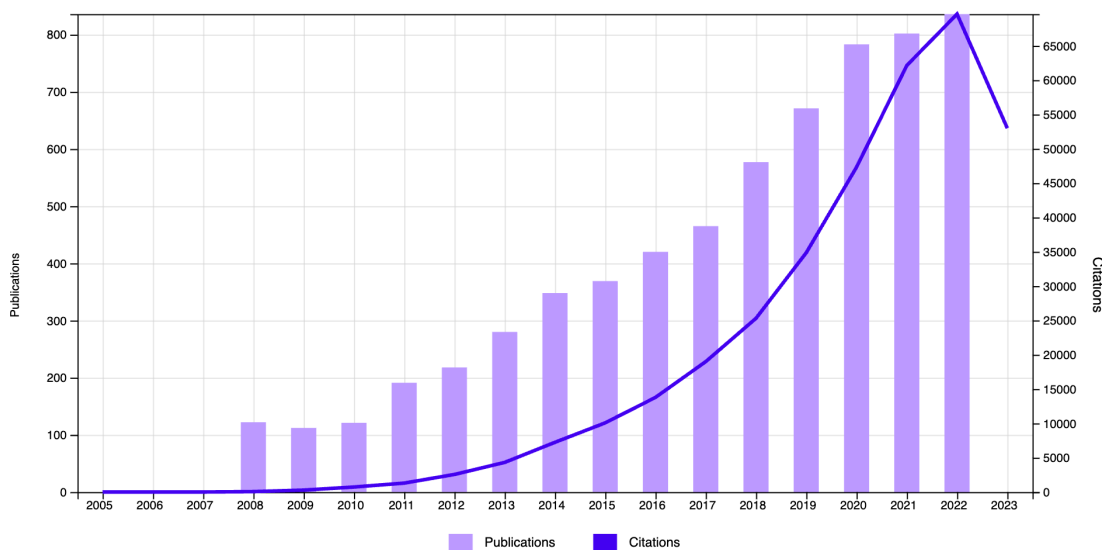


Figure 7.6: Total number of LDES publications and citations between 2008-2022

Figure 7.6 also elucidates another noteworthy aspect—the number of citations garnered by these publications. This measure is indicative of the impact and relevance of the research conducted. Over the same period, there has been a notable and consistent increase in the number of citations. This underscores not only the growing body of research but also its increasing influence within the scientific community and beyond. The 746% increase in the number of publications observed over this period underscores the expanding footprint of LDES technologies within the broader scientific discourse.

The combined data presented in Figure 7.7 portrays a vibrant landscape of research knowledge development within the LDES innovation system. It signifies a community of researchers and innovators fervently dedicated to advancing these technologies, as evidenced by the growing number of publications and their impact as measured by citations. This thriving research ecosystem bodes well for the continued evolution and maturation of LDES, positioning it as a promising frontier in energy storage innovation.

As knowledge development unfolds, a crucial juncture is reached when research endeavors begin to transition into the realm of intellectual property. This transition marks the critical bridge

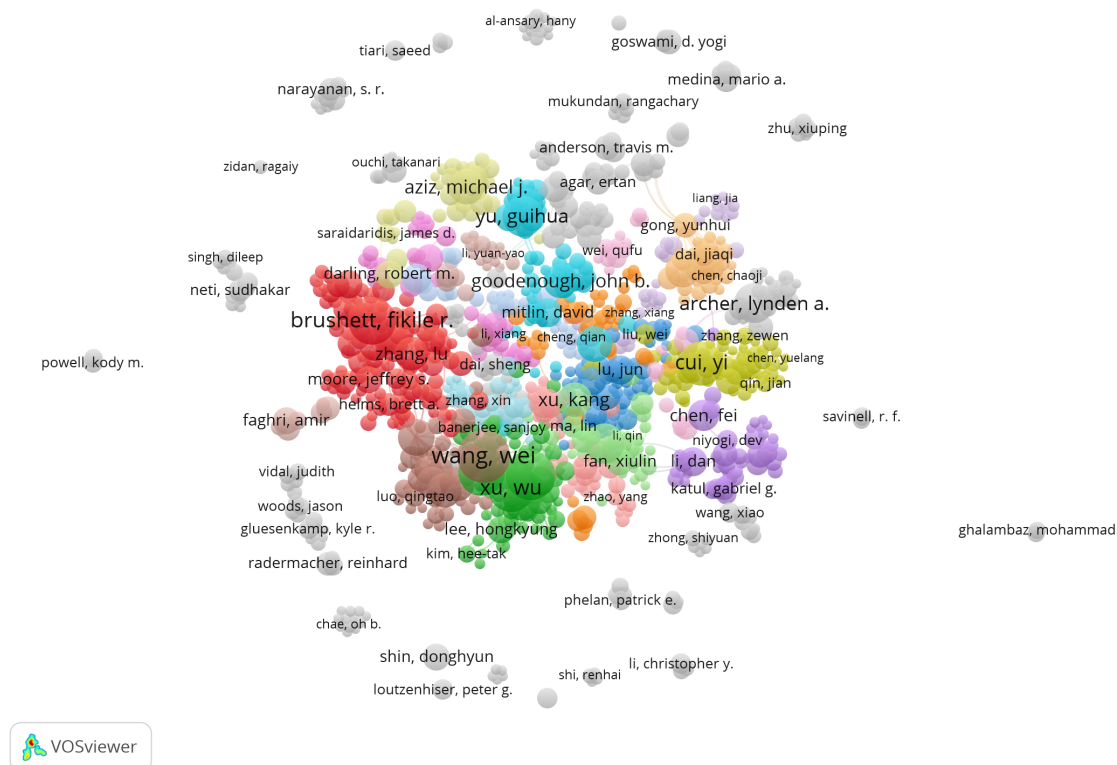


Figure 7.7: Networks of LDES researchers based on publications in Figure 7.6

between academia and commercialization and can be assessed through the lens of patent activity, both in terms of quantity and quality, within the domains of electrochemical and thermal LDES technologies. Figure 7.8 serves as a visual guide to understanding the dynamics of this stage from 2008 to 2022. One prominent observation within this graph is the steady ascent in patenting activity. This upward trajectory indicates knowledge development for the purpose of commercialization. It reflects the evolving landscape where scientific discoveries are transforming into intellectual assets with the potential for real-world applications. This positive trend indicates a robust system of innovation with an increasing emphasis on translating research into commercial value. However, it is essential to approach patent data with caution. Patents, though valuable indicators, are inherently "noisy" measures of innovation. They do not encompass the entirety of innovative

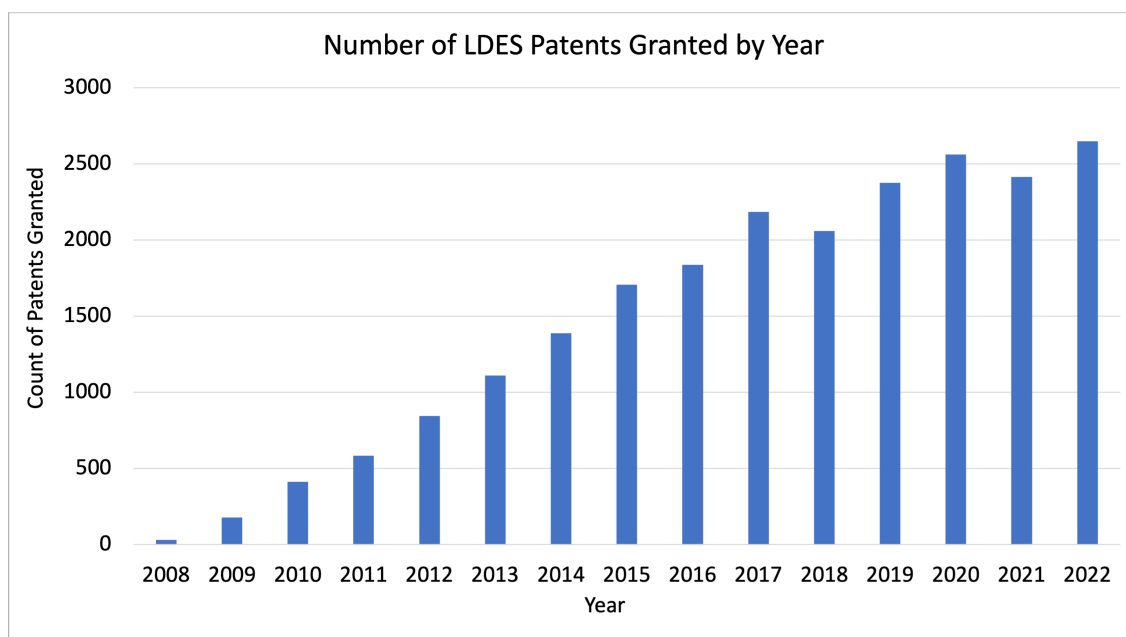


Figure 7.8: Count of LDES patents granted between 2008-2022

activity, as not all innovations are patented, and not all patented inventions necessarily result in successful commercialization [99]. Therefore, while patenting activity provides a broad overview of the journey from laboratory to market readiness, it should not be viewed as a precise measure.

In essence, 7.8 offers a glimpse into the evolving landscape of knowledge development within the electrochemical and thermal LDES domains. The increasing number of patents registered over the years is a promising sign of research transitioning toward commercial application. Yet, it is vital to bear in mind that innovation is a multifaceted and nuanced process, and patent data, while valuable, represents just one facet of this intricate journey.

In conjunction with research and patenting activity, the progression of knowledge from research to commercialization is exemplified by an upsurge in energy storage pilots and demonstration initiatives. While quantifying the exact number of pilots and demonstrations represents an ideal measure for characterizing the Long-Duration Energy Storage (LDES) innovation system, it remains a challenging task. This complexity arises because companies often opt not to disclose information pertaining to pilots and demonstration agreements with partners in order to safeguard their competitive advantage. Therefore, the number of pilots and demonstrations is a measure

of high influence for evaluating early-stage innovation systems in clean energy but is not readily accessible. However, qualitative analyses of reports and documents suggest that there has been a greater focus in supporting pilots and demonstrations in LDES. In 2021, the establishment of the Office of Clean Energy Demonstrations (OCED) by the Department of Energy (DoE) marked a significant step toward facilitating the scalability of emerging technologies. Notably, in 2023, the OCED announced funding for 9 long-duration energy storage test projects, with 5 of these projects focusing on grid-scale electrochemical long-duration storage and one project centered on thermal storage [136]

Based on the observed trends, two primary conclusions can be drawn. First, the LDES innovation system demonstrates a strong emphasis on research-driven knowledge advancement, evident from the substantial surge in publications, patents, and citations. Secondly, the recent support for pilot and demonstration projects, along with heightened investment in these initiatives, signifies a pivotal transitional phase within the innovation system, highlighting its movement towards practical application and commercialization.

### 7.3.2 *F2 Knowledge Exchange*

Measuring knowledge exchange within the Long Duration Energy Storage (LDES) innovation system presents a challenge, particularly when considering informal networks. To address this, an analysis of the co-authorship networks of LDES publications sheds light on the collaborative dynamics among researchers. This network visualization depicts a complex interconnection of LDES scholars in the United States, with closely clustered groups reflecting a tightly knit research community, interwoven with boundary-spanners facilitating collaboration across various research domains. Additionally, a thematic analysis of publication titles revealed four primary interconnected research areas: flow batteries, lithium metal batteries, general energy storage, and other pertinent topics, demonstrating the multidimensional nature of knowledge dissemination across diverse research communities.

[Add graphs] Figure 7.8

Furthermore, the shift of the LDES innovation system into its commercialization stage has spurred a heightened interest in pilot projects to translate research technologies into tangible ap-

plications. A qualitative examination of formal industry and academic networks of knowledge exchange has uncovered various key players and initiatives, summarized in 7.3

Knowledge Exchange Networks	Year Initiated	Types of Actors
Joint Center for Energy Storage Research (JCESR)	2012	13 universities, 6 national laboratories, and 1 industry partner
Energy Storage Summit USA	2018	394 industry and risk capital actors attended the summit in 2023 including utilities, technology developers and 1 national laboratory
Long Duration Energy Storage Council (LDES Council)	2021	[Add] Site was down
Long Duration Energy Shot Programs	2021	16 universities and 4 national laboratories

Table 7.3: Different knowledge exchange networks in the LDES technological innovation systems

Additionally, interaction across the university-industry divide can also be quantified by looking at the number and success of spin-off companies. 7.4 highlights LDES companies that are officially university spin-offs, or those who have emerged because of strong ties to the university research community. Spinoffs and companies with strong ties to a university comprise of 17.5% of the technology developers in the LDES innovation system, signifying the important role of universities as a launchpad for commercial innovation in this space. Further, insights garnered from expert interviews emphasize the pivotal role of national laboratories as critical testbeds for fostering innovation in the LDES domain. Collaborative efforts between corporate actors and these laboratories, such as the Pacific Northwest National Laboratory’s (PNNL) Grid Launchpad, showcase the significance of leveraging national laboratory infrastructure for piloting and validating novel technologies. Supported by the U.S. Department of Energy’s (DOE) Office of Electricity, the Grid Launchpad serves as a research and development facility, fostering partnerships across national laboratories and other actors to expedite the deployment of cutting-edge grid storage technologies. This concerted approach signifies a pivotal step in bridging the gap between research and commercialization within the LDES innovation landscape.

The key insight drawn from these observations underscores a pivotal conclusion: the research and development knowledge networks, with the likes of JCESR established back in 2012, have a

Spinout Startups	Year Founded	Spun out from	Notes
Ambri	2010	Massachusetts Institute of Technology (MIT)	Ambri was founded as The Liquid Metal Battery Corporation was formed in 2010 to commercialize the liquid metal battery technology invented by Professor Donald Sadoway and Dr. David Bradwell at MIT.
Form Energy	2017	Massachusetts Institute of Technology (MIT)	Form Energy MIT professor and battery expert Yet-Ming Chiang, former head of battery development at Tesla Mateo Jaramillo, Ted Wiley (Harvard Business School), William Woodford (MIT PhD and 24M Technologies), and Marco Ferrara (MIT PhD).
Malta	2018	Google	Malta was founded as part of Google’s “moonshot” programs based on thermal energy storage research being conducted by the X division of Google.
Noon Energy	2018	NASA (not officially)	Noon Energy was founded by Chris Graves who worked on a tool for NASA’s Perseverance Mars rover that snatches carbon dioxide out of the red planet’s atmosphere and converts it into oxygen. Graves adapted this process to store clean energy very cheaply for longer periods of time than commercially viable lithium-ion.
Electrified Thermal Solutions	2020	Massachusetts Institute of Technology (not officially)	Electrified Thermal Solutions was founded by MIT student Dan Stack based on his PhD thesis work.
EnerVenue	2020	Stanford University	EnerVenue’s nickel-hydrogen battery technology is based on the work of Stanford professor Dr. Yi Cui who also serves as the chairman of the company.
Thermal Battery Corporation	2022	MIT	Thermal Battery Corporation is a MIT spin out commercializing a grid scale rechargeable battery technology that has been developed at MIT and Georgia Tech over the last 10 years.

Table 7.4: Description of LDES spinouts from universities

more mature and established presence compared to the relatively nascent industry and spin-off knowledge networks. This contrast suggests that while the academic and research aspects of Long Duration Energy Storage (LDES) have a longstanding foundation, the commercial and industry-driven facets are in the early stages of development. This nascent stage indicates a recent surge in commercial interest and activity surrounding LDES technologies, signaling a promising trend in their adoption.

However, recognizing the recency of this commercial traction, it becomes imperative to actively nurture and expand these knowledge exchange networks. This strategic approach is essential not only to solidify the emerging industry networks but also to foster a robust ecosystem for spin-off ventures. Building and reinforcing these networks are crucial steps toward instilling market confidence in the value of LDES technologies. Such confidence is vital for garnering support from actors, investors, and the broader market, ultimately serving as a catalyst to accelerate the pace of innovation in the LDES landscape. In essence, the call to action is clear: further cultivating and strengthening these knowledge exchange networks, can propel LDES technologies into a position of

greater prominence and viability within the energy market.

### *7.3.3 F3 Entrepreneurial Experimentation*

Entrepreneurial experimentation is a critical aspect of innovation and involves the process of translating knowledge into viable business opportunities. In essence, it represents the bridge between the conceptualization of novel technologies and their practical application, fostering innovation within emerging sectors. This type of experimentation is primarily spearheaded by an entrepreneur who performs market-oriented experiments that drive the commercialization of emerging technologies and result in the evolution of institutions around those technologies. However, it is important to acknowledge the inherent challenges in assessing entrepreneurial experimentation, particularly within emerging sectors. Often, available data tends to be skewed, heavily favoring successful experiments, while the valuable lessons gleaned from unsuccessful ventures remain unreported. In quantifying entrepreneurial experimentation, several key quantitative measures come into play. One of the fundamental measures involves evaluating the sheer number of enterprises operating within a specific domain. Figure 7.9 illustrates this by showcasing the total count of companies engaged in the development of both electrochemical (N=19) and thermal (N=21) technologies within the LDES landscape. The chart highlights a noteworthy observation - there exists a nearly an equal distribution of companies across both thermal and electrochemical storage sectors. This parity implies a parallel level of entrepreneurial experimentation in both technology domains.

To understand the growth of entrepreneurship in LDES, Figure 7.10 depicts the number of LDES companies founded in different years. It is worth noting that companies founded prior to the year 2000 predominantly comprise major corporations such as Raytheon, Schlumberger, Siemens, and the like. These industry giants are not only engaged in the development of LDES technologies but have also occasionally sought to strengthen their capabilities through acquisitions of LDES.

The trajectory of companies being founded unravels some interesting insights. Notably, there's a discernible upswing in the number of LDES companies founded between 2008 and 2011. This uptick in entrepreneurial activity overlaps with what is often referred to as "Cleantech 1.0." During this period, venture capital firms poured a staggering \$25 billion into ventures dedicated to clean energy solutions. However, 90% of Series A investments in Cleantech 1.0 ventures failed to deliver

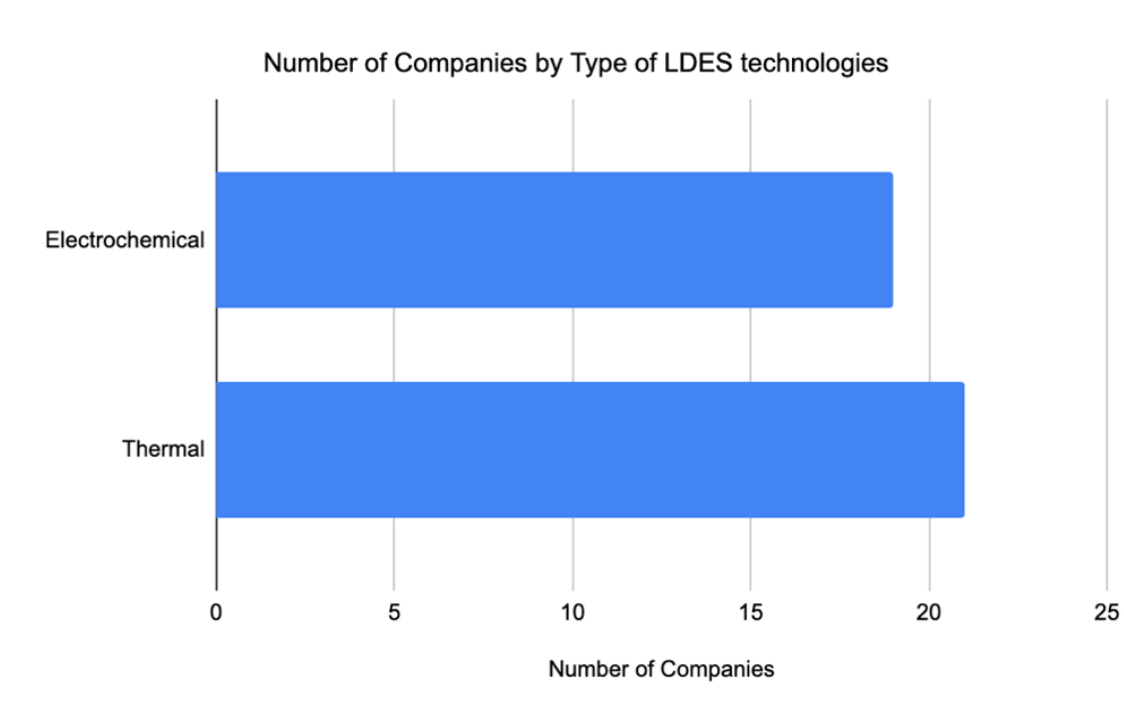


Figure 7.9: Count of LDES companies by technology type

the expected returns [78]. This high rate of investment failure, coupled with the global financial crisis of 2008, created a perfect storm, causing private capital for clean tech entrepreneurship to dwindle. This confluence of events explains the subsequent dip in the number of companies emerging in the LDES domain between 2010 and 2013. Around 2017, there once again is an uptick and a more consistent and sustained resurgence in entrepreneurial experimentation within the LDES landscape. In essence, this figure shows the interplay between economic landscapes, technological trends, and the entrepreneurship.

The average age of a startup in the LDES domain is 10 years and the average amount of funding raised by these companies is \$96.77 million. However, as 7.11 shows, the distribution of funding is heavily skewed towards the right. Consequently, a more nuanced measure, the median funding of \$61.44 million, provides a more representative perspective. Amid this distribution, a standout outlier emerges in the form of Form Energy, an electrochemical LDES company that emerged from the Massachusetts Institute of Technology in 2017. Form Energy's meteoric rise, bolstered

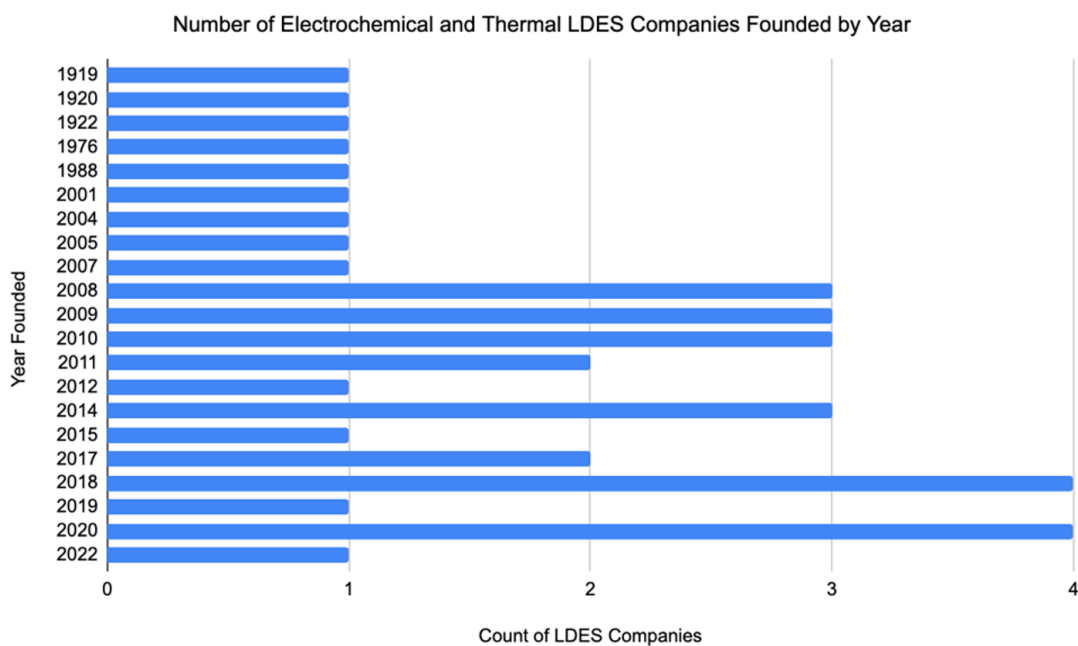


Figure 7.10: Number of LDES startups and companies founded by year

by an astounding \$816 million in funding, merits closer inspection. While technological prowess certainly contributes to their success, a significant part of this phenomenon can be attributed to the credentials of the company’s founders, Mateo Jaramillo, and Yet-Ming Chiang. Jaramillo, the former head of battery development at Tesla, and Chiang, a renowned battery expert, bring not only technical expertise but also credibility and brand value to the table. These attributes instill confidence in investors, underscoring the pivotal role that experienced and reputable founders can play in securing substantial funding for LDES ventures.

However, the LDES sector remains a volatile arena, as exemplified by the recent bankruptcy of Azelio, a seemingly promising thermal LDES company in 2023. Prior to its closure, Azelio had managed to raise \$126.2 million, indicative of significant traction in the market. Nevertheless, its inability to secure sufficient financing for negotiations with a potential strategic partner led to its unfortunate exit. This highlights the unpredictable nature of the LDES landscape, where success is far from guaranteed.

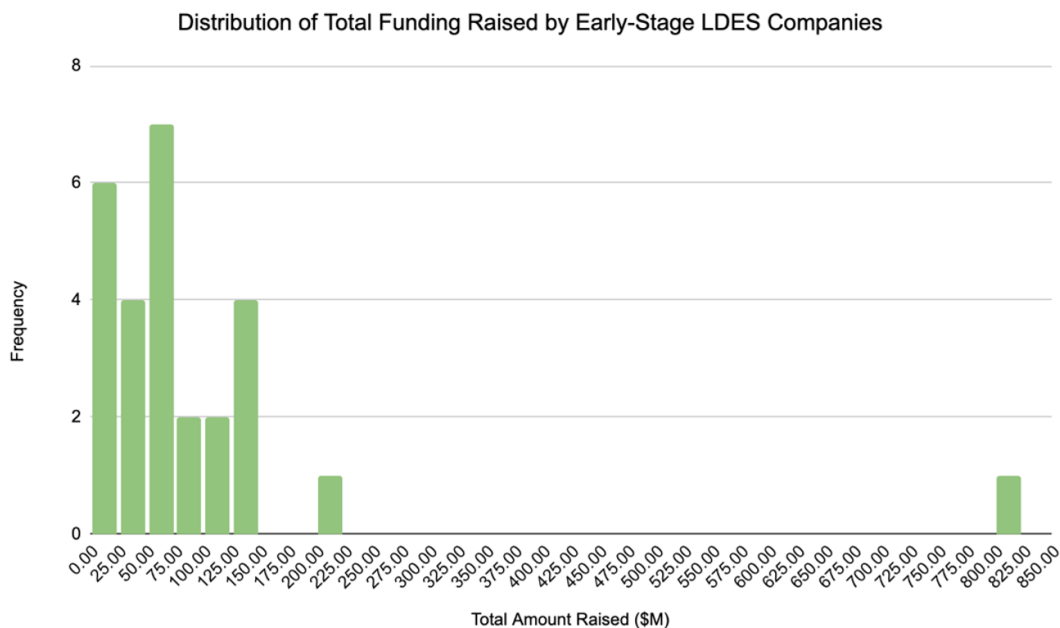


Figure 7.11: Distribution of total funding raised by LDES early-stage companies (in \$M) between 2008-2022

Expert insights from interviews shed light on the persistent challenges faced by LDES technologies in securing funding and carving a niche in the market. The crux of the issue lies in the current cost competitiveness of emerging LDES technologies. Both thermal and electrochemical LDES technologies find themselves in direct competition with mature technologies like lithium-ion storage and natural gas. These incumbents benefit from well-established manufacturing processes and supply chains, rendering them formidable adversaries. To emerge as genuine contenders, LDES technologies must reduce costs by 45-50% while concurrently enhancing their round-trip efficiency by 7-15% before 2030. This challenge presents a classic causality dilemma. On one hand, capital infusion is imperative to conduct demonstration and pilot projects that can drive the advancement of LDES technologies, making them more cost-effective and efficient. On the other hand, these technologies need to exhibit cost efficiency and efficacy to attract the necessary capital. The interplay of all these factors underscores the intricacies of the LDES landscape, where technological

improvement, capital, and market readiness converge to shape the future of long-duration energy storage.

The analysis of Entrepreneurial Experimentation within the Long Duration Energy Storage (LDES) innovation system leads to some key conclusions. First, there has been a notable surge in entrepreneurial experimentation since 2018, signifying a crucial shift from research and development to the commercialization phase of the innovation system. This shift is indicative of a dynamic landscape where novel technologies are transitioning into practical applications. However, the second conclusion underscores the persisting challenges and market barriers accompanying this transition, illustrated vividly by the bankruptcy of Azelio. This case serves as a stark reminder that, despite the increased entrepreneurial activity, the LDES sector is not immune to uncertainties and setbacks. Insights from expert interviews shed light on the formidable competition LDES technologies encounter from established technologies like lithium-ion storage and natural gas. Moreover, there exists a prevailing hesitancy and lack of confidence in recognizing the value proposition of LDES, leading to cautious support for pilot and demonstration projects initiated by new startups. This cautious approach highlights the need for a concerted effort to enhance awareness and understanding of the potential benefits offered by LDES technologies, addressing a critical aspect of market readiness and acceptance.

#### *7.3.4 F4 Guidance of Search*

A fundamental prerequisite for development of a TIS is the presence of compelling incentives and pressures that signal new firms and organizations into the innovation ecosystem. At its core, the "Guidance of Search" function serves as the compass that influences the trajectories of exploration within the TIS. It determines the avenues of inquiry, the focal points of research and development, and the target domains within the landscape of competing technologies, applications, markets, and business models. This guidance emerges from a complex interplay of factors—visions, expectations, beliefs, roadmaps, regulations, and more—introduced by the different actors in the TIS.

Quantifying the "Guidance of Search" function is not a straightforward task. Its impact can be assessed through both quantitative and qualitative measures, contingent upon the specific context of the innovation system. In the context of Long-Duration Energy Storage (LDES) technologies,

the "Guidance of Search" function is driven regulatory frameworks, policy initiatives, and strategic roadmaps. Within the United States, this guidance of search is notably shaped by a confluence of federal and state-level initiatives 7.5.

Key Signals	Level	Description
Net Zero Emissions by 2050 100% Carbon-pollution free electricity by 2035	Federal	In 2021, President Biden's administration issued executive order 14057 on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability and set policy targets on achieving carbon pollution-free electricity sector by 2035 and net-zero emissions economy-wide by no later than 2050.
Electric Storage Participation in Markets Operated by Regional Transmission Organizations and Independent System Operators, Order No. 841 and Order No. 2222		Order directing regional energy system operators to remove barriers for energy storage in wholesale markets, paving the way for energy storage resources to participate fully in energy, capacity, and ancillary services markets.
Renewable Portfolio Standards	State	Renewable portfolio standards (RPS) are policies designed to increase the use of renewable energy sources for electricity generation. RPS are state level policies that different states can choose to enact.
Mandates for Achieving 100% clean or net-zero energy by 2050		22 U.S states also have a target for 100% renewable energy or 100% carbon-free electricity by certain dates.
Energy Storage Procurement Targets and Incentives		Procurement targets require utilities to obtain specified quantities of energy storage, typically by a specified deadline. They have generally been adopted in cases where a state has identified specific issues that storage may address, and existing practices may prevent storage from adoption. Procurement targets also provide a supportive signal for investment and reduce regulatory uncertainty associated with new technologies
Demonstration Projects		Demonstration projects can help states in understanding the logistics and benefits of energy storage deployment. These projects have highlighted various operational and economic characteristics of energy storage in low-risk, low-cost settings, leading to a better grasp of permitting challenges, construction obstacles, and deficiencies in current building and electric codes.

Table 7.5: Key federal and state level policies that have driven the "guidance of search" function of the LDES TIS

### *The role of Federal Policy and Federal Research Funding*

At the federal level, the Biden administration's commitment to achieve Net Zero emissions by 2050 and the target of 100% carbon-pollution free electricity by 2035 are stimulating innovation in the nation's energy landscape including for LDES technologies [52]. They not only establish a clear trajectory but also elevate the sense of urgency, compelling innovation to address the pressing challenges of sustainability. In 2018, the Federal Energy Regulatory Commission (FERC) issued Order 841, which directed regional energy system operators to remove barriers for energy storage in wholesale markets. The order allows for full participation of energy storage resources in energy, capacity, and ancillary services markets. Successively, in September 2020, FERC issued Order 2222, allowing bundled behind-the-meter distributed energy resources to participate in wholesale energy

markets. The order defines distributed energy resources to include electric storage, among other technologies further opening up a market for energy storage technologies.

The U.S. Department of Energy (DoE) has emerged as a key player in the "Guidance of Search" narrative. The Energy Storage Grand Challenge, initiated in 2020, articulates the DoE's vision for energy storage. It envisions a diversified portfolio of LDES technologies, fostering innovations that improve manufacturing costs, and nurture collaborative knowledge exchange between laboratories and external partners [117]. This comprehensive strategy has fueled the LDES ecosystem, propelling it to achieve breakthroughs. Moreover, The U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) unveiled the Long Duration Storage Shot in 2021, an Energy Earthshot program. This initiative sets its sights on reducing storage costs by a staggering 90% within a single decade for systems delivering 10+ hours of storage. It serves as a testament to the federal government's unwavering commitment to LDES innovation [135].

### *The Role of State Policy*

Beyond the federal sphere, individual states have emerged as important propellers of innovation, each forging its distinctive approach. 23 states have established binding or nonbinding mandates for achieving 100% clean or net-zero energy by 2050. Fueling these overarching goals are Renewable Portfolio Standards (RPS), which 39 states have committed to. These standards steer innovation by mandating specific percentages of electricity to be sourced from renewable resources. Specifically of interest in the LDES context, are carve-outs. Carve-outs are policies built into a state's RPS that ensure the development of specific renewable technologies. They can help states fuel investment in parts of the energy market that may need some help to get started by creating demand for specific technologies. These requirements and standards are pushing the adoption of renewable sources of energy in US, guiding the need for long duration storage technologies to help combat the variability that comes with renewable energy.

State legislatures across the US have increasingly focused on bolstering the role of energy storage in their efforts to achieve clean energy goals. The National Conference of State Legislatures (NCSL) has reported a significant surge in energy storage-related measures, with over 260 bills tracked in 2019 and 2020, compared to 88 bills in the preceding two years. Some states, including California

and Oregon, were early adopters of energy storage legislation, establishing procurement targets as far back as 2010 and 2015, respectively. California has implemented aggressive procurement targets and incentive programs for large-scale and residential energy storage. Other states like Nevada and Colorado have enacted legislation directing their public utilities commissions to establish energy storage procurement targets. Nevada's SB 204 led to the establishment of a 100 MW target by 2020, escalating to 1,000 MW by 2030. Similarly, Colorado's HB 1270 mandated the development of rules for utility procurement of energy storage resources.

Furthermore, various states have pursued energy storage initiatives through regulatory means, integrating storage into broader clean energy legislation aimed at decarbonization. Massachusetts, New Jersey, New York, Washington, and Virginia are among the states that have implemented or proposed clean energy laws with provisions promoting renewable energy and energy storage technologies. These initiatives include establishing energy storage procurement goals, designing programs to benefit disadvantaged communities, and setting targets for the installed capacity of clean energy resources. In Virginia, for instance, the Clean Economy Act requires the acquisition or construction of at least 3.1 GW of energy storage resources by 2035, as part of a comprehensive strategy to achieve a carbon-free economy [141]. These initiatives open doors for the advancement of long duration energy storage technologies. Additionally, several states including Washington and Massachusetts have funded demonstration storage projects which allows them to identify how different types of battery storage can serve their respective electricity and storage needs.

Additionally, there has been a notable shift in the landscape of utility-scale storage in the United States between 2010 and 2017, with non-pumped hydro and compressed air resources experiencing a significant surge from approximately 50 MW to over 1100 MW. Further, the cost of a lithium-ion batteries saw a reduction from approximately \$1000 per kilowatt-hour (kWh) to around \$200 per kWh during the same period [192]. These findings underscore the influence that various state mechanisms, guiding the exploration of energy storage solutions, can exert on the cost trajectory of emerging technologies. The evident association between policy-driven initiatives and the declining costs of energy storage technologies emphasizes the critical importance of implementing tailored, state-level long-duration storage policies and solutions to further bolster the advancement of energy storage initiatives nationwide.

In sum, the "Guidance of Search" in the realm of LDES technologies is joint effort of federal

and state policies, complemented by strategic initiatives from the U.S. Department of Energy. The interplay of these factors is shaping the search for transformative long-duration storage solutions that can power a reliable and resilient energy grid. The acceleration of these activities since 2020, catalyzed by the Biden administration's ambitious net-zero targets, underscores the dynamism of the LDES innovation landscape.

Additionally, actors' perceptions serve as a compass, revealing both the progress made and the hurdles yet to be overcome on the journey toward commercialization. While federal policy goals and roadmaps have set a promising stage for the "Guidance of Search" function, it's essential to understand that the impact of these initiatives is an unfolding narrative.

- **Uncertain Path:** Interviews with experts underscore a sense of ambiguity surrounding the developmental trajectory of LDES technologies. While pumped hydroelectric storage stands as a mature and efficient option, its large size and steep capital requirements hinder its widespread adoption. The dilemma arises when choosing between electrochemical and thermal LDES technologies, as experts abstain from making definitive bets. This reluctance signals a lack of confidence in the success of these technologies, with both options still unproven at scale and over time, directly hindering the "Guidance of Search."
- **Investment Hesitation:** The hesitation from investors and customers to embrace electrochemical and thermal LDES technologies stems from their unproven track records. In the world of innovation, skepticism often shadows untested technologies, resulting in cautious financial backing and adoption. While federal policies and roadmaps create a conducive environment, they fall short of providing the granular, binding goals required to ignite the commercialization. This hesitancy among investors and customers, in turn, leads to insufficient resource allocation for the "Guidance of Search" process, particularly in commercial markets, hindering the emergence of a dominant LDES technology.
- **The Incumbent Challenge:** A recurring theme emerges in actor perspectives—the inclination toward the tried-and-tested incumbent, lithium-ion long-duration storage. Incumbent technologies wield a formidable advantage, particularly in terms of reliability and cost-effectiveness for short-duration applications. However, as the duration requirements stretch,

their appeal wanes due to escalating costs. This incumbent favoritism creates a divergence in the guidance of search, steering industry players away from the novel LDES solutions.

The findings in this section illuminate critical aspects of the Guidance of Search process in Long-Duration Energy Storage (LDES) innovation systems. Firstly, the federal government has played a pivotal role in nurturing the research and development phase of LDES technologies through substantial funding programs. Moreover, it has established policy goals and incentives that lay the groundwork for the potential commercial adoption of LDES. However, given the dependency of the energy system on local conditions, the influence of state governments becomes even more significant. States play a paramount role in shaping regulatory frameworks and policy incentives at a local level, which can act as catalysts for the widespread adoption of LDES technologies on a large scale. Despite states crafting policies to support grid-scale energy storage, there exists a potential challenge. The incentives designed may not be comprehensive enough to propel the adoption of Long-Duration Energy Storage (LDES), potentially allowing lithium-ion (Li-ion) storage to persist as the dominant market force. This diversion in the Guidance of Search could shift focus away from grid-scale LDES solutions towards grid-scale Li-ion solutions. Actor interviews echo this concern by underscoring the unproven nature of LDES technologies. This uncertainty acts as a significant barrier, impeding widespread adoption and causing hesitation among investors. This, in turn, poses a challenge to the Guidance of Search, hindering the exploration and adoption of successful grid-scale LDES solutions. Addressing these uncertainties and investor concerns is crucial to steering the Guidance of Search towards the successful integration of Long-Duration Energy Storage into the grid infrastructure.

A crucial thing to note about this function is that there are no explicit quantitative indicators used to evaluate the guidance of search other than federal research funding. This activity for the LDES innovation system has been assessed by analyzing the number of policies that guide search and their impact, both which can be better measured and assessed. Therefore, a missing measure here would be evaluating and tracking the number of policies that guide search in the direction of LDES technologies and operationalizing their impact.

### 7.3.5 F5 Market Formation

In newly emerging TIS such as the one for LDES technologies, the formation of robust markets plays a pivotal role in shaping the trajectory of emerging technologies. Currently, the LDES market operates within the framework of a "nursing market," characterized by its nascent state and the urgent need for further development to create a fertile ground for the flourishing of a TIS. This status is primarily due to the early stages of market development where demand remains in its infancy and the price-performance dynamics have yet to attain competitiveness. Moreover, the emerging electrochemical and thermal technologies within the LDES sector encounter obstacles such as underdeveloped supply chains and manufacturing processes, impeding their progress [16]. To grasp why the LDES market is a nursing market, it is imperative to quantify the timing, scale, and nature of the markets that have materialized. Several crucial measures serve to illuminate the process of market formation:

- **Active LDES Firms:** A significant indicator of market formation is the number of active LDES firms. Currently, there are approximately 40 such firms operating in the LDES landscape. However, it is important to note that this number is not static, and the continuously evolving nature of innovation suggests the emergence of other early-stage companies, contributing to the dynamic market. Most of these companies are less than 25 years old and are in the initial stages of technological development, with a few well-established industry leaders, such as Siemens, developing their own LDES solutions. The presence of a mix of companies without a clear market leader underscores the immaturity of the market.
- **Current and Planned LDES Capacity:** Another vital measure for assessing market formation involves the evaluation of existing and projected LDES capacity. Examining the broader landscape of battery capacity in the United States provides valuable insights. According to the U.S. Energy Information Administration (EIA), battery storage capacity has witnessed a rapid surge, particularly since 2020. In 2022, the U.S. boasted 7.8 GW of utility-scale battery storage in operation, with an anticipated addition of another 20.8 GW of battery storage between 2023 and 2025 [61]. Notably, over 75% of this planned capacity is concentrated in Texas and California. This significant expansion in grid-scale battery capacity

signifies a promising market for grid storage. However, much of the planned grid storage capacity is currently expected to be fulfilled by lithium-ion batteries. Therefore, an increase in planned storage capacity does not directly imply a clear win for LDES technologies, given stiff competition from lithium-ion.

The U.S. Department of Energy's Liff report illustrates that a net-zero grid could include 60-460 GW of LDES by 2050 under different modeling scenarios, indicating a substantial market opportunity for LDES players. However, the report also highlights the need for a substantial capital investment of approximately \$330 billion to scale LDES technologies. The report outlines three scenarios, including the Business-as-Usual Scenario, Net Zero by 2050 (with LDES), and Net Zero by 2050 (no LDES), demonstrating the potential impact of LDES technology on the energy landscape:

1. **Business-as-Usual Scenario:** This scenario represents the current trajectory of energy development. It includes the effects of the 2022 Inflation Reduction Act but does not incorporate any interventions related to LDES commercialization.
2. **Net Zero by 2050 (with LDES):** In this scenario, the focus is on achieving Net Zero emissions by 2050, if LDES successfully scales and is integrated into the energy landscape.
3. **Net Zero by 2050 (no LDES):** This scenario, too, aims for Net Zero emissions by 2050 but does not incorporate LDES technology.

The DoE liftoff report demonstrates models of LDES capacity and its potential to displace a significant portion of new natural gas capacity, emphasizing the lucrative market opportunity for LDES technologies and their critical role in the transition towards a sustainable energy grid [52]. However, the competitiveness of novel electrochemical and thermal storage within the LDES market is contingent on the cost competitiveness of lithium-ion batteries, with direct competition expected, especially in scenarios involving shorter durations. It is anticipated that around 85% of the inter-day LDES market will be dominated by lithium-ion batteries, potentially limiting the market prospects for LDES in this category.

The commercialization of LDES technologies is intimately dependent on cost and performance trajectory of lithium-ion batteries. Currently, lithium-ion batteries excel in shorter duration applications and high-frequency cycling. These batteries have predominantly evolved due to substantial capital investments in the electric vehicle industry, epitomized by the rise of companies like Tesla. Consequently, contemporary configurations of lithium-ion batteries possess characteristics such as high energy density, high power density, high roundtrip efficiency, and compact size, all of which are highly desirable for electric vehicles. However, not all these features align with the requirements of grid-level storage. In a grid application, features like energy density lose their significance since grid storage doesn't necessitate mobility. Conversely, grid storage demands a longer lifespan and more extensive cycles compared to what lithium-ion batteries can currently offer. Attempting to stack lithium-ion batteries to provide extended-duration grid storage proves to be inefficient and costly, as these batteries are not engineered for extended-duration storage [4]. This very aspect forms the foundational argument in favor of new thermal and electrochemical LDES technologies, addressing a crucial gap in the energy storage market.

Nevertheless, the extent to which LDES technologies can compete with lithium-ion, especially for shorter duration applications (inter-day storage), fluctuates significantly. In moderate scenarios considering Li-ion cost and performance improvements, LDES technologies have the potential to deploy around 274 GW of inter-day capacity by 2050, surpassing the 40 GW of Li-ion deployment. The competitiveness threshold for LDES in this scenario entails achieving moderately to high roundtrip efficiency (60%+) and ensuring long system life (at least 20–25 years). On the other hand, aggressive scenarios for Li-ion improvements, with substantial cost reductions and enhanced performance, can lead to Li-ion dominance in many shorter duration applications, resulting in 35 GW of inter-day LDES deployment compared to approximately 317 GW of Li-ion. Nevertheless, multi-day and multi-week LDES solutions remain optimal for extended durations, anticipating a deployment of approximately 197 GW. As of the present, most electrochemical and thermal LDES technologies are positioned in various stages of Research and Development (R&D), pilot testing, or demonstration.

The findings in this section elucidate that despite the large market opportunity and compelling necessity for LDES technologies, significant barriers persist. One of the most prominent challenges lies in the "lack of market" perception. Over half of the experts interviewed share the belief that

the primary hurdle impeding the commercialization and scaling of LDES technologies is the current absence of a robust market. Potential customers and users have yet to recognize the value proposition presented by emerging LDES technologies within the existing energy landscape. Existing market mechanisms were originally designed to accommodate systems reliant on conventional fossil-fuel-based energy sources, with limited integration of grid-scale variable renewables or storage. Consequently, the flexibility and resilience provided by long-duration grid-scale storage are not fully appreciated within these markets. Simple measures like the levelized cost of energy (LCOE) fall short in quantifying the value of energy storage in comparison to alternative methods of electricity generation on the grid [98]. Therefore, the industry faces a pressing need for new market mechanisms and measures that can accurately assess and attribute value to long-duration storage capacity on the grid, allowing emerging LDES technologies to be truly valued, establish a market presence, and achieve scalability. Therefore, while there is a large market opportunity in grid-scale energy storage, it remains to be seen how much of that market will be captured by novel electrochemical and thermal LDES technologies.

### 7.3.6 F6 Resource Mobilization

The advancement of any emerging Technological Innovation System (TIS) hinges on the effective mobilization of critical resources, encompassing human capital, financial capital, and an array of complementary assets such as products, services, networks, and infrastructure. There are various avenues through which analysts can gauge the extent of resource mobilization, including:

1. **Capital Volume:** Measuring the volume of capital invested in the sector, which encompasses public and private funding sources, is a fundamental indicator. This includes both government investments and private venture capital.
2. **Seed and Venture Capital:** Focusing on the volume of seed and venture capital invested in the sector, as these early-stage investments are often crucial for technology development and commercialization.
3. **Human Capital:** Assessing the number of individuals engaged in the sector who possess advanced degrees or specialized expertise, highlighting the intellectual resources dedicated to

innovation.

However, gathering comprehensive resource mobilization measures in emerging sectors, particularly those related to private capital, poses significant challenges. This is primarily due to the confidential nature of much of this data, especially concerning private investment. While government funding sources are generally more transparent and publicly reported, they often represent only a portion of the overall investment landscape. In contrast, early-stage venture capital and angel investment measures are frequently not readily available. Many investment funds choose to keep their investments in early-stage companies confidential to maintain a competitive edge in building their portfolios. This secrecy can lead to under reporting of early-stage venture funding activities, as smaller companies and venture funds may be inclined to withhold data if they are not performing well. Moreover, unless a company or fund is publicly traded, making their financial information accessible through Securities and Exchange Commission (SEC) filings, much of the data regarding early-stage venture funding relies on self-reporting. This self-reporting introduces the potential for bias, as smaller companies and venture funds may be hesitant to disclose less favorable financial details.

Given these inherent challenges and data gaps, the information presented here provides a snapshot of the resources being utilized in the LDES sector. While not exhaustive, it offers insights into the dynamics of resource mobilization within this emerging technological landscape.

### *Federal Capital*

Table 7.6: Key LDES Federal Funding Programs

Organization Name	Total Funding (in \$ million)
ARPA-E DAYS Program	39.45
DoE Office of Clean Energy Demonstrations	325
DoE Office of Electricity Energy Storage Grand Challenge	30
DoE Office of Electricity Grid Storage Launchpad Facility	75

Table 7.6 shows the amount of funding allocated by different federal programs to drive the invention and commercialization of LDES technologies.

### *Seed and Venture Capital*

Early-stage investment in LDES technologies has boomed since 2020, coinciding with the Biden Administration's Net Zero by 2050 policy goals. Note that 2021 has an unusually large amount of capital invested, this is because of a reverse merger of ESS (a battery storage company) with ACON S2 for \$1 billion. After 2008 and until 2020, venture funding for LDES technologies is lower due to the 2008 financial crisis. The increase in funding since 2020 signals that more resources are being made available for the commercialization of electrochemical and thermal LDES (See Figure 7.12).

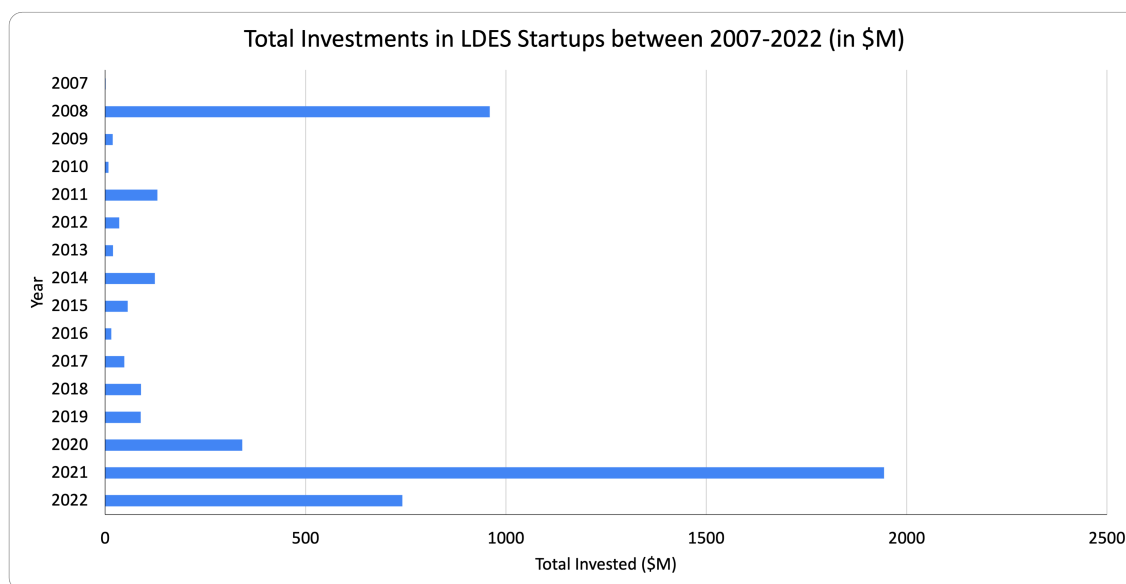


Figure 7.12: Count of LDES companies by technology type

### *Human Capital*

In 2022, within the transmission, distribution and storage sector of clean energy, battery storage had the most jobs, employing 72,923 workers. Just under one-fifth (13,600 or 18.6%) of battery storage

jobs are in manufacturing. This was nearly nine times the 8,333 employed in pumped storage hydropower, the next largest storage sector in terms of jobs. Employment in other technologies ranged from 70 in nuclear storage to 1,928 in mechanical storage [51]. However, note that jobs in distribution and storage may not directly translate to jobs in LDES. The chemistry, supply, and manufacturing of LDES storage is different from lithium-ion batteries. Therefore, expertise in the incumbent lithium-ion space does not imply expertise in LDES.

The findings underscore pivotal insights into resource mobilization within the LDES innovation system. Firstly, the robust backing from federal initiatives, exemplified by substantial funding in programs like ARPA-E DAYS and the DoE's Energy Storage Grand Challenge and Grid Storage Launchpad Facility, has propelled the research and development of LDES technologies. Secondly, the impetus provided by federal policies, notably the Net Zero by 2050 objectives, has ignited increased venture capital and seed investments, indicating a concerted effort to expedite the commercialization of LDES. The surge in private investment, particularly in seed and venture capital since 2020, reflects an increasing interest in advancing LDES technologies commercially. Despite this positive momentum, challenges persist in obtaining comprehensive private investment data, including confidentiality issues and underreporting, impacting a holistic understanding of resource mobilization. Additionally, the pivotal role of battery storage in job creation within the clean energy sector is noteworthy. With a significant workforce employed in this domain, including almost one-fifth in manufacturing, there's a potential human capital ready to contribute to the LDES space. In conclusion, the resource mobilization landscape for the LDES innovation system appears promising, with concerted investments from public, private, and human resources propelling the growth of storage technologies, poised to benefit the burgeoning LDES sector.

### *7.3.7 F7 Legitimation*

Legitimation is the process through which a new technology gains acceptance and approval within existing institutional frameworks. This acceptance is a fundamental prerequisite for the successful development and evolution of new Technological Innovation Systems (TISs). Legitimacy, however, is not a passive state that is automatically bestowed upon a new technology. Instead, it is a dynamic and evolving process that necessitates active engagement from a many organizations and

individuals. The new technology must find acceptance within the established institutional structures and norms that govern the relevant industry or sector. This entails aligning with existing regulations, standards, and practices. A variety of actors, including industry players, regulatory bodies, research institutions, and consumers, play critical roles in the legitimization process. These actors must actively engage with the technology, either through its development, testing, or utilization. Incumbent organizations and technologies can often act as barriers to the legitimization of new technologies. Resistance to change is a common challenge that emerging technologies must confront and overcome.

In the context of LDES, legitimacy has come from the ambitious goals set by the Biden Administration, specifically the Net Zero 2050 objectives, and the transformative Infrastructure Investment and Jobs Act. These policy mandates have spurred a substantial influx of federal capital into the realm of clean energy initiatives. The impact of these policy instruments on legitimizing innovation in LDES is palpable, as discussed in the preceding sections. Despite the absence of explicit LDES policies or carve-outs, expert insights gleaned from interviews reveal a growing acknowledgment of LDES value on the grid among key actors such as utilities and state energy commissions. However, the journey to comprehensive acceptance is nuanced. Actors, as revealed by both preceding sections and expert interviews, exhibit a degree of hesitancy regarding the potential value that LDES technologies can deliver. This hesitancy is rooted in the unproven nature of LDES, its associated high capital costs, and the formidable competition posed by incumbent technologies like Li-ion.

The lack of full legitimation from these market-oriented actors is pivotal; without it, the commercial adoption of LDES technologies faces a substantial risk, potentially leading to the failure of the LDES innovation system. To garner further legitimation, LDES technologies must undergo rigorous validation through pilots and demonstrations, ideally at lower capital costs. This strategic move is poised to position LDES as a competitive option for grid-scale storage, thereby bolstering its acceptance in the market. Furthermore, adjustments in market and regulatory mechanisms are imperative. Recognizing and valuing long-term grid reliability and resilience will be pivotal in enhancing the perceived value of LDES technologies in a future cleaner grid scenario. This realignment can elevate the legitimacy of LDES, positioning it not merely as a technological innovation but as a valuable component contributing to the robustness and sustainability of the evolving energy landscape.

### 7.3.8 Evaluative Measures of LDES Innovation

The preceding sections provided an overview of the U.S. Long Duration Energy Storage (LDES) technological innovation system, delving into its structure and functions, while examining the inducement and blocking mechanisms influencing its trajectory. Integral to this analysis were multiple evaluative measures, including publications, patents, and the proliferation of startups within the LDES TIS (refer to Table 7.7 for a comprehensive summary). These measures offered valuable insights into the current state of the LDES TIS, shedding light on its developmental phase and serving as a catalyst for a more comprehensive investigation into the hurdles impeding its progress. Nonetheless, it is imperative to acknowledge that while these measures effectively serve as benchmarks for evaluating innovation activities within the system, their applicability in driving actionable insights for diverse actors can be limited.

TIS Function	Measures
F1 Knowledge Development	Number of publications and citations over time, patents
F2 Knowledge Exchange	Co-authorship network, interconnected topic areas in publications, number of formal knowledge exchange networks (such as JCESR), number of university spinoffs
F3 Entrepreneurial Experimentation	Number and types of LDES startups founded by year, amount raised by startups over time
F4 Guidance of Search	Number of significant policy, regulatory and market signals, actor perceptions
F5 Market Formation	Number of active LDES firms, total market size and forecast as predicted by the amount of energy storage planned in the future, key competitors
F6 Resource Mobilization	Capital volume and type in LDES TIS, seed and venture capital funding, number of current and predicted jobs in energy storage
F7 Legitimation	Number of key policies and legislation, actor perceptions

Table 7.7: Evaluative measures to assess the state of the LDES technological innovation system

Insights from expert interviews underscored the significance of crafting tailored measures capable of cultivating growth across multiple functions within the LDES TIS. Simultaneously, they highlighted the necessity of reevaluating existing measures that tend to favor incumbent technolo-

gies. A striking example of this emerged in the comparison between lithium-ion (Li-ion) batteries and emerging electrochemical and thermal LDES technologies. Several interviewees emphasized that the extensive adoption of Li-ion storage within the electric vehicle (EV) and transportation sectors had inadvertently propelled the technology forward, rendering it more cost-effective and promoting the development of a robust supply chain. However, they emphasized the dissimilarities between the specific requirements for Li-ion batteries in EVs versus those for grid-scale storage. While EV batteries necessitate higher energy densities and compact sizes, grid-scale storage systems prioritize longevity due to the complexities and costs associated with frequent replacements. This disparity in the performance measures for the same battery chemistry across distinct sectors has led to biased evaluations of technology, as customers tend to prioritize attributes such as energy density, even when such factors are irrelevant within the context of grid-scale storage. The observations from these interviews stress the critical need to recalibrate evaluation methodologies and measures to ensure an appropriate assessment of emerging LDES technologies.

### *7.3.9 The State of the LDES Technological Innovation System*

Based on the LDES TIS analyses as undertaken by assessing the evaluative measures, Table 7.8 summarizes conclusions that can be drawn about functions of and the general state of the LDES innovation system.

The above analyses of the Long Duration Energy Storage (LDES) technological innovation system (TIS), indicate that the LDES TIS is in a state of transition from the Development phase towards the Take-off phase.

In the Development Phase, entrepreneurial experimentation along with Knowledge Development are the key functional patterns. However, in this phase, Knowledge Exchange and Resource Mobilization and Guidance of Search are focused away from Knowledge Development to Entrepreneurial Experimentation. With a rise in the number of electrochemical and thermal LDES startups, it is evident that Entrepreneurial Experimentation is an emerging functional pattern in the LDES TIS. The Entrepreneurial Experimentation is also supported by the recent formation of the LDES Council (in 2021), which is a key industry focused Knowledge Exchange organization. Further, the recent availability of grants for pilots and demonstration projects specific to LDES commer-

TIS Function	Research & Development	Commercialization	Notes
F1 Knowledge Development	Developed	Emerging	The basic and applied research knowledge is well developed (given the increasing publications, patents, and citations). The commercialization knowledge is in the state of development
F2 Knowledge Exchange	Developed	Emerging	Research and development knowledge networks are well established (JCESR, Earthshot Programs), whereas university-industry and other industry knowledge networks are still emerging.
F3 Entrepreneurial Experimentation	-	Underdeveloped-Emerging	There has been a notable surge in entrepreneurial experimentation since 2018. However, there are persisting challenges and market barriers that entrepreneurs need to overcome in the form of unproven technology, competition from lithium-ion, and lack of market incentives for LDES.
F4 Guidance of Search	Developed	Emerging	The federal government has many LDES-specific funding programs that direct funding to basic and applied research. Guidance of search function is still emerging for commercializing LDES technology in the form of state level policies for storage and buy-in from industrial actors.
F5 Market Formation	-	Underdeveloped-Emerging	There is a large market opportunity for LDES technologies as exemplified in many reports. However, significant market formation barriers persist. One of the most prominent challenges lies in the "lack of market" perception. Potential customers have yet to recognize the value proposition presented by emerging LDES technologies within the existing energy landscape. Existing market mechanisms do not place value on the flexibility and resilience services provided by long-duration grid-scale storage, resulting in the lack of customers and investors wanting to buy or invest in this technology.
F6 Resource Mobilization	Developed	Emerging	Research and development of LDES technologies has robust backing from federal initiatives, through programs like ARPA-E DAYS and the DoE's Energy Storage Grand Challenge and Grid Storage Launchpad Facility. However, the resource mobilization function is still developing for commercialization of these technologies. Impetus provided by federal policies, notably the Net Zero by 2050 objectives, has ignited increased venture capital and seed investments, especially since 2020. Additionally, there has been a rise in the workforce employed for battery storage projects.
F7 Legitimation	Developed	Underdeveloped-Emerging	Research and development of LDES technologies has found legitimacy by the federal government in the form of the different funding programs and reports targeted towards LDES. However, LDES technologies face challenge in complete acceptance from industry and other non-academic actors, who are concerned about technology and market risk in the light of LDES technologies being unproven (when compared to competitors) and not have a well-defined market.

Table 7.8: The state of different functions of the LDES technological innovation system

cialization proves the existence of a mobilizing resources in a guided manner. However, despite these advancements, the LDES innovation system stands at the precipice of the Take-Off phase. In the Take-Off Phase, Legitimation and Entrepreneurial Experimentation are the primary functional patterns of a TIS. Legitimation supports Market Formation, which further informs Guidance of Search. Legitimation also strengthens Resource Mobilization as social acceptance may often lead to further investment in a technology. Legitimation and Entrepreneurial Experimentation feed into each other as stronger Legitimation supports more Entrepreneurial Experimentation and vice versa. While Legitimation has gained traction through federal programs like the Long Duration Energy Shot and Storage Demonstration Programs, there remains a lingering skepticism within the market regarding the true potential and value proposition of novel electrochemical and thermal technologies. Challenges persist, including high capital costs and market hesitancy towards these emerging solutions, especially when juxtaposed against well-established lithium-ion technologies.

Consequently, the functional patterns of the LDES technological innovation system mirror those of an advanced Development phase or an early Take-Off phase, denoting a critical need for further

Legitimation and strengthened Entrepreneurial Experimentation. Addressing these concerns and fostering a more robust network of support, market acceptance, and funding mechanisms will be imperative in propelling the LDES innovation system towards a Take-Off phase, enabling it to realize its full potential within the energy storage landscape. The next section discusses the various inducement and blocking mechanisms that accelerate and hinder progress in the LDES innovation system.

### *7.3.10 Inducement and Blocking Mechanisms in LDES TIS*

The emergence of new technological innovation systems (TISs) is often accelerated or impeded by various factors that favor incumbent systems, leading to slow development of the emerging TISs. Efforts are needed to focus on understanding the inducement and blocking mechanisms that shape TIS dynamics, including organizational weaknesses, underdeveloped capabilities among potential customers, and network failures. Therefore, it is imperative to thoroughly examine the interplay between inducement and blocking mechanisms to effectively facilitate the advancement of emerging TISs.

#### *LDES Inducement Mechanisms*

In the context of the Long Duration Energy Storage (LDES) innovation system, the passing of the Infrastructure Investment and Jobs Act (IIJA) has been a pivotal inducement mechanism, driving substantial investments toward a resilient and clean energy grid. With provisions such as the allocation of over \$62 billion for the Department of Energy (DoE), including significant funding for battery supply chain development and grants for enhancing energy infrastructure resilience, the IIJA has actively mobilized resources, providing crucial impetus for the LDES sector [50]. As part of the deal, more than \$7 billion is slated to be invested in supply chain for batteries. Additionally, the deal will provide \$11 billion in grants to states, tribes, and utilities to enhance the resilience of their energy infrastructure under extreme weather conditions. An additional \$3 billion will be invested to expand the Smart Grid Investment Matching Grant Program focusing on improvements on grid flexibility through activities such as deploying storage. IIJA is the impetus that activated investment into a resilient and clean grid. This legislative push has not only impacted resource

mobilization but has also contributed to the legitimization of LDES technologies by signaling institutional acceptance of their potential role in achieving sustainable energy goals.

IIJA along with the Biden-Harris Administration's NetZero goals for 2050, resulted in the establishment of DoE's Office of Clean Energy Demonstration which was setup to provide support for emerging technological demonstrations. IIJA appropriates \$505 million for the development of LDES demonstrations and OCED is responsible for distributing this funding to relevant LDES demonstration projects. Therefore, the funding through OCED supports Entrepreneurial Experimentation and Guidance of Search functions in the LDES innovation system by supporting technological scale-up and backing specific technologies through selecting competitive proposals. Biden-Harris' Administration's NetZero goals have also resulted in targeted LDES programs through the DoE that support various stages of technological innovation. The Long Duration Storage Shot program, which is part of the Energy Earthshot Initiative has set a target to reduce the cost of grid-scale energy storage by 90% for systems that deliver 10+ hours of duration within the 10 years. The program funds and supports basic and applied research in all types of technologies – electrochemical, mechanical, thermal, chemical carriers, or any combination thereof that can potentially meet the duration and cost targets. The Long Duration Shot supports the Knowledge Development and Exchange functions by fostering research collaborations between researchers, national laboratories, and industry actors. The program also serves as Guidance of Search function by providing funding to competitive research proposals. Additionally, programs such as the American-Made Challenge support the acceleration of emerging technologies to real-world application by providing funding in the form of prizes and access to mentors and resources that can help with the commercialization of technologies. This program supports Entrepreneurial Experimentation and Knowledge Exchange by helping scale emerging technologies and connecting participants with relevant actors in the system. Further, the challenge also drives search by selecting competitive technologies to be part of the program.

Policy instruments play a key role in helping create market mechanisms for novel technologies. Renewable Portfolio Standards (RPS) and other state level mandates provide opportunities for LDES market formation. States can mandate policy carve outs in RPSs for deployment of energy storage and for specific types of storage technologies. This can help activate the market for LDES technologies.

Additionally, Federal Energy Resource Commission (FERC) Order Nos 841 and 2222 have created space for energy storage technologies to participate in various energy markets, therefore creating a market mechanism to assign value to storage and opening the market for LDES. Both policy instruments also signal Legitimation of energy storage and opens doors for the Legitimation of LDES technologies. Moreover, government, academic and industry reports such as the DoE's Long Duration Storage Liftoff Report, McKinsey's "NetZero Power: Long-duration energy storage for a renewable grid", Massachusetts Institute of Technology's "The Future of Energy Storage Reports" offer insightful research and models that highlight the value of LDES systems especially under the assumption that the grid will receive over most of its energy from renewable sources in the near future, thus increasing the demand for solutions that enhance reliability and resilience. These reports support the Guidance of Search function as they provide policy and recommendations on next steps in LDES innovation. Further, they enhance the Legitimation of LDES technologies through dissemination and support Knowledge Exchange by bringing together communities who are convinced of the value of LDES technologies. A clear example of this is the formation of the LDES Council which was a direct consequence of the McKinsey report as revealed by one of the interviewers and LDES council member [121].

The LDES innovation system has been significantly influenced by various inducement mechanisms (See Figure B.1 in Appendix B). These mechanisms together have helped the LDES TIS transition from pre-development through the development phases, have strengthened the research and development knowledge infrastructure and supported entrepreneurial experimentation, market formation and legitimation. However, as the LDES TIS transitions from the development to the take-off phase, it faces pressing blocking mechanisms that impede its success and further commercial scale-up.

### *7.3.11 LDES Blocking Mechanisms*

Based on expert interviews and qualitative document analysis, one of the major blocking mechanisms for the commercialization of LDES technologies was that novel electrochemical and thermal technologies are unproven at scale and in time. As a few interviewees mentioned, that to attract investors and customers, novel LDES technologies need to prove that there are going to be just

as efficient decades later as they are now. Therefore, the fact that novel LDES technologies are unproven blocks multiple TIS functions including Entrepreneurial Experimentation, Market Formation, Guidance of Search, and Legitimation. Another related blocking mechanism is cost concerns especially when compared to competitive technologies such as lithium-ion and natural gas. According to the Department of Energy's Lifford Reports [52], the cost of an LDES system must come down by 45–55% to be competitive. Such a significant decrease in cost is a tall order and poses a significant investment risk in conjunction with the technology being unproven. On the other hand, both natural gas and lithium-ion technologies are proven and cheaper than novel LDES technologies. Therefore, high capital and operational expenditures associated with LDES systems block further Knowledge Development for commercialization, Entrepreneurial Experimentation, Market Formation and Resource Mobilization due to investor and market hesitation, and Legitimation as system actors are not yet convinced whether novel electrochemical and thermal technologies will win out.

Another blocking mechanism impacting the LDES TIS is lack of clarity on beach-head customers and a fragmented potential market. Section 7.2 discussed various potential customers for LDES technologies. However, given the unproven technology and high capital costs, many of these potential target customers are hesitant to invest in, pilot and adopt LDES systems. For example, during expert interviews, two interviewees were clear about the slow-changing nature of utilities and short-term resource planning process that utilities undertake. These characteristics make them a challenging first customer segment to market to. Thermal storage startups are positioning themselves as helping decarbonize the process heat industry. As one interviewee put it “they need heat, we have heat”. The customer profile and strategy for capturing the utilities market vs. industrial heat market vs. the large energy consumers is very different as their energy demands and use profiles are significantly different. Therefore, emerging LDES developers have be careful and persistent in picking the appropriate initial target market, as there is no clear demand signal from the different potential customer segments. In some cases, the needs of different customers are further complicated geographical barriers and characteristics. For example, if an LDES developer is helping solve a problem in the Midwest, they will be solving for wind intermittency challenges given that wind is the main source of renewable energy in that region. Therefore, the number of cycles in a year and prices when the storage will be called on going to be different as compared to the same

battery solving solar intermittency challenges in California. Therefore, the same LDES technology will have different returns and value depending on where it is located.

Permitting and infrastructure challenges form the next set of blocking mechanisms. One of the main infrastructure challenges to emerge are long lead times due to long interconnection queues. Electric transmission system operators require that new projects that want to get connected to the grid run impact studies before they can be built. These studies help highlight upgrades that may be needed and the cost of those upgrades before a project can connect to the system and assigns the costs of that equipment. Interconnection queues are a list of such projects waiting to be studied. Queues have been known to create delays of more than 4 years [52]. This increases the lead time for new LDES developers to pilot their technology at scale requiring greater investment as they wait. If the LDES system is too big in size, then the project may run into other permitting delays caused by conflicting land-use needs or complaints from surrounding “neighbors”. These permitting and infrastructure challenges severely block Entrepreneurial Experimentation and Market Formation as they prevent the further testing and development of LDES technologies, hindering the path to validation.

Underdeveloped manufacturing and supply chains also pose significant blocks to Entrepreneurial Experimentation, Market Formation and Resource Mobilization functions of the LDES TIS. The DoE’s Liftoff reports estimate that by 2030, sufficient supply chain capabilities should be developed to support at least 3 GW of annual LDES manufacturing and deployment, as compared to less than 1 GW in 2020 [52]. The need for more mature manufacturing and supply chains was echoed in the expert interviews. Current LDES developers are trying to develop their technologies using cheaper material with existing supply chains. One interviewee discussed how manufacturing and supply chain is constrained by the lack of standardization in the LDES innovation system. Since no single technology or battery chemistry is dominating, it becomes challenging to achieve economies of scale which in turn make the manufacturing and supply chain process cost-effective. However, this is an example of the causality dilemma, where to have an optimized supply chain, some technologies might need to emerge as dominate. But, for some technologies to emerge as dominant, an established manufacturing and supply chain is key. This causality dilemma results in failed entrepreneurial ventures, investor hesitation and general hesitation from potential customers, impacting the TIS functions.

Both qualitative document analysis and interviews revealed the lack of appropriate market and regulatory mechanisms as another important blocking mechanism for the LDES TIS to fully transition into the Take-off Phase. Existing market mechanisms for energy pricing were designed for convention fossil-fuel based sources of energy. These mechanisms do not consider the dispatch flexibility that energy storage technologies bring to the grid, especially as the grid is further decarbonized. In 2023, no electricity market supports LDES economics. Further, support for grid scale LDES is highly dependent on geography as different states have different energy policies, power market dynamics and grid structures. Not having a way to value the services provided by LDES technologies stifles Market Formation and consequently Entrepreneurial Experimentation as there is a perception of there being “no market for LDES” due to there being no way for these technologies to bring revenue. This also stifles Legitimation because not having mechanisms that value LDES systems on the grid also signals that the impact of these technologies on the grid may not be accepted or clear.

One of the key reasons why it is challenging to change market mechanisms and assign more value to LDES systems is because of the lack of appropriate and advanced models and modeling methodologies that can help simulate how specific LDES systems may help enhance grid reliability under different geographies and grid conditions. For instance, as one interviewee discussed, one of the reasons Form Energy (an iron-air battery startup) has been successful in bagging multiple pilots and demonstration projects with utilities is because they invested the same amount of effort to develop software to model specific use cases to different customers and show them how their technology can be used for that specific customer. This allowed them to articulate and model a very specific use case and convince customers to try them out. A related constraint is the fact that utilities typically model storage needs for parts of the year and update their resource plans every two years. Their models do not capture long term storage dynamics (for around 3-5 years). Therefore, current methodologies do not capture the system benefits of LDES systems. The lack of models and modeling methodologies that can highlight the system benefits of LDES block further Knowledge Development, Entrepreneurial Experimentation, Market Formation and Legitimation functions. Better models can aid in further knowledge being developed regarding how LDES can benefit utilities, which can in turn spur market formation and entrepreneurship. Moreover, having models capable of demonstrating the value of LDES to the grid can further legitimize the technology

and advance its commercialization.

The last blocking mechanism that impacts all aspects of the LDES TIS is the perception of actors in the innovation system. Based on interviews and qualitative analysis, actor perceptions on the success of LDES technologies is mixed. Most actors acknowledge that the grid will be decarbonized in the near future and will require storage to help mitigate intermittency challenges. However, actors are not confident whether novel electrochemical and thermal LDES technologies will capture the market adequately, especially in light of stiff competition from lithium-ion batteries. None of the interviewees were willing to place a bet on which technology will “win out”. In fact, some interviewees voiced the general perception that various system actors believe that there may not be an actual market for LDES technologies due to the blocking mechanisms. The general hesitation around the value of the technology and lack of confidence in whether the various challenges will be overcome presents a blocking mechanism that may slow down all aspects of the system functions.

The LDES innovation system is confronted with many challenges that impede the successful transition of LDES technologies into the commercial market (See Figure B.2 in Appendix B). Addressing these blocking mechanisms will require a comprehensive and concerted effort from various actors, including policymakers, industry players, and research institutions. Overcoming the technology’s unproven nature, high costs, and customer adoption challenges will necessitate robust demonstration programs, targeted research initiatives, and innovative pilot projects to validate the effectiveness and economic viability of LDES technologies. Mitigating infrastructure obstacles, developing standardized manufacturing processes, and streamlining regulatory frameworks will be essential in fostering a conducive environment for the growth of LDES systems. Implementing effective market mechanisms and advanced modeling methodologies that accurately reflect the benefits of LDES technologies in enhancing grid reliability and decarbonization efforts will be crucial for bolstering investor confidence and promoting technology acceptance. Aligning actor perceptions through collaborative knowledge exchange, awareness campaigns, and industry engagement can further drive the market’s acceptance of LDES technologies, fostering a supportive ecosystem for their widespread adoption and integration into the evolving energy landscape.

#### 7.4 RQ2: Actor-Centric Measures for LDES TIS

To study existing assessment frameworks, especially in the context of the distinctive functionalities inherent in the grid-scale storage domain, six specific use cases of Long Duration Energy Storage (LDES) technologies were examined, drawing from a Department of Energy Liftoff report [52]. These use cases not only explain the measures crucial for evaluating the technical and economic performance of both electrochemical and thermal LDES technologies in comparison to Lithium-ion (Li-ion), but also underscore the diverse actors integral to this evaluative process.

The U.S. Long Duration Energy Storage (LDES) innovation system faces various challenges that impede its adoption and integration, particularly in comparison to the more established lithium-ion (Li-ion) technology. Crafting actor-centric measures within the LDES context can help address these challenges and promote the uptake of LDES technologies. Use cases across different applications of LDES technologies highlight the actors involved, the blocking mechanisms, and the potential inducement mechanisms, underscoring the need for tailored approaches. The table below Table 7.9 shows the different use cases, actors involved and competitors.

Use Case	Actors Involved	Competitor
Load management services such as for large EV fleets	LDES Developer, Customer (corporations, Department of Defense, city governments etc.)	Lithium-ion
Firming for future Power Purchase Agreements (PPAs)	LDES Developer, Customer (corporations), Renewable Energy Developers, ISOs	Lithium-ion
Transmission and distribution deferral	LDES Developers, Customers (typically utilities), Public Utility Commissions (PUCs)	Transmission and substation upgrade costs
Microgrid and resiliency	LDES Developers, Grid Operators, Governments	Lithium-ion
Utility resource planning	LDES Developers, Customers (typically utilities), Public Utility Commissions (PUCs)	Lithium-ion
Energy market participation	LDES Developers, Renewable Energy Developers, Independent Power Producers, Asset Investors (private equity, infrastructure firms etc.)	Lithium-ion

Table 7.9: Actors involved in different potential use cases of LDES technologies

The use cases presented in 7.9 offer insights into the diverse actors, current obstacles, and potential incentives within the Long Duration Energy Storage (LDES) innovation system. These use

cases are ordered based on the phase of development, ranging from initial demonstrations to further scale-up and deployment. In particular, the load management, Power Purchase Agreement (PPA) firming, and transmission deferral use cases are representative of initial LDES demonstrations, typically requiring capacities of around 10MW to 20MW. On the other hand, the microgrid planning and utility resource planning use cases represent scenarios for further scale-up, involving larger systems with capacities ranging from 40MW to over 100MW. The energy market participation use case serves as an example of LDES technology deployment, often necessitating capacities exceeding 100MW and potentially requiring broader market and regulatory adjustments. Notably, most of the use cases involve direct competition between LDES systems and the more established lithium-ion (Li-ion) systems. Each use case involves different sets of actors and decision-makers operating within distinct contexts, under varying blocking and inducing mechanisms. These differences emphasize the critical necessity for tailored measures that cater to the specific needs and concerns of individual use cases and the corresponding actors.

Table 7.10 provides a comprehensive summary of diverse measures relevant to different use cases. These measures encompass various aspects, including technical performance, cost considerations, and other contextual factors, thereby facilitating a more holistic evaluation of the potential of LDES technologies in the specific contexts outlined. By leveraging these refined measures, actors can effectively gauge the progress and impact of LDES initiatives.

The provided table outlines essential categories of measures pertinent to various Long Duration Energy Storage (LDES) use cases: success measures, technical performance measures, cost measures, and use-case specific measures. These measures play a crucial role in assessing and comparing LDES systems with incumbent solutions and competitors, thereby aiding in the measurement of innovation and the formulation of effective strategies for LDES adoption. Across all use cases, the primary success measure is the target annual return or revenue savings achieved by implementing an LDES system compared to other competitive solutions. This measure serves as a fundamental indicator of the economic viability and effectiveness of LDES technologies in addressing the specific use-case challenges. However, in the case of firming Power Purchase Agreements (PPAs), the focus shifts to the levelized cost of energy (LCOE) as a measure, reflecting the cost efficiency of LDES systems in the context of PPAs.

Technical measures are largely consistent across the use cases, encompassing factors such as

Use Case	Success Measures	Technical Measures	Cost Measures	Use Case Specific Measures
Load management services such as for large EV fleets	Target annual return % that demonstrates savings from LDES	<ul style="list-style-type: none"> <li>Capacity required (in MW)</li> <li>Battery Duration for LDES vs. Li-ion</li> <li>Operating life for LDES vs. Li-ion</li> <li>Round Trip Efficiency for LDES vs. Li-ion</li> </ul>	<ul style="list-style-type: none"> <li>Capital costs for LDES vs. Li-ion</li> <li>Investment Tax Credit</li> <li>Depreciable basis reduction</li> <li>Tax rate</li> <li>Revenue/savings from LDES or Li-ion</li> <li>Operational Expenditure</li> <li>Debt structure</li> </ul>	<ul style="list-style-type: none"> <li>Amount of grid electricity use</li> <li>Actor's timing and use of electricity</li> <li>Electricity pricing schedule for the local utility</li> </ul>
Firming for future Power Purchase Agreements (PPAs)	Levelized cost of energy	<ul style="list-style-type: none"> <li>Capacity required (in MW)</li> <li>Battery Duration for LDES vs. Li-ion</li> <li>Operating life for LDES vs. Li-ion</li> <li>Round Trip Efficiency for LDES vs. Li-ion</li> </ul>	<ul style="list-style-type: none"> <li>Local solar and wind prices</li> </ul>	<ul style="list-style-type: none"> <li>Hourly electricity demand profile of the use case.</li> <li>PPA firming model</li> </ul>
Transmission and distribution deferral		<ul style="list-style-type: none"> <li>Capacity required (in MW)</li> <li>Battery Duration for LDES.</li> <li>Operating life for LDES.</li> <li>Round Trip Efficiency for LDES.</li> </ul>	<ul style="list-style-type: none"> <li>Capital costs for LDES including energy capital cost and power and balance of the system costs.</li> <li>Investment Tax Credit</li> <li>Rate of return</li> <li>Cost to upgrade transmission constraint</li> </ul>	<ul style="list-style-type: none"> <li>Size of the transmission constraint (substation upgrades, transmission line extensions etc.)</li> <li>Length of deferral</li> </ul>
Microgrid and resiliency	Target annual return % that demonstrates savings from LDES	<ul style="list-style-type: none"> <li>Battery Duration for LDES vs. Li-ion.</li> <li>Operating life for LDES diurnal, LDES seasonal and Li-ion.</li> <li>Round Trip Efficiency for LDES diurnal, LDES seasonal and Li-ion.</li> </ul>	<ul style="list-style-type: none"> <li>Weighted average cost of capital for LDES diurnal, LDES seasonal and Li-ion.</li> <li>Fixed operational expenditure for LDES diurnal, LDES seasonal and Li-ion.</li> </ul>	<ul style="list-style-type: none"> <li>Variable renewable generation profile in the system (mix of wind, solar, other)</li> <li>Characteristics of local power system.</li> <li>Cost, efficiency and other characteristics of other storage and generation technologies</li> </ul>
Utility resource planning		<ul style="list-style-type: none"> <li>Battery Duration for LDES vs. Li-ion.</li> <li>Operating life for inter-day LDES, multi-day LDES and Li-ion.</li> <li>Round Trip Efficiency for inter-day LDES, multi-day LDES and Li-ion.</li> </ul>	<ul style="list-style-type: none"> <li>Weighted average cost of capital for inter-day LDES, multi-day LDES and Li-ion.</li> <li>Fixed operational expenditure for inter-day LDES, multi-day LDES and Li-ion.</li> </ul>	<ul style="list-style-type: none"> <li>Characteristics of local power system</li> <li>Capacity expansion model using variable renewable sources (capacity, cost of capital and lifetime of wind, solar and other sources).</li> </ul>
Energy market participation		<ul style="list-style-type: none"> <li>Capacity required (in MW)</li> <li>Battery Duration for LDES vs. Li-ion</li> <li>Operating life for LDES vs. Li-ion</li> <li>Round Trip Efficiency for LDES vs. Li-ion</li> </ul>	<ul style="list-style-type: none"> <li>Capital costs for LDES vs. Li-ion</li> <li>Investment Tax Credit</li> <li>Depreciable basis reduction</li> <li>Tax rate</li> <li>Revenue/savings for LDES for Li-ion</li> <li>Operational Expenditure</li> <li>Tax Equity</li> <li>Debt structure</li> </ul>	<ul style="list-style-type: none"> <li>Project location</li> <li>Capacity expansion model using variable renewable sources.</li> <li>Battery dispatch model to determine when the battery is charged or discharged.</li> <li>Financial model to determine project economics.</li> </ul>

Table 7.10: Actor centric measures of LDES innovation

capacity requirements, battery duration, round trip efficiency (RTE), and operating life. These technical measures are pivotal in evaluating the technical performance of LDES systems relative to competitors, helping actors make informed decisions. Similarly, cost measures cut across all use cases, with a primary emphasis on capital costs (Capex), operational expenditure (OpEx), revenue, savings, and rate of return. These measures are integral in assessing the economic feasibility and competitiveness of LDES systems. Tax rates and tax credits also come into play as relevant cost measures, depending on the specific use-case and jurisdiction. It is worth noting that actors can choose between capex-led and OpEx-led strategies based on their specific goals and available funding opportunities [180]. CapEx represents the upfront costs of purchasing, installing, and commissioning the LDES system, while OpEx includes the ongoing operational and maintenance costs. Decisions regarding the balance between these two cost categories are influenced by factors such as government funding, system longevity, and degradation rates. For instance, if a developer wants to take advantage of government funding for capital expenditures, the higher initial capital cost of an LDES system compared to Li-ion one may be advantageous. Analogously, knowing

that a Li-ion system degrades fast and may need to be augmented, decision-makers may decide to increase the size of the installed battery and take advantage of CapEx funding opportunities, instead of paying for replacements in 8-10 years. Therefore, CapEx and OpEx should be viewed in conjunction with other contextual factors to design the most optimal storage portfolio for a particular use case.

Use-case specific measures are tailored to the unique characteristics and requirements of each scenario. These may include capacity expansion models that simulate capacity investments in response to future energy demand, technology cost, and regulatory factors. Additionally, local power system attributes, such as pricing schedules, power import/export dynamics, and local renewable resources, play a role in shaping the specific measures relevant to the context. The development and application of actor-centric measures in the context of Long Duration Energy Storage (LDES) use cases serve as a strategic response to various blocking and inducement mechanisms identified within the LDES ecosystem. By aligning these measures with specific actor needs and priorities, the hurdles inhibiting the widespread adoption and innovation of LDES technologies can be effectively addressed.

#### *7.4.1 Blocking and Inducement Mechanisms for LDES Use Cases*

The previous section focused on identifying actors and actor-centric measures that were pertinent to different LDES use cases. These measures were categorized into four categories: success measures, technical measures, cost measures and use-case specific measures. While these measures showcase what actors are looking for when they evaluate the use of LDES technologies in their context, they do not necessarily highlight measures that assess challenges and opportunities that can guide informed decision-making. Based on the blocking and inducement mechanisms that emerged from the TIS analysis in Section 7.3, Table 7.11 categorizes different blocking and inducement mechanisms for each of the use cases considered in the previous sections.

The table highlights areas where further measures can be beneficial. For example, information on interconnection queues can be found readily through government websites and sources. The median interconnection wait time for projects built in 2022 was five years [104]. The interconnection queue wait time varies by location of the interconnection request but can be obtained. Expert

Use Case	Existing Blocking Mechanisms	Potential Inducement Mechanisms
Load management services such as for large EV fleets	<ul style="list-style-type: none"> <li>• Unproven Technology and its value</li> <li>• Actor Perceptions (lack of education around LDES value)</li> <li>•</li> </ul>	<ul style="list-style-type: none"> <li>• Academic, industry and government reports modeling the long-term value of LDES.</li> <li>• New models, planning, and data tools.</li> <li>• Knowledge exchange to educate actors about the value of LDES.</li> <li>• Grants or performance-based subsidies to mitigate initial risk</li> </ul>
Firming for future Power Purchase Agreements (PPAs)	<ul style="list-style-type: none"> <li>• Actor Perceptions (lack of education around sizing and operating LDES as part of PPAs)</li> <li>•</li> </ul>	<ul style="list-style-type: none"> <li>• Grants providing 100% of the differential in LDES and Li-ion capital costs.</li> <li>• Utility mandates and policies to ensure a significant percentage of the renewable energy benefits such as jobs and taxes are provided to community</li> </ul>
Transmission and distribution deferral	<ul style="list-style-type: none"> <li>• Permitting and siting barriers</li> <li>• Lack of market and regulatory mechanisms to value LDES as some ISOs or PUCs also may not consider LDES as a T&amp;D resource.</li> </ul>	<ul style="list-style-type: none"> <li>• New models, planning and data tools that can help better target LDES-appropriate locations on the grid.</li> <li>• Developing and disseminating a common knowledge base around LDES codification and considerations for grid usage.</li> </ul>
Microgrid and resiliency	<ul style="list-style-type: none"> <li>• Permitting and siting barriers</li> <li>• Long interconnection queues</li> <li>• Actor perceptions (lack of actor support)</li> </ul>	<ul style="list-style-type: none"> <li>• Streamlining interconnections by letting developers use already interconnected assets.</li> <li>• New models, planning and data tools that can help better target LDES-appropriate locations on the grid.</li> <li>• Academic, industry and government reports modeling the long-term value of LDES to build actor support.</li> <li>• Knowledge exchange to educate actors about the value of LDES.</li> </ul>
Utility resource planning	<ul style="list-style-type: none"> <li>• Permitting and siting barriers</li> <li>• Actor perceptions (lack of actor support particularly from ISOs and PUCs)</li> </ul>	<ul style="list-style-type: none"> <li>• New models, planning and data tools that can help highlight the benefits of LDES.</li> <li>• State mandates and targets so that utilities can obtain a minimum amount of LDES storage.</li> <li>• Local, state and government grants to fund LDES projects.</li> </ul>
Energy market participation	<ul style="list-style-type: none"> <li>• Permitting and siting barriers</li> <li>• Long interconnection queues</li> </ul>	<ul style="list-style-type: none"> <li>• Streamlining interconnections by letting developers use already interconnected assets.</li> <li>• Local, state and government grants to fund and/or subsidize LDES projects.</li> </ul>

Table 7.11: Blocking and inducing mechanisms for use cases of LDES technologies

interviews and qualitative document analysis also stressed the importance of developing new grid resilience measures that incentivize LDES technologies and can help in market formation. While grid reliability is well defined, the quantification and application of grid resilience is still in its nascent stages. Another key blocking mechanism is permitting barriers. The permitting process for energy projects often requires approval at various levels of authorities; local, state, interstate and federal. The permitting process is typically dependent on the size of the project, its geography, technology, and jurisdiction [181]. Therefore, developing measures for assessing permitting challenges will be a complex endeavor. Having this information can enable actors to make more informed decisions about project timelines, selecting geographies and potential cost associated with obtaining permits.

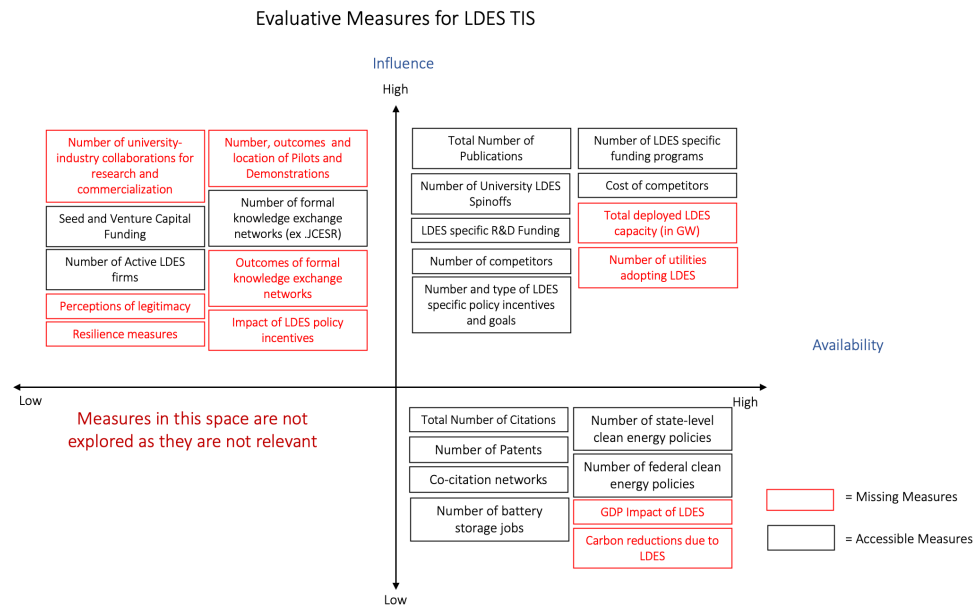


Figure 7.13: Evaluative measures for the LDES technological innovation system as plotted using the availability influence framework

## 7.5 RQ3: Availability and Influence of Measures for LDES TIS

### 7.5.1 Availability and Influence of Evaluative Measures

Evaluative measures are measures that were used in the technological innovation system (TIS) analysis of LDES technologies. These measures assess the output or outcomes of an innovation system. Figure 7.13 shows evaluative measures categorized by their availability and influence on evaluating the innovation system. Measures in the “high-availability” but “low-influence” column are measures that are “good-to-have” but maybe noisy and not provide an accurate picture of innovation in this context. For example, number of patents are known to be noisy measures of commercialization as not all patents are commercialized. Similarly, number of federal and state-level clean energy policies are a good indicator of policy initiatives to support general clean energy efforts and may open doors for LDES innovation, but they are not direct measures of LDES innovation. Instead, the number and type of LDES specific policy initiatives would be a better measure for evaluation. An example of such a policy is the California Public Utilities Commission’s decision

on long-term planning frameworks that identified a minimum 1 GW of LDES needed by 2026 to maintain reliability, released in 2020. Further, as discussed in Section 7.3.6, number of battery storage jobs may indicate a potential workforce ready to contribute to LDES but does not directly provide a measure of human capital, as much of the existing workforce may be trained for incumbent lithium-ion technologies.

In addition to measures that are available and accessible to those evaluating the LDES innovation system. The research also revealed missing measures that are of high influence for assessing the LDES innovation system.

- **Number, outcomes and locations of pilots and demonstrations:** Pilots and demonstrations are by far the most valuable measure of commercialization in the clean energy sector. A growth in the number of pilots and demonstrations indicates increasing willingness for adoption, greater market formation, and legitimation. In the LDES context, there is no straightforward way to find accurate information about pilots and demonstrations. The reason is that much of this information tends to be confidential to developers (especially startups) and currently, there is no database that mines the web to provide this information.
- **Outcomes of formal knowledge exchange networks:** While having a number on the knowledge exchange networks is valuable, it is equally valuable to have a measure that assesses the outcomes of different knowledge exchange networks, whether those are publications, investment/funding, creation of new companies or jobs.
- **Impact of LDES policy incentives:** Specific LDES policies are currently in their nascent state of development. While a count of the number of policies is a sound measure of guidance of search, legitimation, and other TIS functions, evaluating the outcome of these policies is an even more powerful measure. Such an evaluation can be quantitative through validated impact constructs or qualitative reports.
- **Number of university and industry collaborations for research and commercialization:** Having an accessible way to count the number of university and industry partnerships

for research (ex. JCESR) and commercialization (ex. university spinoffs) will be a valuable measure for assessing knowledge exchange in the innovation system.

- **Perceptions of Legitimacy:** Some of the toughest measures to assess in the TIS analysis are actor perceptions and specifically perceptions of legitimacy of the technology. This is the level of belief that different actors have regarding the potential success or chances of success of the technology. Such measures will have to be constructed and validated through surveys, interviews, and other mixed-methods techniques.
- **Resilience measures:** The definition of resilience in a grid context is still emerging. Unlike reliability, which has a clear definition as a metric, resilience as a metric is still being developed. One of the key benefits of LDES is its ability to provide resiliency services to the grid over long durations. Therefore, having measures for resilience will better help characterize the value of different LDES technologies and therefore encourage further adoption and market formation.
- **Total Deployed LDES Capacity and Number of utilities adopting LDES:** This measure could be made readily available if it existed, as the federal government tends to track various battery and storage projects. However, given the nascent stage of LDES commercialization, this data is currently not systematically collected.
- **GDP Impact and Carbon Impact of LDES:** These measures of LDES outcomes and impact are valuable in the long-term, once LDES commercialization has hit a level of maturity. However, due to LDES innovation being in its early stages of commercialization, these measures are difficult to assess and hence do not hold a lot of influence in current stages of development.

Note that the evaluative measures discussed here are not exhaustive but are representative. There may be many more measures that are available and others that are missing. The point of this analysis was to apply the evaluative measures to the availability and influence framework to analyze how valuable different measures may be to evaluating the functioning of a technological innovation system.

7.5.2 Availability and Influence of Actor-Centric Measures

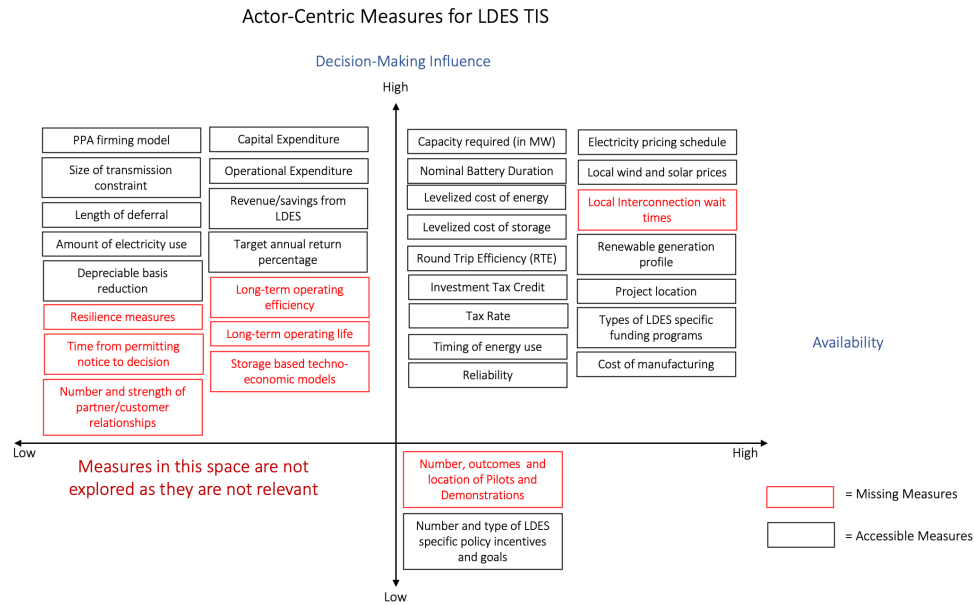


Figure 7.14: Evaluative measures for the LDES technological innovation system as plotted using the availability influence framework

Actor-centric measures are specific to different actors in the innovation system and contextualized to their activities. These measures include criteria that actors use to assess the success and failure of their own activities in an innovation system. Figure 7.14 shows a categorization of actor-centric measures by their availability and influence on actors’ decision-making. Firstly, from both Figures 7.13 and 7.14, the difference between evaluative and actor-centric measures is highly evident. While evaluative measures focus on more “high-level” outcomes and outputs of the innovation system. Actor-centric measures focus more on specific contexts and use cases.

Some evaluative measures such as the number, outcomes and locations of pilots and demonstrations and LDES specific policy incentives and goals might be of interest to actors to evaluate the technological landscape, but eventually they do not have as high of an influence on decision-making. However, other evaluative measures such as resilience are important for utility actors to consider for their resource planning and resource adequacy needs.

The measures discussed in Section 7.4, encompassing technical, cost, and success dimensions, wield significant influence over the decision-making processes of actors. A notable observation on the availability spectrum of measures reveals that certain measures requiring specific actors to perform calculations based on intricate decisions—like CapEx vs. OpEx or revenue/savings—are often not immediately accessible. This lack of accessibility stems from dependencies on various actor-specific variables such as business strategy, project location, and leadership. Consequently, these measures are categorized as not readily available. In contrast, more tangible measures like round trip efficiency, tax rate, and tax credit are typically fixed and readily obtainable.

In addition to measures that are available and accessible, the analysis also revealed missing measures that are of high influence for assessing the LDES innovation system.

- **Local interconnection queues/wait times:** This measures the time it takes to connect to the grid. The median interconnection wait time for projects built in 2022 was five years across all the US. While this provides a good reference, interconnection wait times vary locally, with California having the longest interconnection queues. Therefore, having local interconnection wait times is a good measure that can inform project timelines, schedule, and cost.
- **Long-term operating efficiency and operating life:** A major unproven aspect of LDES technologies is how they will operate decades from now. As one expert commented, “However, these technologies are not proven at this scale yet and don’t have a history. Grid scale tech is tens of millions of dollars. You are asking investors to put down money on something with a 20-30 year life (some equivalency of cycles). So, how do you know what the performance degradation is going to be on the 1000th cycle (20 years in)...need to convince people that the roundtrip efficiency is going to be the same at 20 years. Providing long term performance guarantees”. This measure can be obtained through pilots, demonstrations, and adoption. The operating life and efficiency of a technology is a vital technical measure for actors, as that informs them how long their technological investment will reliably last.
- **Time from permitting notice to decision:** Permitting presents a major blocking mechanism to LDES innovation. Therefore, having access to permitting times associated with

different permitting requirements in different locations will help inform actors on project timelines, schedules, and cost.

- **Storage-based techno-economic models:** Long-term storage is just starting to be considered in utility resource planning and adequacy needs. Therefore, there is an unequivocal need for better models and modeling tools that incorporate long-term storage in planning for energy resources and efficiency needs.
- **Number and strength of partnerships/customer relationships:** One expert who works for an LDES developer commented that, “What pushes customers to work with us is the team and relationships we have developed along with the industry expertise outside their own technology. We take a holistic approach. Customers have this requirement of clean energy, and we have whole process of working with the provider to make that happen.”. Expert interviews emphasized the importance of developing strong customer relationships and partnerships to increase adoption. Number of partnerships/customer relationships is also a positive sign of traction that a developer has from an investor perspective, which highly influences investment decisions.

Like evaluative measures, the actor-centric measures discussed here are not exhaustive but are representative. There are many other actors in the innovation system that are not considered in this analysis such as venture capital and seed investors, scientists, researchers etc. Thus, there are many more measures that are available and others that are missing.

## **7.6 Takeaways and Recommendations**

So far in this chapter, the LDES technological innovation system was assessed using evaluative measures, followed by a discussion of actor-centric measures based on six use cases of LDES technologies. Both these types of measures were then categorized into under the availability and influence framework, which helped highlight measures that are readily available and influential and measures that are influential yet missing. The analysis of these available and influential measures along missing measures offers a starting point to crafting takeaways and recommendations for enhancing the functioning of the LDES TIS through not just better evaluation but actor-centric interventions.

### 7.6.1 Takeaways

1. One of the key takeaways from this analysis is that LDES is an early-stage innovation system (. It is currently at the cusp of being at the Take-off phase. However, for LDES commercialization to take-off, the entrepreneurial experimentation function of the TIS needs to be supported by strengthening the legitimation of the technology. Actors of the system need to believe that LDES is a legitimate technology that could help solve environmental and market problems. This in turn can enable resource mobilization (through funding, network effects etc.) into entrepreneurial experimentation, which can feed into further legitimation of the technology.
2. LDES innovation is blocked by the fact that it is an unproven technology at scale over time.
3. LDES innovation is blocked by immature and expensive manufacturing and supply chains and permitting and infrastructure delays. Currently, lithium-ion supply chains and manufacturing are much more mature, leading adopters to lean towards lithium-ion storage.
4. LDES innovation is also blocked by the lack of appropriate and advanced models and modeling methodologies that can help simulate how specific LDES systems may help enhance grid reliability under different geographies and grid conditions.
5. LDES innovation is also blocked by the lack of appropriate market and regulatory mechanisms. Existing mechanisms do not consider the dispatch flexibility that energy storage technologies bring to the grid, especially as the grid is further decarbonized. Current mechanisms do not provide a way to value the services provided by LDES technologies.
6. LDES innovation is blocked by actors' mixed perceptions on the success of LDES technologies. Some actors are not confident whether novel electrochemical and thermal LDES technologies will capture the market adequately, especially in light of stiff competition from lithium-ion batteries and transmission line buildouts.
7. Federal government investment through the Infrastructure Investment and Jobs Act and the Inflation Reduction Act and policies such as Renewable Portfolio Standards (RPS) and

FERC Orders have heavily and positively influenced the research and commercialization of new LDES technologies.

8. Academic, industry and government reports play a key role in educating different actors on the long-term benefits of LDES technologies by providing research, new models, and recommendations.

### 7.6.2 Recommendations

Based on the takeaways discussed in Section 7.6.1 and on the analyses of evaluative and actor-centric measures, the following recommendations can be considered to enhance the functioning of the LDES technological innovation system:

1. LDES innovation is blocked by the fact that it is an unproven technology at scale over time. Therefore, there is a need to track and invest in more pilots and demonstrations for LDES projects across diverse use-cases. While it may take time for utilities to fully embrace LDES, other upstream uses cases such as load management and microgrids present opportunities to test and prove the technology. Such projects can rapidly increase learnings regarding technological performance, manufacturing costs, operating life, operating efficiency, and return on investment. Further, it is not sufficient to simply conduct demonstrations or pilots, rather the outcomes of these projects should be systematically tracked and disseminated through networks to educate other potential users of the technology. The goal of funding pilots and demonstrations should not be restricted to proving out the technology and its economics, but to actively engage other actors in the system and gain legitimacy. Given below are actions that various actors can take:
  - (a) **Federal and State Government:** Expand programs that provide funding for LDES pilots and demonstrations (such as the Office of Clean Energy Demonstrations)
  - (b) **Early and mid-stage investors:** consider longer time horizons for return on investments for clean energy technology.
  - (c) **Researchers (in universities, industry, and government):** Consider commercializing novel research through their organizations' technology transfer office.

- (d) **Developers:** Work on demonstrating the potential of technology through research articles, new modeling tools and white papers. Actively search for funding and new customers.
  - (e) **Accelerators, incubators:** Educate new entrepreneurs and developers on taking technology to market and connect them to potential investors and customers.
  - (f) **Energy Customers and Utilities:** Consider piloting small-scale ( $\sim 10$  MW) LDES projects to meet needs.
2. LDES innovation is blocked by immature and expensive manufacturing and supply chains. The quickest way to build out manufacturing and supply chain is to robustly conduct pilots and demonstrations. Additional actions can be considered such as subsidies and tax incentives to private entities for providing the materials (such as nickel and vanadium for flow batteries), and components for LDES. Government can also stockpile essential raw materials and components to maintain a reliable supply chain. Given below are actions that various actors can take [52]:
- (a) **Federal and State Government:** Offer tax incentives and subsidies on raw materials and components. Create stockpiles of rare materials.
  - (b) **Developers:** Explore optimal supply chain and manufacturing processes and/or focus technology development in directions that uses shorter supply chains and cheapest materials.
3. LDES innovation is blocked by permitting and infrastructure delays. Permitting delays can be mitigated by first systematically tracking the time from notice to decision so that various actors are aware of the length of delays and can optimally choose locations that would result in less delays. A bigger step would be to reform permitting laws. Such laws are currently being considered, such as setting time limits (1-2 years) for conducting reviews and providing a permit, pre-identifying land that is appropriate for use, using previously completed reviews etc [142]. Systematically tracking permitting time for different permitting rules can help identify specific permitting laws for reform that be a bottleneck for a large number of LDES projects. Given below are actions that various actors can take:

- (a) **Federal and State Government:** Collect, centralize and share permitting wait times. Reform permitting laws that cause the most bottlenecks for new energy projects.
4. LDES innovation is blocked by interconnection queues. While FERC is working to reform the long wait times for interconnections (through a recent Order 2023), these wait times are still a key bottleneck for LDES storage technologies. Therefore, tracking and measuring local interconnection wait times not only allow for optimal scoping of LDES projects, but can also help track the impact of interconnection reforms. Given below are actions that various actors can take:
- (a) **Federal and State Government:** Collect, centralize and share interconnection wait times. Propose policy reforms such as FERC’s Order 2023, that would curtail interconnection wait times.
- (b) **Transmission Providers, ISOs, and RTOs:** Collect, centralize and share permitting wait times.
5. LDES innovation is also blocked by the lack of appropriate and advanced models and modeling methodologies, specifically capacity expansion models. Capacity expansion models (CEM) simulate generation and transmission investment based on future energy needs, prices, and policy. In conventional CEMs, storage is represented as a single homogeneous asset. However, this is not accurate as there is different types of storage, which are typically distinguished by their state of charge over time. To accurately incorporate storage, existing models need to be updated to dynamically account for state of charge over the full charge and discharge cycles. Additionally, for some LDES technologies, energy and power can be sized independently, features that should also be incorporated in existing models [111]. Inappropriate modeling of grid assets such as storage can result in sub-optimal decarbonization strategies and investments. Therefore, further research is required on better models of energy storage followed by practical implementations of those models to drive strategy. Given below are actions that various actors can take:
- (a) **Researchers (in universities, industry, and government):** Develop new modeling

tools and techniques.

- (b) **Utilities, ISOs, and RTOs:** Develop, apply, and validate new capacity expansion models.
  - (c) **Developers:** Develop new models that demonstrate the use of their technology for different use cases to attract customers.
  - (d) **Government and regulators:** Use new models to develop policy incentives that favor LDES.
6. LDES innovation is also blocked by the lack of appropriate market and regulatory mechanisms that guarantee long-term revenues, hindering market adoption. Current mechanisms favor mechanisms that value energy generation. Therefore, generators can estimate the energy they produce and can negotiate payment. However, the use of LDES is less predictable and therefore, harder to remunerate under current mechanisms. Therefore, market and regulatory mechanisms need to evolve to support the services provided by long-duration storage. An example of this is the need to develop measures that value grid resilience given the increasing frequency of extreme-weather events. Given below are actions that various actors can take:
- (a) **Utilities, ISOs, and RTOs:** Develop novel contract structures and remuneration mechanisms that value longer duration storage.
  - (b) **Government and regulators:** Develop policy and storage carveouts under existing policy instruments such as Renewable Portfolio Standards.
7. While the federal government has invested extensively in the research and commercialization of LDES technologies, further capital is needed to fund further technological development, pilots, and demonstrations. Therefore, LDES customers and investors can share their findings on what worked (or did not work) in the context of business models, revenue mechanisms, technical performance, and costs. Given below are actions that various actors can take:
- (a) **Early and mid-stage investors:** Consider longer time horizons for return on investments in LDES. Explore new business models, and success measures.

- (b) **Universities and government laboratories:** Consider starting additional funding programs or infrastructure (such as testbeds) that help commercialization.
  - (c) **Accelerators, incubators:** Provide a seed and pre-seed funding to new and emerging developers.
  - (d) **Industry Customers:** Consider having in-house and external incubation programs that fund early-stage technologies and provide new entrepreneurs with industry expertise and guidance.
8. Forming and convening various channels of knowledge exchange such as industry councils (such as LDES councils), research networks (JCESR) and other cross-stakeholder groups can enable exchange of knowledge that could help accelerate adoption and solve blockers such as manufacturing, supply chain and workforce needs. More and frequent channels of knowledge exchange through workshops, conferences, research-industry collaborations, seminars, and other avenues can enable the dissemination of learnings quicker, leading to faster and more optimal adoption. Given below are actions that various actors can take:
- (a) In this case, any of the actors can take initiative to convene various actor groups by organizing the events mentioned above.
9. The formation of a central database that tracks the various measures identified and making this information available to the various actors in the LDES innovation system can enable better assessment of where LDES technologies are today and actions that need to be taken to accelerate their innovation. Having access to an up-to-date database of CapEx targets, RTE targets, policy targets, wait times etc. can inform various actors on how they can enhance LDES innovation. For example, developers can aim to hit desired CapEx and RTE targets that are posed by their potential customers. Similarly, reform around specific permitting laws or local interconnections can shorten delays and accelerate project timelines. Given below are actions that various actors can take:
- (a) **Federal and State Government, Universities, National Laboratories and Consulting Groups:** Develop, disseminate, and maintain public dashboards with various

measures.

## **7.7 Conclusions**

The actor interviews discussed in the preceding chapter (Chapter 5) underscored the need for actionable and targeted innovation measures in a specific technology and sector, prompting a deeper investigation into innovation measurement for long-duration energy storage (LDES) technologies in the energy sector. This topic served as a case study to apply and validate the measurement frameworks developed in Studies 1 and 2. The first research question of the study focused on analyzing the structure of the LDES technological innovation system (TIS). It delved into the different actors and their roles within the LDES TIS. The second research question used evaluative measures derived from literature to assess the various functions of the TIS. From this analysis, conclusions about the state of the TIS were drawn and various inducement and blocking mechanisms were discussed. The third research question discussed the different actor-centric measures associated with LDES and which inducement and blocking mechanisms were associated with which use-case. Both the first and second research questions provided an insight on the types of measures relevant to evaluate different aspects of LDES innovation. The third research question further analyzed these measures by looking where these measures rested on the availability-influence framework developed in Chapter 5. Both evaluative and actor-centric measures consisted of missing measures that are not considered in the evaluation of the LDES innovation system. Identifying these measures and interpreting results from all research questions resulted in takeaways and recommendations for enhancing the functioning of the LDES TIS.

The goal of this chapter was to demonstrate how the different innovation measurement frameworks developed in Studies 1 and 2 can be applied to assess innovation in a specific technology and sector. The result of this investigation is not just the strategic recommendations that emerged, but also the underlying process of analyzing and applying measures of innovation (Figure Appendix C.1 in Appendix C). The measurement frameworks that emerged in this dissertation allows for the assessment of innovation from four perspective: evaluative, actor-centric, availability and influence. These perspectives harmonize the needs of those studying innovation and those “doing” innovation. This case study successfully applied the four perspectives to comprehensively understand innovation in LDES and suggest recommendations that can help LDES innovation move forward.

## Chapter 8

## CONCLUSIONS AND CRITICAL REFLECTIONS

As stated in the introduction, the goal of this dissertation was to make a substantive contribution to the understanding of measures of innovation. The key question that all inquiries in this dissertation lead back to was: “How can we measure innovation?” The dissertation successfully proposed two key frameworks of framing measures of innovation. The first framework categorized measures as evaluative or actor centric.

- **Evaluative measures:** Evaluative measures assess the current state of an innovation system by observing its outputs or outcomes such as patents, publications, investment etc. Evaluative measures for assessing innovation system functions are well-understood in literature. Three broad areas of measures have traditionally been used for innovation analysis, each shedding light on different aspects of the innovation process.
- **Actor centric measures:** Actor-centric measures are measures specific to different actors in the innovation system, they may use to conduct innovative activities. Actors of an innovation system may use these measures to determine success and failures pertaining to the technology for their use case.

The second framework placed measures onto an availability-influence paradigm. The availability-influence paradigm analyzes measures by asking two questions: (1) are the measures readily available? and (2) are the measures influential in decision-making and evaluation? This framework is meant to let users reassess their availability bias and rethink the decision-making power of different measures. Just because a measure is available may not mean that it is useful for making effective decisions. However, just because a measure/ construct is unavailable does not mean that it is not useful for decision-making.

The two frameworks help combine two distinct elements of measurement, (1) who is measuring and why? and (2) are said measures available and useful? These frameworks are inherently

action oriented, in that they are not meant to just study innovation but are meant to impact it. Incorporating actor centric needs into existing evaluative frameworks of innovation measurement fills the crucial gap between research on innovation and practice of innovation. These measurement frameworks can enable researchers and practitioners alike to derive effective measures as they study or participate in innovative activities

### **8.1 Summary of Main Results**

The two frameworks emerged from two studies conducted as part of this dissertation and was validated via application to a particular sector and industry (in Study 3). Given below are the key results that emerged in the different studies that contributed to this dissertation.

#### *8.1.1 Study 1: University-Industry Partnerships for Education*

This study focused on studying the knowledge development (F1) and knowledge exchange (F2) of an innovation system in an educational context. The setting was an industry sponsored engineering design capstone program. This setting acted as a small-scale “laboratory” to study micro-interactions between two actors on how they exchange and transfer knowledge to work towards producing often novel project results. It was a window into small-scale innovation. The study resulted in three key contributions:

- 1. Measures of Student Perceptions of Support, Individual Ability, and Learning:**

These measures of perception included measures of industry and peer support along with measures of preparedness, design self-efficacy, engineering design and decision-making and adaptability. These were novel measures that characterized students’ experiences in an industry sponsored engineering design capstone that demonstrated the importance of support (from industry and peers) and notions of individual ability on perceptions of learning. These measures provided an insight into which actors support which aspects of the innovative process. Peers significantly supported engineering design and decision-making, whereas industry mentors supported students in adapting to uncertainty in their design process. The measures also demonstrate an example of constructs that could be used to study knowledge exchange interactions.

2. **Measures of Student Learning:** These were novel measures that characterized students' design problem scoping process. They included five scoping metrics (total number of design criteria, criteria met, not met, partially met, and not addressed) that measured how well students scoped their projects. In a way, these measures assessed how well the program guided students in scoping their projects and provided multiple directions for interventions.
  
3. **An evaluative and actor-centric framework for innovation measurement:** Interpreting the measures of perceptions and learning from the lens of innovation but reframing the capstone as a small-scale innovation system resulted in framing the measures as evaluative and actor centric. Every innovation system has outcomes and actors. Therefore, it only makes sense to evaluate the “efficacy” of an innovation system” and define measures that are relevant to different actors in an innovation system. The needs and perceptions of the different actors in an innovation system may not often align with the overall outcomes of the system. For example, in the case of the capstone, an industry sponsor maybe more interested in getting a product than student learning, which is fundamentally at odds with the goals of the capstone. Therefore, assessing different actors' perspectives is equally important to obtaining actionable measures.

Therefore, this study served as a foundation for organizing innovation measures into evaluative and actor-centric measures. The study not only provided a unique perspective on education in an innovation context but helped understand the effectiveness of industry-sponsored engineering capstone projects. The actor-centric measures for students (perceptions of support and individual learning) revealed critical insights into the challenges of collaborative educational initiatives, thus guiding program improvements and effective knowledge development and exchange.

### *8.1.2 Study 2: Exploring Actors' Perspective on Innovation Measures*

The second study yielded an availability-influence framework by delving into a broader exploration of actors' perspectives as pertaining to research and entrepreneurship within a regional innovation system (Seattle). Unlike the previous study that incorporated one or two actor groups, this study consisted of 5 different actor groups ranging from university stakeholders to entrepreneurs. The

setting of this study as a medium scale “laboratory” to study actor perceptions across different innovative activities (as framed by the technological innovation systems framework). The key findings of this study include:

1. **Validating the gap between theory and practice:** Evaluative measures are not often sufficient to guide decision-making for different actors. Just because they might be available, does not mean that they have high influence when it comes to decision-making for different actors. The findings of the study validated the gap between innovation measures developed in literature and their use in practice.
2. **The availability-influence framework for innovation measurement:** Not all available measures are useful for effective decision-making. This finding gave rise to a novel availability-influence lens of innovation measurement. Additionally, the study also emphasized the insufficiency of quantitative measures in guiding decision-making and highlighted the role of qualitative constructs that could capture important measures, especially those pertaining to strength of networks, partnerships, trust, and experience.
3. **Validating the emphasis on industry-specificity:** The study revealed the significance of industry and technology specific measures. Some of the most influential actor-centric measures tend to be measures that are specific to the industry or even the product. Therefore, while regional or national innovation system approaches might be sound approaches for evaluating an innovation system, a technology and industry centric approach is needed to have actionable measures for innovation.

This study unveiled perceptions of different actors in an innovation system and provided a theoretical concept the influence-availability framework for innovation measurement. The study further set the stage for its application in a subsequent case study within specific industries and technologies, namely clean energy, and long duration energy storage (LDES) respectively.

### *8.1.3 Study 3: Integrating Innovation Measurement Frameworks for LDES Technologies*

The third study was a case study that was used to apply and validate the theoretical frameworks developed in study 1 and study 2 in a specific technological innovation system: long-duration energy

storage (LDES) technologies. The study demonstrated the value of these theoretical frameworks by deriving strategic and actor-centric interventions for enhancing LDES innovation. The study resulted in the following key findings:

1. **The long-duration energy storage innovation system is at the precipice of take-off:**

While the research function of the innovation system is well developed, the commercialization and education functions have much further to go. Legitimation (especially perceptions and beliefs around commercialization) and entrepreneurial experimentation need to be better supported through more pilots and demonstration. This requires greater investments from public and private actors, shorter permitting and interconnection wait times, development of supply chain and manufacturing, change in market and regulatory mechanism, and better modeling tools. Federal and state governments are the most crucial actors in this innovation system, followed by energy customers such as utilities.

2. **Development, tracking and dissemination of better measures that focus on the needs of various actors and value the technology for its benefits:**

Not only do existing measures need to be better tracked and shared, but better measures also need to be developed to open the market for LDES technologies. These include better measures for valuing resilience and knowing when to use existing measures such as LCOS (levelized cost of storage) to ensure an apples-to-apples comparison. Additionally, existing measures such as targets for LCOS, Round Trip Efficiency, CapEx, interconnection queues, permitting delays etc. should be tracked in a centralized and easily accessible database to help educate potential developers, customers, investors, and policymakers of the state of LDES innovation and help them make decisions about their activities.

3. **Validating the process of measuring innovation:**

The study showed the utility of measuring innovation through the two frameworks that emerged in this study. It demonstrated the stark differences between measures that are used to evaluate an innovation system and measures that are useful for the different actors in an innovation system. It also showcased why thinking about availability and influence is beneficial in conducting innovation measurement.

This case study not only provided strategic recommendations for enhancing the functioning of the LDES innovation system, but provided an example of how the frameworks developed in this dissertation can be applied to a specific technology and sector. Therefore, the novelty of this study was two-fold, (1) in the recommendations and proposed measures it provided, and (2) validating a novel process for measuring innovation.

## **8.2 Reflection on Methods**

The studies in this dissertation relied on multiple methodologies lying on the spectrum of quantitative to qualitative. The use and limitations of the different methodologies for each of the studies is discussed briefly.

### *8.2.1 Study 1: University-Industry Partnerships for Education*

A sequential mixed-methods approach was utilized to answer the research questions in this study. The first research question was answered using an explanatory sequential mixed-methods design, where quantitative results from a survey were first analyzed following by a qualitative analysis used to explain the quantitative results. In contrast, the second research question was addressed using an exploratory mixed-methods design, where students' final reports were first analyzed to derive scoping metrics, which were then statistically analyzed for differences.

The strength of mixed-methods research design is typically associated with triangulation. Triangulation is a way to strengthen the validity of a study by using multiple forms of data, methods, researchers and/or, theoretical perspectives. A sequential mixed-methods approach was selected for these studies because (1) in research question 1, there was a need to "explain" the quantitative results, and (2) in research question 2 there was a need to first explore problem scoping perceptions through a qualitative analysis of the final reports before crafting adequate measure [42]. Both these questions warranted quantitative and qualitative methods to corroborate and confirm findings.

However, no method is perfect. This study draws on a capstone design experience at a single institution and the generalizability to other academic settings may be limited (a question of external validity). A limitation of the qualitative analysis in this study is that the analysis and interpretation are based on the subjectivity of the researcher [Merriam]. Another limitation is the positionality of the author as a teaching assistant for the capstone program during the setting being studied.

Therefore, her interpretation of students' design experience is prone to some "biases, dispositions and assumptions regarding the research" [122] that could have influenced the themes.

### *8.2.2 Study 2: Exploring Actors' Perspective on Innovation Measures*

A qualitative semi-structured interview methodology was used for this study. An interview study was selected to address the question in this study as the study was focused on exploring the subjects' opinions and experiences without observing their behavior. Since the participant pool for this study was broad and diverse, an interview strategy seemed apt in representing a broad range of ideas [Merriam]. The interview was complemented by a nested think-aloud study to observe participant's behavior and opinions about specific measures. A think aloud methodology was selected to observe how participants used different measures of innovation. The strength of interviewing as a methodology is the ability to generate a large and rich amount of data that encompasses broad perspectives, which was the goal of this study.

However, this methodology is not without its faults. The key limitations of semi-structured interviews are validity and bias. Semi-structured interviews have lower validity than structured interviews or quantitative methods because of their flexibility, which makes comparisons across participants challenging. Bias emerges from the researcher, who might accidentally ask leading questions. Therefore, care and rigor need to be exercised when developing interview protocols followed by conducting pilots that can help the research catch pitfalls in their protocol. These mitigating strategies were used to develop protocols and conduct interviews for this study.

### *8.2.3 Study 3: Integrating Innovation Measurement Frameworks for LDES Technologies*

Multiple methodologies were used to conduct this case study, with three of them being prominent: (1) technological innovation system (TIS) analysis, (2) semi-structured expert interviews, and (3) desk research. All of these methods help enhance the validity of the case study as they provide multiple sources of data and ways to interpret that data to triangulate results. The limitations of the TIS analysis and semi-structured interviews are covered previously in Sections 6.5 respectively. The limitation of desk research is the veracity of the sources of information. It is imperative to use reliable sources of information to conduct desk research. Therefore, for this study sources of desk

research were primarily public documents, government research reports and reports from trusted media outlets.

### ***8.3 Avenues for Further Research***

The frameworks of innovation measurement were emerged from studies that were embedded in specific contexts (industry capstone for study 1 and Seattle for study 2). Further, the frameworks were applied in a specific industry sector and technological context. Finally, all this research was conducted in the context of the US. Therefore, while the research basis for is contextually limited, the framework emerged from findings across diverse domains and was successfully applied in a completely different domain. This supports the interdisciplinary nature of the measurement frameworks. The framework emerged from and was applied to different settings with different groups of actors and institutions. This suggest that the frameworks hints of robustness to application in other areas. The application and validation of the frameworks in one setting, does imply its completeness, something that is not possible despite of research design. There may be other dimensions and complementary frameworks that may enhance and complement actor-centric measurement of innovation developed in this dissertation. The generalization of these frameworks to other settings, industries and technologies requires further research and study. Given below are some avenues of future research.

- More studies applying the frameworks developed in this dissertation should be conducted in different contexts, technologies, and sectors to validate and enhance the frameworks.
- Further research needs to be conducted to study the overlap and interactions between evaluative and actor-centric measures of innovation that sheds light on the difference between studying innovation, doing innovation and how both those activities can complement each other. These research studies should aim at answering questions such as when evaluative measures are influential in actors' decision-making and vice versa (which actor-centric measures can also be evaluative measures).
- Further research and measures are needed to assess relationships and interactions between actors in an innovation system. This has been well explored in university-industry partner-

ships for research and entrepreneurship. But, like the context of education and workforce development, other modes of knowledge exchange can be explored further.

- Further work can be directed at studying and developing qualitative and quantitative measures for assessing Guidance of Search and Legitimation functions of technological innovation system.

#### **8.4 Critical Reflections: Lessons from Practice**

Even though a dissertation is theoretical and research oriented, I embedded myself in various practices of innovation through different program and opportunities afforded to me through the Buerk Center for Entrepreneurship and Pack Ventures. These opportunities provided a “boots on the ground” view of what it means to be “doing” innovation, beyond just measures. This section outlines some lessons learned from these experiences and elements of the research that formally did not make it into the three studies but provided opportunities for critical reflection.

##### *8.4.1 Messiness of “doing” innovation*

Having reached the finals of a business plan competition (Hollomon Health Innovation Challenge), completed a technology commercialization fellowship, volunteered for a technology accelerator, and interned at a venture capital fund, provided a first-hand exposure to the human element of innovation. Measures of innovation can only go so far in capturing the complex process of innovation. Through these experiences, I learned that oftentimes human relationships play a much more important role in innovation than literature or research assert. For example, in many cases, a technology might be much more superior, but the entrepreneur may not be liked by their investors, or may not be “coachable”, which may lead the investors to invest in a somewhat inferior technology with a likeable or “coachable” CEO. No measure discussed in this dissertation addresses this important aspect of the process. Additionally, there is no right way to innovate. Actor perceptions and guesses about a technology, market or sector are often contradictory and inaccurate. Their beliefs about a technology are a function of their network. Therefore, it is common to find groups of actors who may hold one belief regarding the success of an innovation and another group who may hold an opposing belief. An example of this was when I was helping a digital health CEO with

go-to-market for his product. Some mentors wanted the CEO to be more conservative with funding conversations and not directly say that he will close the next round of funding to attract investors on the fence. While others wanted him to be clear that he would close the round. Similarly, some mentor immediately understood what the company was doing, while others needed more time and were more skeptical. Therefore, while measures of innovation maybe able to measure perceptions, they may never be able to measure accuracy of those perceptions. This push and pull between confidence and skepticism is what drives an innovation system and results in certain innovations gaining prominence over others. Finally, confirmation bias is real. In many cases, actors maybe persistent regarding their belief about an innovation. No amount of data, measuring or assessment can change that belief. This can break the availability-influence framework, as despite the availability of a measure and potential influence, the decision has already been made and is unchangeable.

An additional lesson learned was that just because an idea or innovation is good for society does not mean that it is good for business. Many times, innovations that are focused on social good find a hard time finding a market or investors. LDES technologies are a prime example of this. Scientific studies have shown that in the longer-term LDES can result in lower cost strategies for decarbonization, however the skepticism among actors persists. I encountered the same phenomenon when being involved with novel medical devices or digital health applications for social good. In the US, early-stage innovation is focused on traction and revenue. Many social good innovations either do not have a clear path to profit or require partnering with government organizations, which are slow, result in longer sales cycles and are not suitable for fast-paced early companies. Therefore, while considering further evaluative measures for social impact, one might want to consider this.

Finally, in the words of an industry executive I once met “statistical significance does not mean business significance”. Just because a technology is technically proven through studies and trials does not immediately guarantee success. This is a clear case of when an invention may not be an innovation and another reason why simply measuring research publications and patents are not the best indicators of innovation.

#### 8.4.2 *Are we “doing” innovation?*

A semi-structured interview study that is not officially discussed in the dissertation was an interview study of 9 industry sponsored engineering capstone students who were first asked what innovation meant to them, followed by a description of what they did during the capstone and then asked do they think they were innovating during the capstone. A distinct finding of the study was that almost none of the students explicitly thought that they were “doing innovation” during the capstone. However, their personal definitions of what innovation meant to them aligned with their descriptions of their project work. For example, some students described innovation as using existing theories or technologies to make products better, develop new products or applying them to other domains. In many cases, that is exactly what students ended up doing, “taking bits and pieces from other people’s projects and calling it their own” as one student put. However, none of these students recognized that what they were doing during the capstone was innovation at a small-scale. This demonstrates a need for measures of innovation in education, so that students can recognize that they are learning actual innovation skills that can be applied once they graduate. Further, measuring innovation in an educational setting help universities and industry assess how they are currently preparing and how they can better prepare their students for skills of the future.

#### 8.4.3 *The Equity Problem*

A theme that was implicit in some of the interviews in Chapter 5 was that of equity. Throughout different conversations, question of “who is able to innovate and participate in innovation ecosystems?” lingered. It emerged that innovation systems are inherently inequitable. These inequities were systemic and pervaded actor interactions with both digital tools and human resources. A key source of inequity was the social and generational capital required to be an entrepreneur or an investor. One entrepreneur commented how she was advised to raise an initial “friends and family” round of funding, where she sought funding through personal network and family ties. However, she commented that she did not have friends and family who were able to fund her enterprise, which potentially set her back. Similarly, social, and generational capital also determines who an individual is connected to [198], which plays an important role in who an individual can reach out to for their information needs. Those who do not have adequate social and generational capital

to support their innovative activities must do an immense amount of work upfront to build that kind of capital. A related source of inequity is systemic underrepresentation of minorities in related disciplines. This dissertation is primarily focused on “high-technology” and STEM industries. It is no secret that minorities are underrepresented in these fields [200, 77]. Therefore, who goes through the STEM pipeline as a student, scientist, employee, entrepreneur etc. has downstream effects on who is able to participate in a technological innovation system. Finally, inequity in the context of digital tools exist in the cost associated with these tools. For example, an annual license for Pitchbook costs \$25,000 [190]. Similarly, market and industry report costs are in the range of \$1500-\$8000 each [20]. Additionally, different academic publishing venues also impose annual subscription costs to access articles [133, 71]. Therefore, the pricing of these tools indicates that they are not built to support low-resource stakeholders who do not have the means or organizational ties (for example, being at a university) to purchase these digital services.

These inequities are also seen across institutions and regions, when looking at university spinoffs, a few universities emerged as being at the forefront, namely Stanford and MIT. Similarly, looking at regional difference in innovation activity (via R&D funding, venture funding etc.), California, Massachusetts and New York emerged as being at the top by a long shot. Therefore the “innovation capital” in the US is located in a few regions and (often elite) institutions. Therefore, if an individual does not have the privilege to be in these locations and institutions, then their access to the intellectual, social, and financial capital for innovating is limited by a large degree.

Just like many other systems and fields of practice, the system and practice of innovation is an inequitable one. Not only do innovation systems favor those who have the social and generational capital to engage in innovative activities, but it may also favor certain personality types (those who may be willing to be more “agreeable”, “coachable” or “outgoing”), certain institutions and certain locations. Therefore, a question to consider is “what are ways in which we can ensure that doing innovation is equitable?” This opens the door to the inclusion of new types of measures that can answer questions such as “how do we measure diversity in innovation?”, “how do we include underrepresented voices in the innovation process?” and “how do we education the general populace on the various ways in which they can participate in their chosen innovation system?”

### **8.5 *In Closing***

This dissertation opened with the question of how innovation can be measured. It then delved into the details of framing innovation in various settings and contexts, which resulted in the emergence of two complementary frameworks innovation measurement. Are these frameworks enough for measuring innovation? The short answer is no. As discussed in the critical reflections (Section 8.4), the innovation process is messy, complex, and unpredictable. The frameworks developed in this dissertation provide a lens to frame the process in order to measure it. The hope is that these frameworks can enable a more holistic measurement of innovation that harmonize the study of innovation with the practice of doing innovation. The concluding claim of this work is that combining the study of the innovation process with the practice of innovation can help bridge the gap between both realms that can ultimately enhance both, the study of innovation and the practice of innovation.

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## Appendix A

## TASKS AND ACTIVITIES OF ACTORS IN AN INNOVATION SYSTEM

Participant #	Group	Tasks	Key Innovation Functions
1	O & U	This participant was involved in setting up a chapter of an accelerator program geared towards advancing technologies in computational health in the Seattle region. This involved raising funds from donors, corporate sponsors, and non-profit organizations to operate the accelerator, get buy-in from over 25 industry-specific mentors, moderating sessions between entrepreneurs and mentors, and sourcing and vetting cohort companies. Within an innovation system, this participant's work is in the earlier stages of innovation.	Resource mobilization, guidance of search, knowledge exchange, legitimization
2	C	This participant worked at a large technology corporation. Their main goal was to expand the company's key product portfolio by "selling a deal" to potential clients. Within the innovation system, this participant's work lies in the later stages of the innovation process; after a product has been commercialized. This participant evaluated different potential deals to sell the product of their company and worked with internal teams to ensure that the deals are signed and delivered responsibly to a client.	Market formation
3	C	This participant worked at a small consulting company that created market and innovation reports for different clients. Within the innovation system, this participant's work is not directly impacting the innovation of a product or a technology but is evaluating the "lay of the land" for a specific industry. The participant's role involved doing market research and research on risk capital in a specific technological or industrial topic as requested by a client.	Knowledge development, guidance of search
4	O & C	This participant worked at an accelerator, in charge of operations. Prior to their work at the accelerator, they worked at a medium sized start-up as a sales representative. In their role at the accelerator, their key responsibilities included helping source and vet early-stage start-ups for the accelerator cohort, designing, and updating documents following the company's progress through the accelerator, facilitating mentorships between the startup founders and mentors, and overseeing other venture managers doing the same role. In an innovation system, this participant, just like participant #1 falls in the early stages of the innovation process.	Resource mobilization, guidance of search
5	U	This participant works at a university and oversees the engineering college's industry partnership program for education. Their role is to source and vet companies for the program in collaboration with department heads, manage the program budget, ensure that legal agreements are signed, ensure that industry partners are paired with student teams and that partner projects are successfully progressing through the program. Within an innovation system, this participant's work does not directly impact the creation of an innovation but focuses on the development of a workforce who may then work in organizations/companies that directly participate in the innovation process.	Resource mobilization, knowledge exchange

Participant #	Group	Tasks	Key Innovation Functions
6	ED	This participant worked at a regional economic development agency as a program manager. Their job is to oversee the agency's innovation portfolio, work with the state and federal government to address regional economic issues and administer economic development studies to measure the impact of their programs. Within an innovation system, this participant's work focuses on driving mission-based innovation projects and convening actors and funds to support the same.	Legitimation, knowledge exchange, resource mobilization
7	E	This participant works at an early-stage medical devices start-up. Their role involves overseeing the marketing and sales efforts, manage strategies for clients, address client pain points through the product, incorporate customer feedback into product development, set business goals for the company and source new customers. Within an innovation system, this participant is in the early stages of the innovation process.	Entrepreneurial experimentation, knowledge development, resource mobilization
8	U	This participant is a technology transfer manager at a university. Their role involves reporting innovation disclosures out of research labs at the university and filing copyright claims for university's software IP. Within an innovation system, this participant lies in the very early stages of the innovation process, just as technology is coming out of a research lab.	Legitimation
9	U	This participant works at a university's entrepreneurship department. Her key responsibilities are managing the department's annual healthcare business case competition, manage all the graduate programs for the department, and manage fellowships that the department runs over the summer. Her tasks include helping with admissions and graduation to and from the program, finding judges for the competition, selecting teams for the competition, event management and organization and help prepare teams for the competition. Within an innovation system, this participant's work lies under two categories: (1) their work with the business case competition addresses the early stages of the innovation process, and (2) their work with entrepreneurship education is like participant #5, where it does not directly contribute to innovation but helps develop the talent and workforce who might eventually contribute to the innovation process.	Resource mobilization, knowledge exchange, guidance of search
10	ED & E	This participant works as at a small consulting firm and their responsibility is to help international clients find market access in the US. The participant often works with clients who develop novel technologies and are looking to expand their market. Their main task is to source and vet these clients and connect them to other system actors. Within an innovation system, this participant somewhat directly supports the innovation process, by support early-stage innovations find adoption.	Market formation
11	E	This participant works at an early-stage internet start-up. Their role involves developing software for their product, acquiring new customers, obtaining funding and plan business strategy. Within an innovation system, this participant works in the early stages of the innovation process.	Entrepreneurial experimentation, knowledge development, resource mobilization
12	E & R	This participant works as both an entrepreneur and an investor. Their responsibility towards their start-up includes defining business development goals, raising funds, developing the product and acquiring new customers. As an investor and partner in multiple venture firms, they are involved in sourcing new deals (companies) to the venture firm and making strategic investment decisions based on what they know about the technology and the business. Within an innovation system they operate in the early stages of the innovation process before the new product or process has seen large-scale commercialization.	Entrepreneurial experimentation, knowledge development, resource mobilization, guidance of search
13	U	This participant is a technology transfer manager at a university. Their role involves reporting innovation disclosures out of research labs at the university and filing patents and licenses for university's software IP. Within an innovation system, this participant lies in the very early stages of the innovation process, just as technology is coming out of a research lab.	Legitimation

Table A.1: Actor Tasks and Activities

## Appendix B

**INDUCING AND BLOCKING MECHANISMS FOR THE LONG**

## DURATION STORAGE INNOVATION SYSTEM

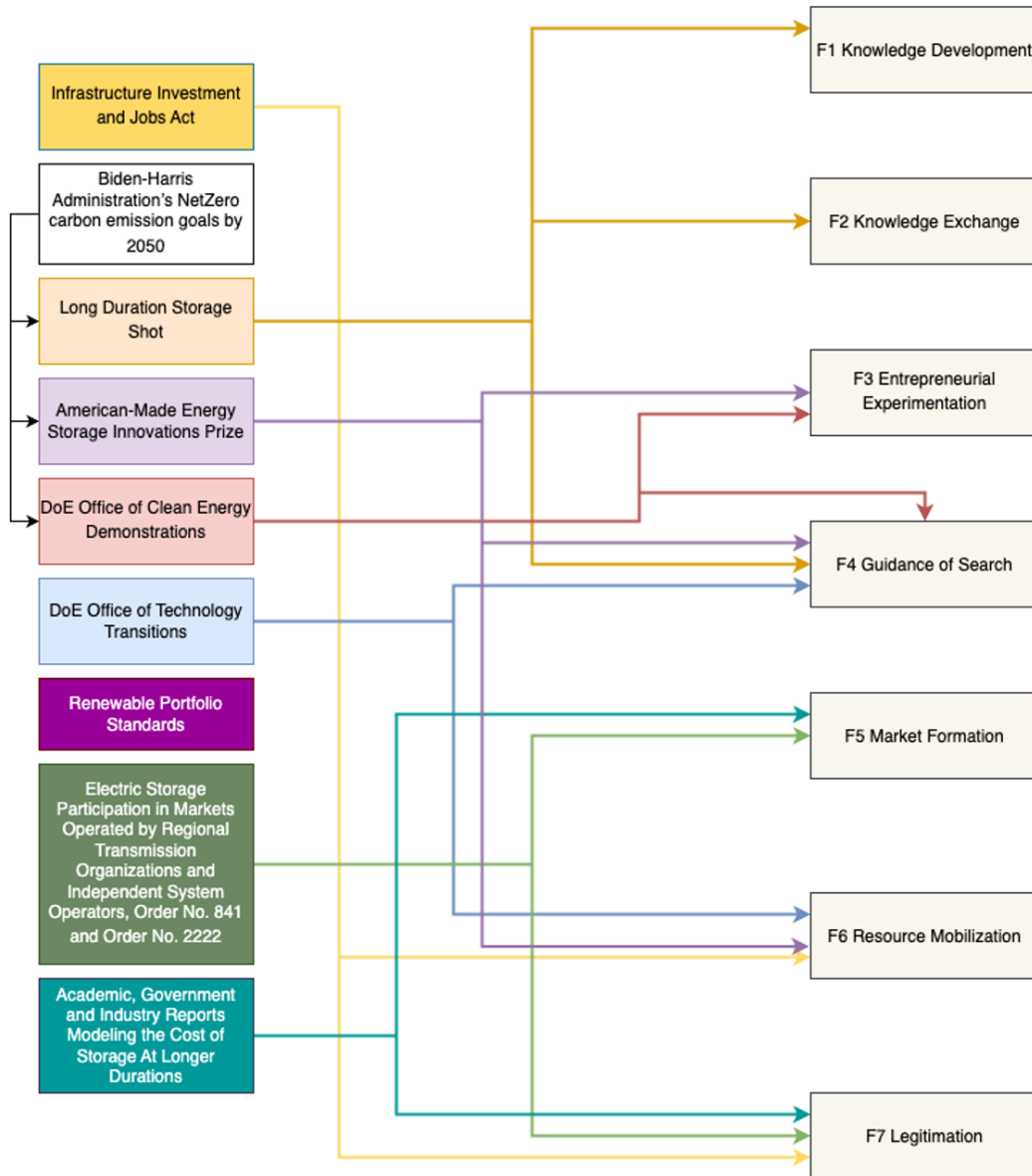


Figure B.1: LDES Innovation System Inducement Mechanisms

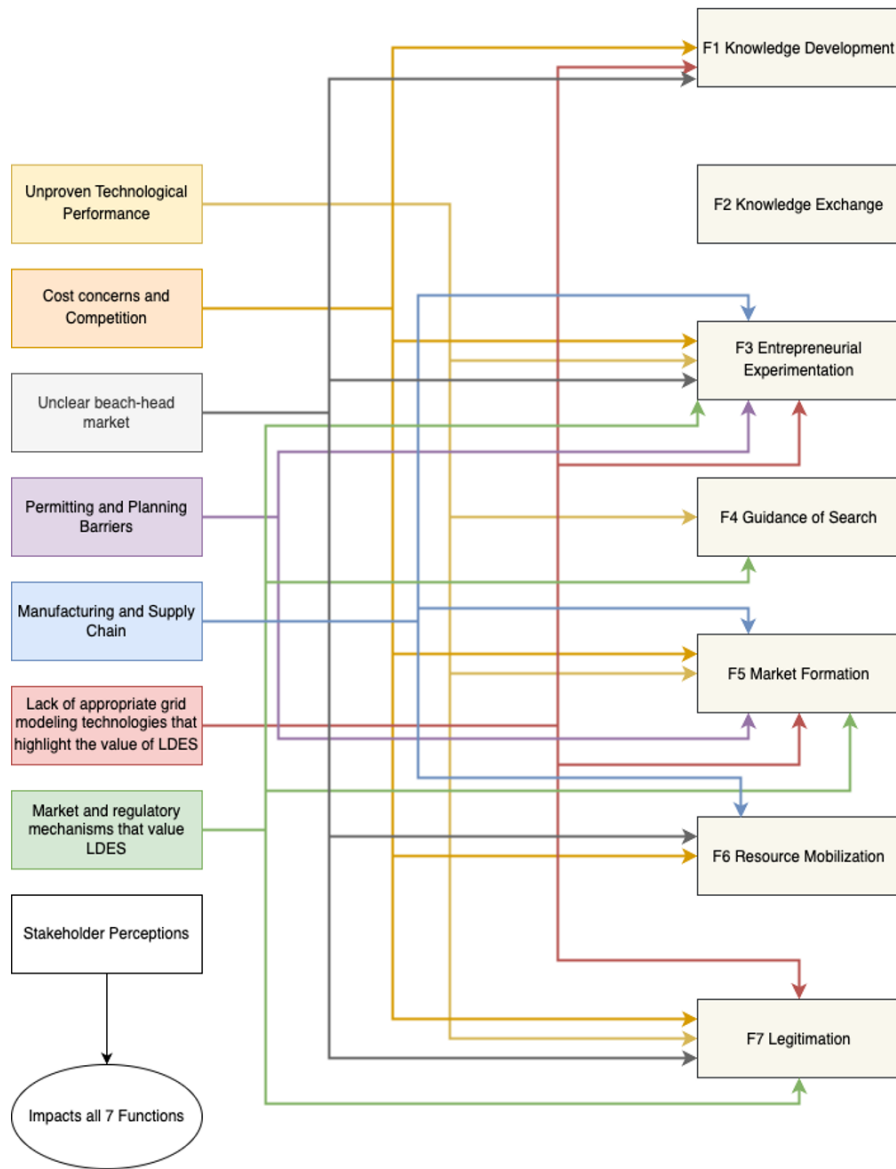


Figure B.2: LDES Innovation System Blocking Mechanisms

## Appendix C

## FRAMEWORK OF INNOVATION MEASUREMENT FOR THE LONG DURATION STORAGE INNOVATION SYSTEM

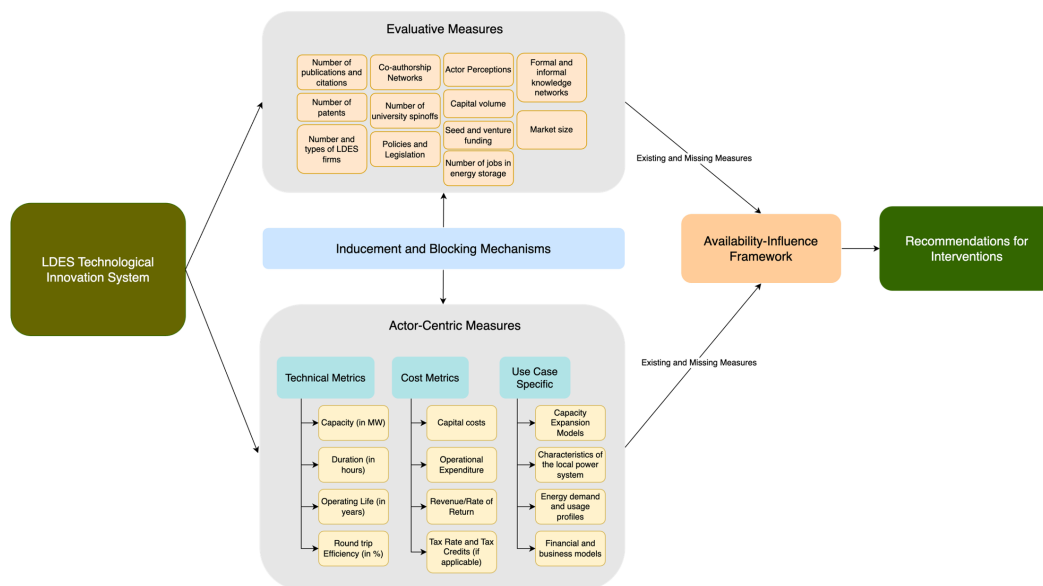


Figure C.1: The process of analyzing and identifying evaluative and actor centric measures to obtain recommendations for the long duration energy storage innovation system