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Scaling up battery innovation for carbon neutrality: From Lab Bench to Marketplace

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Acronyms and Abbreviations

BNEF	BloombergNEF
CalSEED	California Sustainable Energy Entrepreneur Development
CEC	California Energy Commission
DOE	U.S. Department of Energy
IEA	International Energy Agency
kWh	Kilowatt-hour
LIB	Lithium-ion battery
MW	Megawatt
PV	Photovoltaic
R&D	Research and Development
RD&D	Research, Development and Demonstration
SGIP	Self-Generation Incentive Program
TRL	Technological Readiness Level
U.S.	United States

Executive Summary

As many regions and countries in the world commit to carbon neutrality goals, they are also looking at ways to deploy innovations on a large scale to advance climate change mitigation and adaptation. According to a 2018 Intergovernmental Panel on Climate Change report (Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, 2018), limiting global warming to 1.5°C will require "rapid and unprecedented" changes in all aspects of society over the next decade, with widespread adoption of climate-driven innovation and practices. According to the U.S. Department of Energy (DOE) Energy Innovation Portfolio Plan, the projected value of the global clean energy market over the next 20 years is more than $60 trillion (U.S. Department of Energy, 2017).

Successfully deploying energy innovations at scale requires coordinated effort among multiple local and global actors. Governments, the research community, private-sector firms, and the public all play critical roles in developing and scaling up clean energy innovations. These roles and activities include generating knowledge, facilitating access to resources, and creating effective business and institutional environments for developing and deploying clean energy innovations. The roles and activities undertaken by each participant evolve over time, in tandem with the development and maturation of a particular innovative technology.

According to Organization for Economic Co-operation and Development (OECD), innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practices, workplace organization or external relations (OECD/Eurostat, 2005). It is well understood that innovations entail more than science and technology; transforming knowledge into product, processes, or services, requiring "a network that includes all important economic, social, political, organizational, institutional and other factors that influence the innovation development, diffusion and use" (C. Edquist & Johnson, 1997). Many innovation studies thus take an "innovation system" approach to understand the flows of technology, information, and finance among people, enterprises and institutions (OECD, 1997a).

Numerous studies have characterized the elements of clean energy innovation system in the U.S. Previous work (Breakthrough Energy, IHS Markit, & Energy Futures Initiative, 2019; National Academies of Sciences Engineering and Medicine, 2021; Surana et al., 2020) agreed that the U.S. excels at funding the beginning of the innovation cycle, but technologies face substantial barriers at the point of scale-up. It calls for more successful models and actions to guide clean energy innovation at the federal and regional levels, as well as from private sector. These works also highlighted that the energy systems have distinct features that make energy innovation especially challenging, and that not all energy innovations and regions follow the same diffusion model.

Building upon the existing studies, this report provides an overview of a clean energy innovation system using battery storage as an illustration. We highlight the evolution of actors during the process of building a clean energy innovation system, focusing on two elements: changes in actors' roles, and the nature of public and private participants' activities during various stages of

the development of innovative clean technology and at varying points in the supply chain for the particular technology.

Our description is based on a review of current academic and grey literature, 50 stakeholder interviews, and industry data from the research firm BloombergNEF (BNEF). Understanding the changing dynamics of a clean energy innovation system as it grows will help inform future research and development (R&D) and industry decision making to address the pressing climate crisis.

Adaptation: the evolution of actors in the clean energy innovation environment

As clean energy technologies have matured during the past 10 years, the systems supporting the development of innovative new technologies have evolved to become more strategic and adaptive. Roles of public and private actors in the innovation environment have shifted, and new actors have entered the mix, demonstrating the importance of institutional (government and corporate) participation in the scaling up of clean energy technologies. Accelerator programs have emerged, and non-traditional actors such as banks and insurance companies have also become engaged. These phenomena indicate that the traditional "triple helix" of participants -- government, academic researchers, and industry -- has evolved and expanded. Changes in one of the agents force the other agents to evolve. Figure ES shows how actors engage in developing and deploying clean energy technologies through the stages of the innovation process. Note that the actor engagement is shown as their levels of investment in this figure. Other types of engagements in terms of creating new programs and new entry of actors will be discussed below.

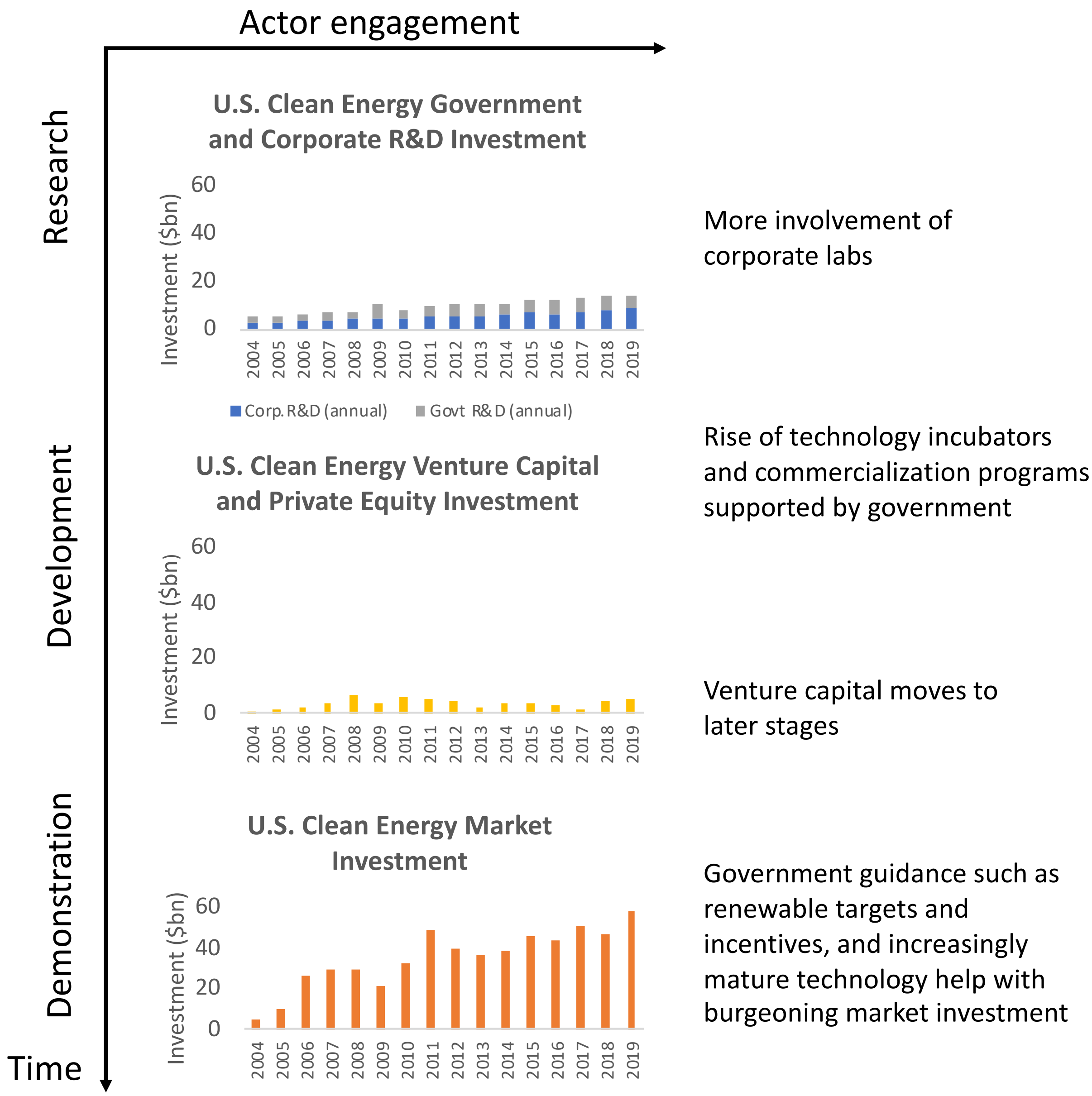

Figure ES-1. Evolution of actor engagement in developing and deploying clean energy technologies at different innovation stages[1]

The key findings from our analysis of the adaptations that have taken place in the innovation system supporting battery storage as the technology has evolved in the U.S. focus on:

[1] Note: The quantitative investment data was sourced from BNEF; Market investment includes asset finance (dominant asset type), public markets, small scale solar investment, and re-invested equity; Clean Energy covers wind, solar, biofuels, biomass & waste, energy smart technologies (i.e., digital energy, smart grids, power storage, hydrogen and fuel cells, advanced transportation and energy efficiency on both the demand and supply side), as well as other renewables including small hydro, geothermal, and marine technologies. The qualitative statements are supported by the numbers of policy and programs, size of investments, and what we learned from the interviews.

government action to fill gaps left by the private sector, an increase in corporate venture capital, and the appearance of boundary-spanning and cross-cutting intermediary organizations.

Government fills gaps left by private sector

Using battery storage as an example, we find that as battery storage innovations have progressed and policy makers have continued to create guidance and incentives to encourage private investment, some states have stepped up to address gaps in private funding. States have supported creation of intermediary organizations that facilitate knowledge flow and focus on industry segments that have not drawn the attention of venture capital investors. One example is California, which has introduced an energy innovation ecosystem initiative[2] to connect entrepreneurs with resources and training. The state's involvement came in response to a withdrawal of support from private-sector investors starting in 2013.

Increasing involvement of corporate venture capital

Even as government has in some cases taken a more active role in supporting development of battery storage technology, venture capital has in other cases played an increasingly important role. As battery technology innovations matured, corporate venture capitalists began engaging more and earlier with start-up enterprises, providing R&D support (see Figure 1) as well as exit strategies. What was once a sector with investments characterized by a lack of exits has attracted the attention of the automotive industry, oil and gas companies, and utilities and insurance companies. Compared to private venture capital, corporate venture capital has capacity to make larger investments and has greater access to channels for arranging contracts and as well as greater access to customers.

Rise of boundary-spanning and intermediary organizations

Another evolution we see in maturing clean energy innovation systems is an increasing number of accelerator and intermediary organizations managed by government, industry, and university and research institutes. These include professional associations, public funding coordinators, regional innovation clusters, insurance companies, test-bed facilities, and accelerator programs such as Cyclotron Road initiated by both public and private actors. These organizations bridge boundaries among different disciplines and segments of the innovation economy and play critical intermediary roles, fostering knowledge and resource flow among actors.

System building: institutional support through stages of innovation and across industry segments

An effective innovation system is not only adaptive at various stages during the process of developing an innovative technology, but also provides for specific institutional support across the value chain for that technology. Using battery storage as an example, we characterize the activities of government and private actors in various industry segments. Figure ES-2 shows the state of the business and institutional environments for battery storage.

Our overall findings regarding system building and institutional support are that more federal support is needed throughout different stages of innovation development and deployment;

[2] See https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/energy-innovation-ecosystem

Since 2010, the government RD&D support[3] for energy storage has remained much less than the investment in other clean energy technologies including solar, wind, biofuels, and hydrogen and fuel cells, see

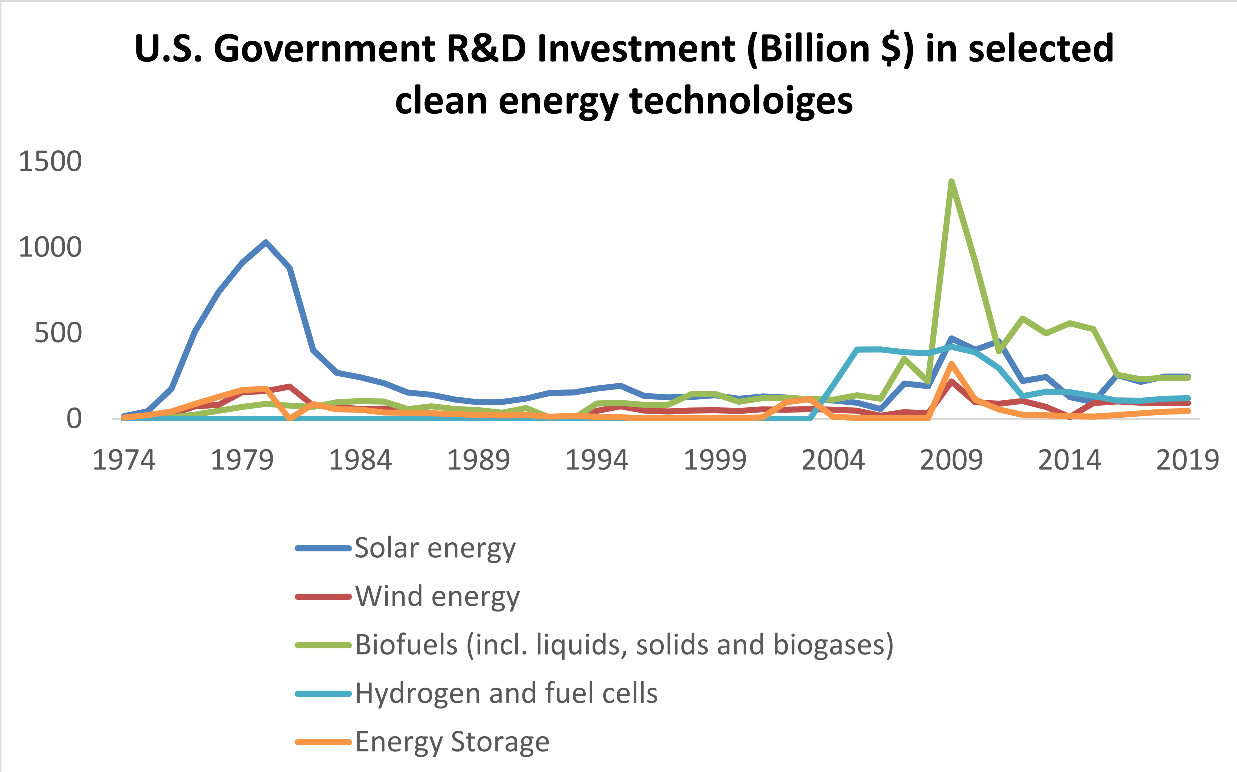

Figure 10. Other insights include the importance of linking different parts of the innovation value chain, as exemplified in the leading regional innovation cluster.

[3] Note that the RD&D data may not be accurate because energy storage spans diverse technologies and applications, and federal RD&D relevant to it is dispersed across the government.

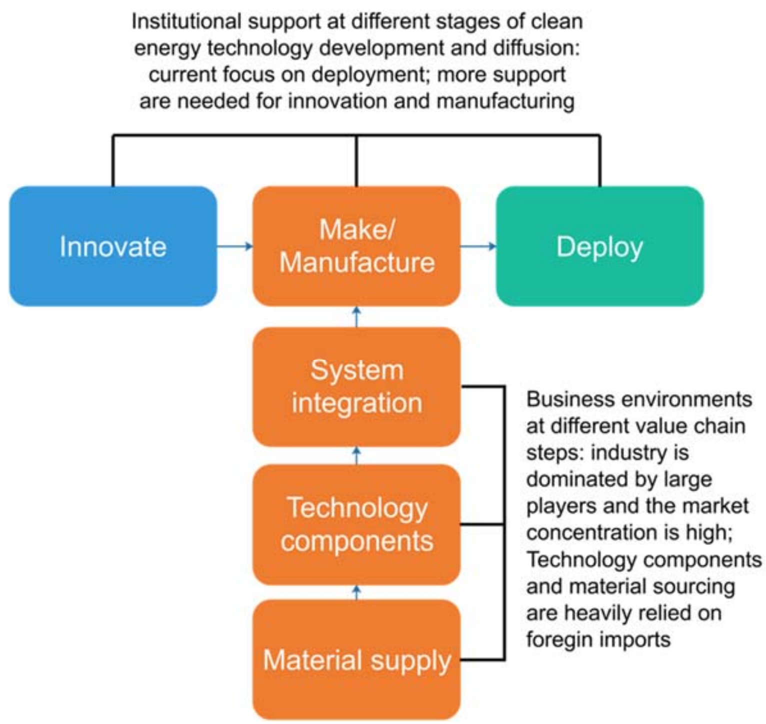

Figure ES-2. The state of business and institutional environments for battery storage

Institutional support from federal government could be essential

At the federal level, mission-oriented innovation policy have started to gain traction recently, e.g., the initiation of "Energy Storage Grand Challenge". Figure 15 mapped out the key federal and state storage related policies over time. Even though lithium-ion battery storage has matured to some degree, increased federal support will be critical to diversify storage technologies and address supply chain issues. Patent activities (International Energy Agency and European Patent Office, 2020) show that the U.S. is less competitive in battery storage knowledge-generation than the countries who are leading in this technology, including Japan and South Korea. Battery innovation takes place in small and medium enterprises that do not have the capacity to make large-scale increases in production and deployment, financial support will be necessary to scale up the new technologies developed by these firms. Similar to European Union (EU) and China, U.S. could also consider reviving manufacturing policy such as loan programs, tax credits, and advanced national EV targets that have successfully driven battery demand in other countries. Because energy storage is a critical element for climate resilience and national security, countries may need to continue drive mission-oriented innovation policies that not only address the economic viability of battery production, but also support R&D and firms that help to sustain a domestic supply chain, even at a higher cost.

Leading regional innovation system encompasses industrial activity for all phases of technology development and deployment

California's institutional supports for battery storage are particularly strong. In addition to effective downstream market-pull policies related to the state's aggressive climate agenda, California has also introduced systemic climate resilience policies in response to recent increases in wildfires and power outages. These include updating building and fire codes to accommodate larger battery storage capacity, clarifying the role of battery storage, mandating solar photovoltaics (PV) for new homes, and providing generous incentives for vulnerable communities to install combined PV and storage. California has also actively engaged with upstream R&D policy and mid-stream manufacturing policies, for example by initiating the "Lithium Valley Commission," a blue-ribbon panel of the California Energy Commission whose mission is to review, investigate, and analyze opportunities and benefits for lithium recovery and use in the state. The state has taken the first step to address a range of issues that arise during various phases of clean energy innovation from R&D to manufacturing and market demand.

U.S. battery storage industry is currently dominated by large players at the late steps of the value chain

Most federal and state policies foster downstream battery storage demand, and most firms' activities follow a similar pattern. The U.S. battery storage industry is characterized by a few big players focused on the demand sector (with a HHI score[4] ranging between 2000 to 6000 since 2011), including electric vehicles. The relation between innovation and competition is extremely complex. From a public policy perspective, it will be important to ensure firms' access to production-related technology knowledge and innovation funding mechanisms, because battery technologies are still changing rapidly. Looking at the value chain, the industry has so far not been able to fully capture values at the upstream and mid-stream, and is particularly vulnerable as far as supply chain security is concerned. This indicates the importance of supporting knowledge and financial resources needed for materials recovery and manufacturing capacity, as well as developing alternative technologies that are not constrained by current supply chain limitations (e.g., lack of domestic supply of key raw materials components of batteries). To address these concerns, DOE in 2020 initiated the Energy Storage Grand Challenge program, which was well-received by the research community and industry. New federal policies are expected during the next few years to firm up the role of energy storage in energy transition and climate resilience in the U.S.

Future research

This study is a scoping work to understand the high-level architecture of the system that supports battery storage innovation. Future work should characterize detailed new policies and activities for specific innovations and industry segments and revisit existing policies to assess their efficacy as the battery innovation environment evolves.

The framework used in this report enables us to analyze innovation policy gaps by examining actors and their activities during the phases of development of an innovation (over time) and in different industrial segments. We believe this framework can be applied to the development of innovations in other clean energy technology areas, enabling us to answer questions regarding

[4] "HHI" means the Herfindahl–Hirschman Index, a commonly used measure of market concentration. The agencies generally consider markets in which the HHI is between 1,500 and 2,500 points to be moderately concentrated, and consider markets in which the HHI is in excess of 2,500 points to be highly concentrated. See https://www.justice.gov/atr/herfindahl-hirschman-index

who can best diffuse and scale up innovations, and when and how to do so.

1. Introduction

As many regions and countries in the world commit to carbon neutrality, they are looking at ways to deploy technology innovations on a large scale to mitigate and adapt to climate change. According to an Intergovernmental Panel on Climate Change report (Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, 2018), limiting global warming to 1.5°C will require "rapid and unprecedented" changes in all aspects of society over the next decade, including widespread adoption of cleantech innovations[5] and practices to address climate change.

The United States (U.S.) has been seen as a leader in breakthrough science, with many elements in place that support technological innovation, including strong regulatory and business environments, an entrepreneurial culture, and access to highly skilled labor. According to the U.S. Department of Energy (DOE) Energy Innovation Portfolio Plan, the projected value of the global clean energy market in the next 20 years is more than $60 trillion. U.S. participation in development of clean energy innovations would contribute to meeting global climate targets while capturing job and other economic benefits for the American people and U.S. manufacturing (U.S. Department of Energy, 2017). The socio-economic benefits of clean energy innovation are well documented. According to DOE reviews of six public clean energy research and development (R&D) programs, the overall annual rate of return on those R&D investments has been more than 27% since 1975, with a benefit-to-cost ratio of 33:1 (11:1 at a 7% discount rate (Dowd, 2017).

This scoping study looks at the nature of the regulatory, institutional, and business environments in the U.S. that support development of technological innovations, from conception through prototyping, testing, scaling up manufacturing, and bringing new products to market. The successful deployment of clean energy innovations at scale requires coordinated effort by various actors at the global, national, and local levels. The multiple elements that support development of technological innovations are sometimes referred to as an "innovation ecosystem" or "innovation system."

Numerous studies have provided insight into the state-of-the-art ecosystem that supports U.S. clean energy innovations. A report by Breakthrough Energy comprehensively described the groundwork of the clean energy technology innovation ecosystem in the U.S today (Breakthrough Energy et al., 2019), highlighting the role of rich, durable collaboration among governments, universities, research institutions, industry, and entrepreneurs. The success of the U.S. scientific breakthrough and how it connects with innovation system in other countries has been illustrated in the development of solar photovoltaic (PV) technology (Gregory F., 2019). By comparing cleantech to other industries such as biomedical and software, a study (Gaddy, Sivaram, & O'Sullivan, 2016) points out that some cleantech, especially products and services that rely heavily on hardware and material innovation, does not fit the risk, return, or time profiles of traditional venture capital investors. The authors argue that the clean energy sector requires a more diverse set of innovation models and actors, especially policy makers, institutional investors

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[5] We use the term "cleantech innovations" to refer to energy-efficiency, demand-side management, electric vehicles, and smart grid technologies along with renewable energy and energy storage.

and corporations.

Building on these prior studies, we use battery storage as an example to paint a dynamic picture of the evolution of the innovation system supporting development of clean energy technologies in the U.S. We chose battery storage because this technology has evolved rapidly, as has its supporting innovation system. We focus on two elements of the evolution of the innovation system that has supported development of new battery technologies: changes in the roles of actors participating in the system, and the nature of the support for technological innovation during the steps in the process and across the links in the value chain for that technology.

The roles of actors in the system supporting clean energy innovation include mobilizing resources, networking, providing policy support, generating and managing knowledge, managing and carrying out activities in each link of the value chain. Our research highlights the importance of adaptation as the innovation system evolves along with the technology.

The work described in this report is based on 50 stakeholder interviews, proprietary data, and an extensive literature review.

The remainder of the report is organized as follows:

- Section 2 introduces key concepts and framework for mapping the clean energy innovation support system.
- Section 3 describes the battery storage case study, highlighting the roles of actors in the battery storage innovation system, access to resources, and the institutional and business environments in which lithium-ion battery technologies (LIB) have evolved.
- Section 4 summarizes our key findings.
- Sections 5 and 6 contain reference and appendix material, respectively.

2. Mapping a Clean Energy Innovation System

According to OECD, innovation is the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organizational method in business practices, workplace organization or external relations (OECD/Eurostat, 2005). Clean energy innovations typically increase the efficiency of fuel use, produce cleaner energy, and create more sustainable lifestyles or approaches to consumption. In the case of battery technologies, innovations have encompassed not only new chemistries and materials, but also new processes for every link in the value chain, from conception through manufacturing to distribution.

It is well understood that innovations entail more than science and technology; they are embedded in a network that includes "all important economic, social, political, organizational, institutional and other factors that influence" their "development, diffusion and use" (Charles Edquist, 1997). The "system of innovation" approach "stresses that the flows of technology and information among people, enterprises and institutions are key to the innovative process (…) [that is] the result of a complex set of relationships among actors in the system, which includes enterprises, government, and universities and research institutes" (OECD, 1997b). Innovation systems can be analyzed at many levels: global, national, regional, sectoral, and technological.

In this report, we focus on the innovation system that supports development and diffusion of clean energy technology, using battery storage as an illustration. We focus primarily on innovation activities in the U.S. but recognize that knowledge from outside the country influences domestic innovation. When appropriate, we discuss clean energy technology innovations at the global, national, and regional levels, with attention to how these activities impact the U.S. clean energy sector during different phases of the innovation process and in different industry segments.

There are multiple ways to define the elements of an innovation system and their relationships. Actors, institutions, and the relationships (networks) among the participants in the system are often identified as the main components. Actors are participants in the system, and the network encompasses the relations and interactions among individuals, groups, and organizations. Institutions can be defined as sets of shared habits, norms, routines, practices, rules, or laws that regulate activities among actors (C. Edquist & Johnson, 1997).

One way to understand the relationships among the components of an innovation system is to focus on what happens in the system, i.e., what activities are carried out by the system participants. The actors, including firms, governments, researchers, consumers, and other supporting organizations, share the same goal: to develop and diffuse innovations. Innovation scholars generally agree on the wide range of activities that should be part of the system although disagreements persist regarding the key determinants that influence the innovation process. From a policy perspective, the system generally encompasses:

- the provision of knowledge, which can be seen as an input to the innovation system
- innovation activities that take place in two key environments: institutional environments that are shaped primarily by public actors, and business environments where firms compete and collaborate

- innovation outputs, which are characterized by the rate and direction of technology advancements and their associated socio-economic impacts.

Figure 1 illustrates these key elements, which involve many and varied actors.

In this report, we focus on evolution of the role of public and private actors in the innovation process and the activities that these actors undertake, which help to build the innovation system for a particular technology. We argue that adaptation and system building are two critical strategies of an effective innovation system.

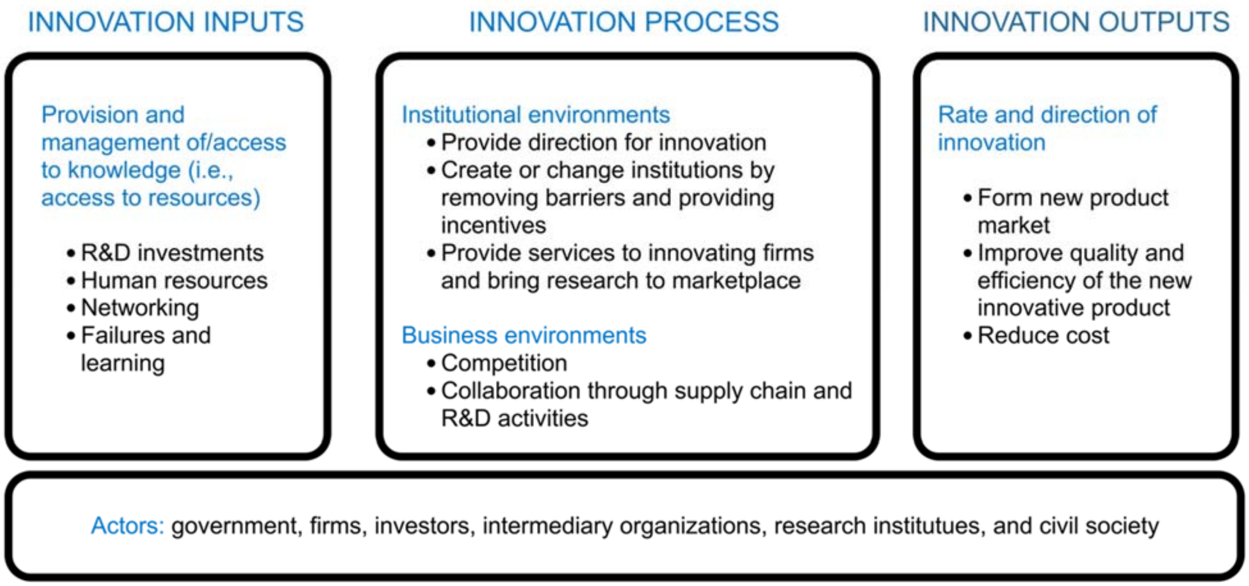


Figure 1 Key activities that influence innovation processes

2.1 Stakeholders and networks

Innovation system actors play dynamic roles, adapting depending on their own expectations and on how others behave as an innovation moves through different stages of development. Although actors in an innovation system share the goal of developing and diffusing innovation, their motivations vary. Aligning varying motivations is one of the key goals of innovation policy. The ultimate goal of governments participating in cleantech innovation is to pursue the societal benefits of economic and environmental sustainability, but national and local government roles differ. National governments are typically more involved in setting long-term R&D direction and supporting basic science whereas local governments tend to be more involved in supporting technology testing and demonstration during later stages of an innovation's development. Investors and private sector look for return on their investments, and some may also act out of a sense of social responsibility.

Innovation depends on coordination among organizations as well as on communication flows along the value chain. Networking is a key topic in innovation studies. The triple helix model,[6] which has been proposed as the basis of Silicon Valley's success, has revealed the importance

[6] The "triple helix model" (Leydesdorff & Etzkowitz, 1996) postulates that, in a knowledge-based society, the boundaries among the public and private sectors, science and technology, and university and industry are increasingly fading, giving rise to a system of overlapping interactions.

of interactions among government, industry, and academia, as well as adaptation to the evolving global economy.

We can observe the changing roles of actors in networks by analyzing their actions. These actions include which resources to access and use, which other actors to team up with, and which networking goals to deem realistic within time and resource limitations (Nyström & Elvung, 2014). Networks can be divided into two types, vertical and horizontal (Porter, 1985). Vertical networks connect firms along a particular production process, and horizontal networks connect individuals or organizations within particular functional areas, such as research, production, logistics, or marketing (Nyström & Elvung, 2014).

2.2 Access to resources

A key determination for actors in an innovation system is which resources to access and use. Resources include financial, human, and social capital. At the outset, R&D investment is an important basis for innovation, particularly for sustainability-driven technologies. Public and private R&D can differ significantly among countries. In the U.S., industry investment in R&D is substantially greater than public investment. The industry share of investment has been as high as 73% in 2018 (NSF, 2020). Since 1980, private R&D has played an increasingly important role in the U.S. economy (see ***Figure 2***). In addition to R&D activities, human capital and learning are important innovation inputs. The analysis in this report will focus primarily on R&D in the public and private sectors.

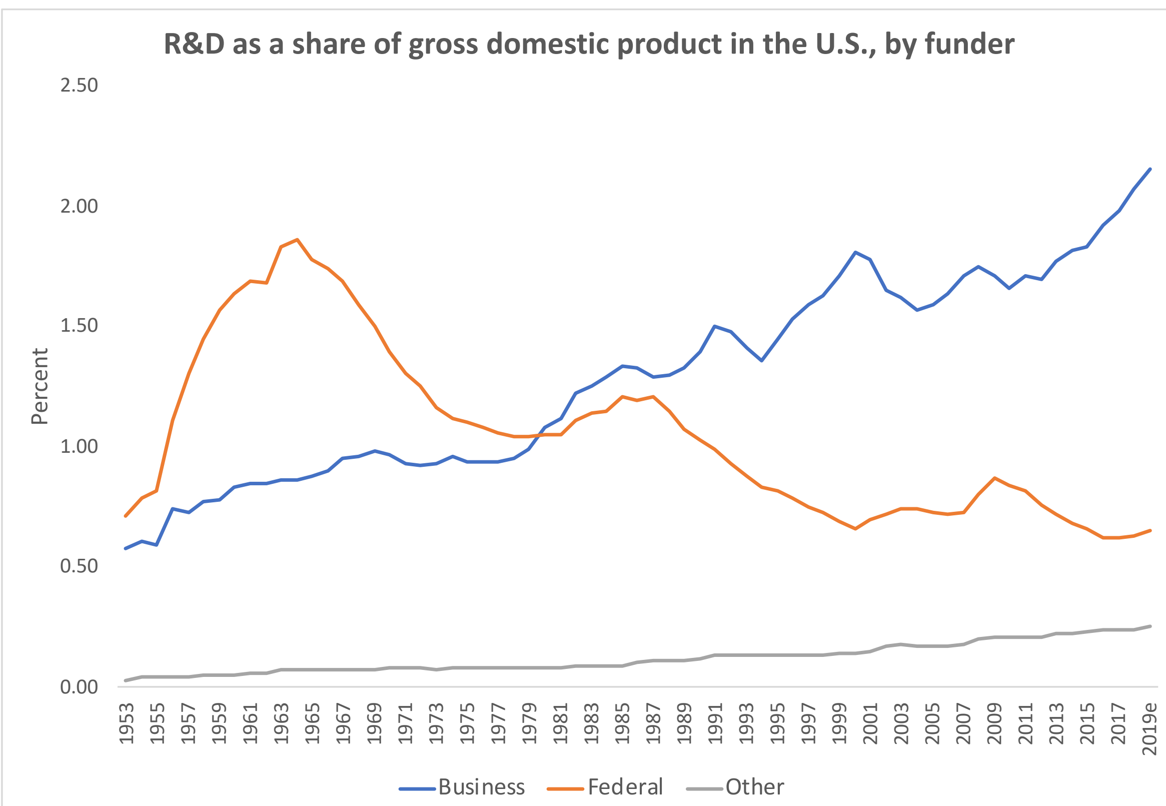


Figure 2 R&D as a share of gross domestic product, by funder

2.3 Institutional environments

Institutions in this report refer not to organizations but to sets of established habits, routines, practices, rules, or laws that regulate the relations and interactions among individuals and groups (C. Edquist & Johnson, 1997). Institutions in this context can be considered the rules of the game. Our analysis focuses narrowly on formal regulatory institutions, encompassing policies specifically designed to address technical, social, and economic barriers to innovation. We differentiate the types of policies that are useful at different stages in the development of an innovation, ranging from upstream R&D (supporting development of an innovation concept), to mid-stream production (supporting manufacture of prototypes and first products), to downstream market pull (supporting deployment of finished products). Upstream R&D policies provide guidance for allocating funding to drive mission-oriented innovation. Mid-stream policies aim to provide incentives and resources for manufacturing. Downstream policies aim to affect the market using strategies such as target-setting, enacting market rules, providing incentives, and devising relevant sectoral policies. Cross-cutting policies are systemic policies that have direct and indirect impacts on an innovation. An example is the climate mitigation and adaptation policies triggered by recent wildfires in the U.S. ***Figure 3*** provides a general overview of policies and their relationship to the stages of development of an innovation, which are abbreviated as “Innovate,” “Make,” and “Deploy.”

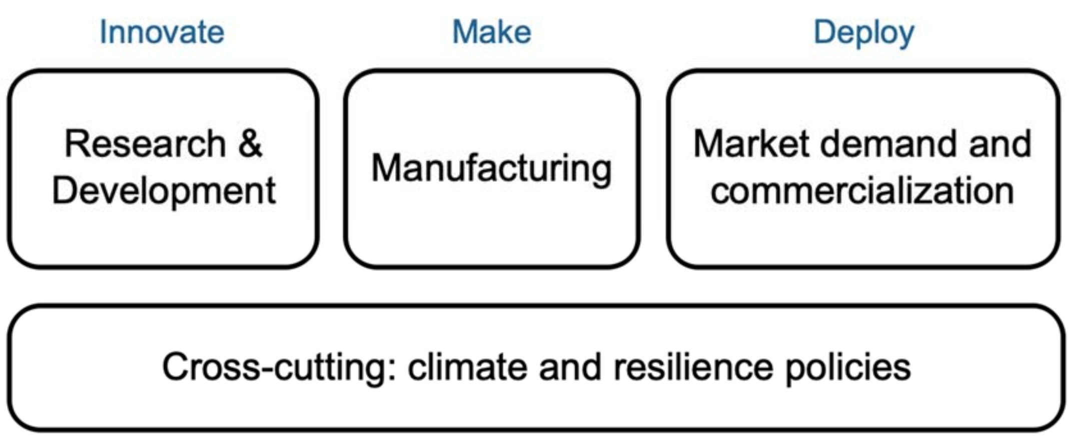


Figure 3 Types of policies and their relationship to stages in the development of an innovative technology

Governments can guide long-term technological vision, support early-stage breakthrough research, stimulate demand through incentives and government contracting, provide services to transfer knowledge from labs to marketplaces, protect intellectual property, ensure environmental and energy justice, and support competitive markets so that new entrants can flourish. Economic, social, and administrative regulations can have numerous effects, positive and negative, radical and incremental, on innovation (Aghion et al., 2014). Effects may be size dependent, so feedback from corporations and small and medium size enterprises may be different. Regulations intended to spur innovation should be flexible and efficient for the target sector (Atkinson, 2020).

2.4 Business environments

An effective business environment to support innovation includes the institutions, activities, and capabilities of the business community as well as broader societal attitudes and practices that enable innovation (Atkinson, 2020). In this report, we are mainly concerned with the activities of firms along the value chain. This includes the competitive landscape in the relevant industry as well as how firms collaborate through supply-chain activities. According to Porter (Porter, 1985), the value chain is the relationship between a company and its upstream and downstream suppliers. The value chain includes activities such as R&D, design, production, marketing, distribution, and support to the final consumer of a product. The activities that take place at different points along the value chain can be carried out by a single firm or by different firms (Gereffi & Fernandez-Stark, 2016). In the context of globalization, value-chain activities are typically conducted by inter-firm networks on a global scale. One of the goals of national innovation policy is to capture the largest number of values along the global value chain. We focus on how U.S. firms engage in value-chain activities in the battery storage case study, with the goal of identifying policies and resources needed to strengthen innovation policy to support the business community. ***Figure 4*** illustrates the components of the business environment, organized in terms of links in the value chain.

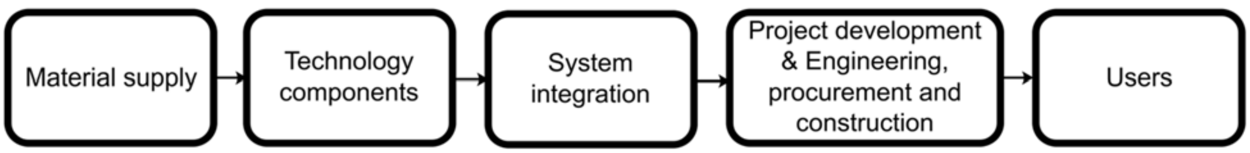


Figure 4 Business environment components organized in relation to the value chain

2.5 Data collection

Our data collection entailed an extensive literature review, gathering of proprietary data from Bloomberg New Energy Finance (BNEF) and Pitchbook, and 50 stakeholder interviews conducted during the summer of 2020. See ***Table 1*** for a summary of the actors interviewed.

Table 1 Scope of Interviews

Stakeholder Type	Types of Entities Interviewed

Investors	❑ Private venture capital
	❑ Corporate venture capital
	    ❑ Automotive
	    ❑ Energy provider
	    ❑ Electrical and electronic manufacturing
	    ❑ Insurance
	❑ Private equity firm
	❑ Bank

Firms	❏ Technology start-ups
	    ❏ Solid-state battery
	    ❏ Battery software
	    ❏ Hydrogen fuel cell

Government	❏ Federal research program advisor ❏ State energy commission ❏ Public funding provider
Intermediary Organizations	❏ Trade association ❏ Public funding coordinator ❏ Regional innovation cluster coordinator ❏ International innovation network ❏ Insurance company ❏ Test bed facility ❏ Federal government funded energy storage research center ❏ State government funded innovation network ❏ Government funded early stage incubator program ❏ Corporate backed accelerator ❏ Private venture capital accelerator
Research Institutions	❏ National laboratory ❏ Think tank ❏ Private R&D branch

3. Battery Storage Case Study

This chapter describes the innovation system supporting development of innovative battery storage technologies. We focus on understanding how battery technologies have evolved in recent decades and how stakeholder roles, resource mobilization, and institutional and business environments have evolved in tandem with the technology. Because lithium-ion batteries (LIBs) make up the majority of the battery storage market today, we highlight this technology. We do not specify battery end uses, so our case study encompasses automobile battery storage as well as stationary batteries for residential, commercial, and utility customers.

3.1 State of battery storage innovation

The first LIB was prototyped in 1979 after decades of scientific and engineering R&D (IEA, 2010). LIBs were introduced commercially in 1990 by Sony. They were not initially developed to serve the energy sector but instead were first used in handheld video cameras and later in smartphones. Over time, they have evolved to become the battery of choice.

The rate of LIB innovation is evident in the rate of new patents related to this technology. According to a recent battery patent analysis by IEA and the European Patent Office (International Energy Agency and European Patent Office, 2020), the number of patents in electricity storage has grown faster than patent activity in all other economic sectors. The annual growth rate of electricity storage patents is 14%, with a notable acceleration in the rate between 2005-2018. In particular, within the subcategory of battery technologies, patents related to LIB cells represent about 45% of all patents for battery-cell innovations. The large number of LIB cell innovations and related patents is a reflection of different performance criteria for different battery applications and of the lack of a dominant battery cell design for each application.

Although U.S. LIB innovation performance is average compared to that of Asia and Europe, whose rates of innovation surpassed that of the U.S. during the past two decades, the U.S. has good standing in development of other battery chemistries. For example, the U.S. is a clear leader in lithium-nickel-cobalt-aluminum oxide battery innovations, accounting for 36% of the related international patent families[7] (IPFs). Lithium-nickel-cobalt-aluminum oxide is increasingly seen as a promising alternative to lithium-manganese-cobalt-oxide, which is regarded as having the best potential for electric vehicle applications in the near term. The most important manufacturer of lithium-nickel-cobalt-aluminum oxide batteries is Panasonic or Panasonic's cooperation partner Tesla. In the area of battery manufacturing and engineering, the U.S.'s performance is behind that of Japan and the Republic of Korea.

Market trends are in line with patent activity. Because LIBs are lightweight with high energy and power densities, LIBs have gradually displaced nickel–metal hydride and nickel-cadmium batteries during the past 10 years (D. Hart & Sarkissian, 2016; Kuriakose, Lewis, Tamanini, & Yusuf, 2017) . At the end of 2018, LIBs accounted for more than 90% of the installed power and energy capacity of large-scale battery storage in operation in the U.S., a total of 869 megawatts (MW). For small-scale storage, utilities reported 234 MW of existing LIB power

[7] A patent family is a collection of patent applications covering the same or similar technical content.

capacity, with the majority (86%) located in California (***Figure 5***) (U.S. Energy Information Administration, 2020) Today LIBs also represent more than 90% of the global grid battery storage market (Zablocki, 2019). The majority of these demands are driven by the expansion of the electric vehicle industry, whose growth is projected to increase (see ***Figure 6).*** Since 2010, demand for electric vehicle batteries, rapid battery innovation, and economies of scale have brought down the unit cost of battery packs by almost 90%. In 2019, the average battery pack price decreased to $156 per kilowatt-hour (kWh) and is anticipated to drop further to approximately $100 per kWh by 2023, based on the latest forecast from BNEF (see ***Figure 7***). Accordingly, the learning rate for LIBs is estimated to be around 20% (IEA, 2020), which is comparable to that of solar PV systems.

It is worth noting that accurately estimating the value of battery storage remains as a challenge because storage provides diversified services and applications. Some of those interviewed for this report said the following.

Lithium ion itself is a collection of technologies. The projected cost curve for Lithium ion is based on the volumetric weighted average and survey reported price, but the kind of Lithium battery product you put in an [electric vehicle], grid storage, vacuum cleaner are different. Therefore, it can be misleading (Venture capital firm)

Cost of storage isn't easy to quantify because [levelized cost of energy] is accurate for disparate technologies providing the same services, but, with storage, the different use cases make it increasingly complex to evaluate the system. Moving forward, it is crucial that the complexity and diversity of energy storage as a resource is grasped. This will better permit the design of adequate reward mechanisms for energy storage resources (Venture capital firm)

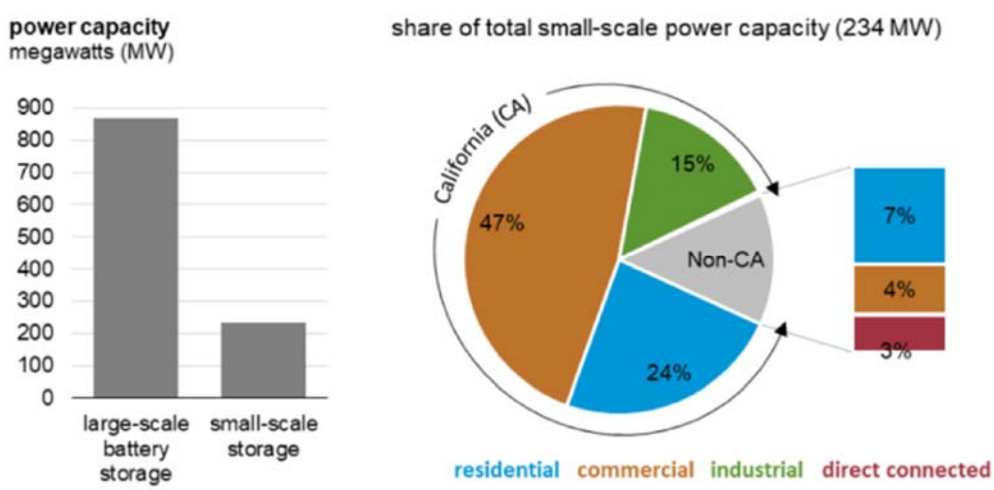


Figure 5 Battery storage in the United States (2018)

Source: (U.S. Energy Information Administration, 2020)

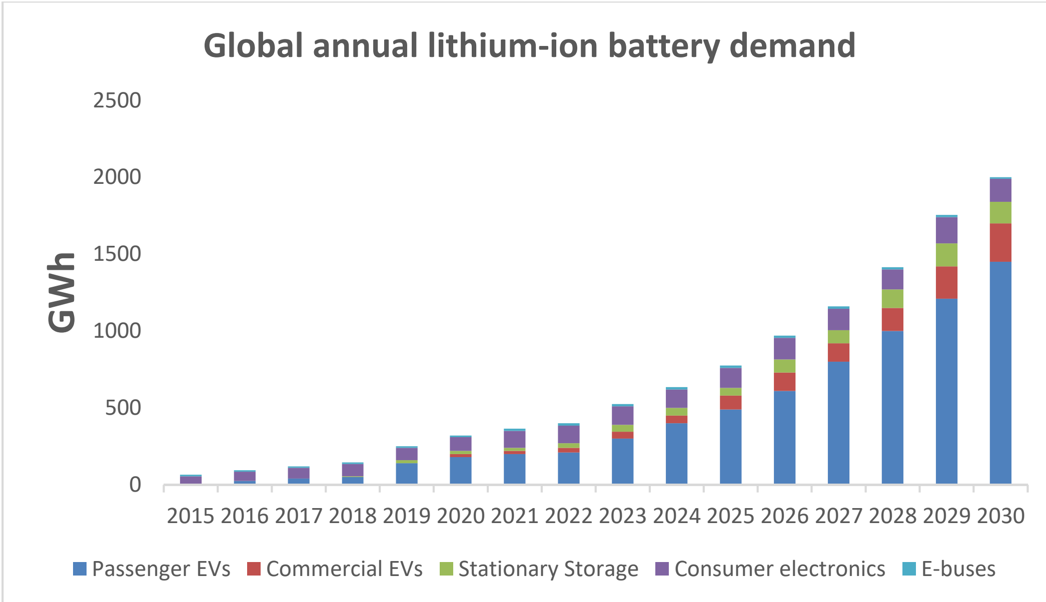


Figure 6 Global annual lithium-ion battery demand

Source: (BNEF, 2019c)

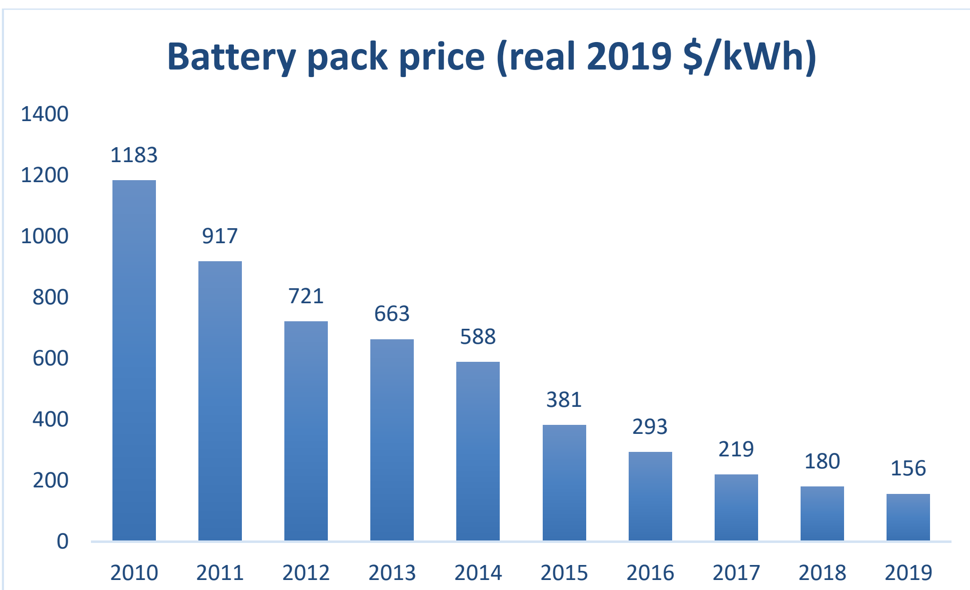


Figure 7 Battery pack price global trends

Source: (BNEF, 2019a)

LIBs consist of four main components: a cathode, an anode, an electrolyte, and a separator. The cathode and anode determine the battery's basic performance, and the electrolyte and separator determine the battery's safety. LIBs require four key materials: lithium, cobalt, nickel, and graphite. The movement of charged lithium particles (ions) between two electrodes allows for the storage or release of energy. For cathodes, cobalt is used to provide stability to the structure of active lithium, which helps ensure safety. Cobalt is less abundant and more expensive and presents political and ethical issues because of the way it is mined in Africa (Li & Lu, 2020). For this reason, most cathodes for LIBs use a combination of metal ions; for example, cobalt with nickel and manganese are used in the majority of the LIBs in electric vehicles today. Finally, graphite is used for anodes because of its stable structure. According to BNEF, combinations of expensive metals such as nickel and cobalt mean that raw materials can account for about 60% of the total cost of a battery cell.

Overall, the battery storage industry has matured over time, and LIBs dominate most battery cell innovation today. The industry's maturity can be seen in the increasing attention to manufacturing processes rather than to the basic science behind LIBs. Analysis (International Energy Agency and European Patent Office, 2020) has shown that patenting activity in manufacturing of battery cells and cell-related engineering developments has grown threefold over the last decade, signifying the maturity of industry.

Although LIBs have become ubiquitous in recent decades, there is still room for improvement in areas such as duration of operation, safety and fire risk, need for costly materials, and need for careful operation (minimizing battery cycling to preserve functionality). These challenges have been the focus of LIB innovations and have opened opportunities for other types of batteries to compete. Alternatives to LIBs use materials such as zinc, vanadium, or sodium and are proving themselves well-suited for many tasks, especially for stationary storage used by utilities (Stringer, 2020). Another possible storage solution is flow batteries that have relatively low energy densities and a long life-cycle, which makes them well-suited for supplying continuous power (Zablocki, 2019). At the end of 2018, flow batteries represented less than 1% of the installed power and energy capacity of large-scale battery storage in the U.S. (U.S. Energy Information Administration, 2020). While opportunities exist for other types of storage technologies to emerge, investors and researchers whom we interviewed shared the view that lithium will continue to dominate the market in the foreseeable future, but other types of batteries such as hydrogen and solid state will increase substantially. Below we summarized these insights in more detail.

Many battery developers see solid state electrolyte and lithium metal anode as the most promising near term outcome (Battery company, one of DOE's energy storage research center)

Financiers assess storage by levelized cost against incumbent Lithium ion technologies (Venture capital firms)

There is more room for winners in the energy storage market (as opposed to when thin film solar lost) because lithium cannot solve problems like long duration energy storage and electrification of industries opens up a huge market (Accelerator)

Expect a diversity of energy storage technologies in the future including thermal energy storage, flow batteries, compressed air, flywheels and other forms of mechanical storage (Trade association)

Difference in geographies and resources will mean that diverse technologies will co-exist

(Insurance company)

3.2 Stakeholders and networks

Federal and state policy makers, as well as private sector actors who are engaged in providing knowledge and deploying technology for LIBs, also support clean energy technologies in general. In this section we will discuss the roles and interactions among, or networks of, these stakeholders, highlighting the changing dynamics that directly and indirectly impact battery innovation.

Shifting public and private roles

Previous research has pointed out that the private sector, and venture capital in particular, has reduced its engagement in clean energy innovation in recent years (Breakthrough Energy and MIT). This is in part because almost half of the $25 billion in venture capital that was invested in clean energy technology between 2006 and 2011 was lost (Gaddy et al., 2016). Since then, the cleantech space has evolved, and both the government and the private sector have transitioned to new roles. The government is currently engaged in activities that span cleantech innovation stages, such as programs that bridge science and technology to marketplace. Examples include the Energy I-Corps, Advanced Research Projects Agency–Energy (ARPA-E), Small Business Innovation Research, the Technology Commercialization Fund, the Environmental Security Technology Certification Program, and DOE loan programs. In contrast, the investor community is focused on later stages of an innovation's development (Muro & Saha, 2017) (see ***Figure 8***). The current distribution of roles shows the importance of government and institutional investors in supporting development of battery storage, which has relied heavily on technological breakthroughs in materials and hardware. A quote from our interviews summarizes well the limits of the risk that the private sector is willing to take:

"We will take engineering risk but not science risk" (Venture capital arm of Corporation)

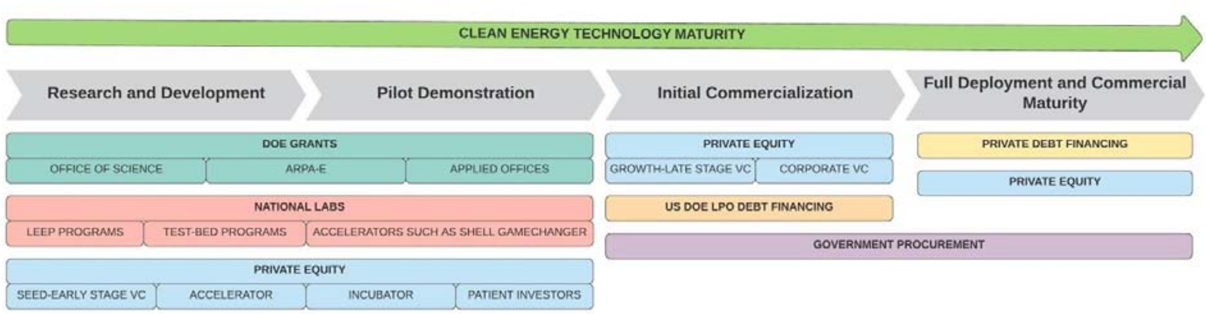


Figure 8 Investment sources for clean energy technologies at different stages of maturity

Source: modified from information from DOE Loan Programs Office

Increased corporate-sector involvement

The cleantech investment sector, which was once characterized by lack of exits, has now attracted the automotive industry, oil and gas companies, utilities, and insurance companies. ***Figure 9*** shows the substantial rise in corporate investment in the cleantech sector over the past two decades.

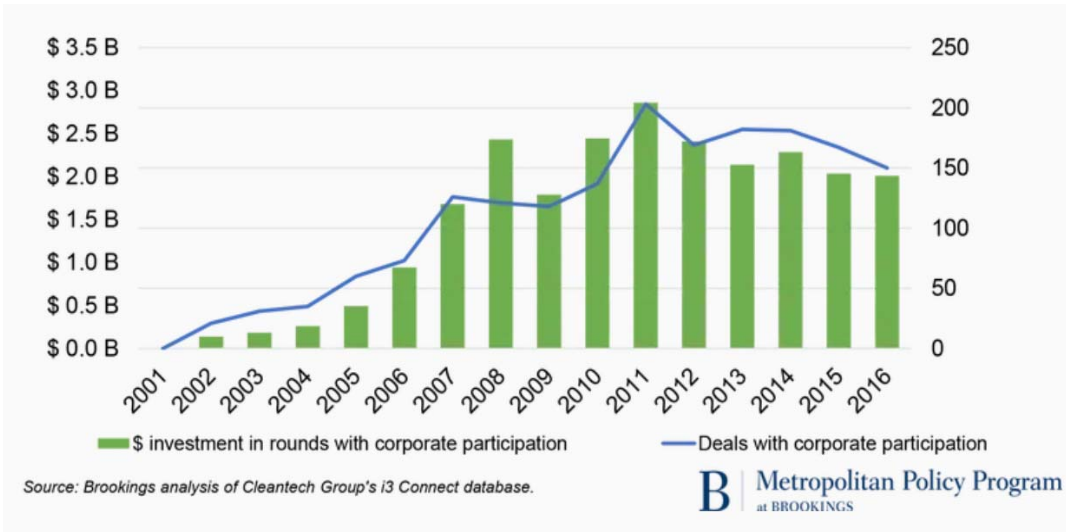


Figure 9 Rise of corporate participation in cleantech funding

Source: (Muro & Saha, 2017)

There is evidence that major energy companies are positioning themselves in new markets both by providing equity and, increasingly, by acquiring enterprises. According to PitchBook data, approximately 40% of the capital invested in the energy industry and cleantech/climate tech has been in mergers or acquisitions. Venture capitalists and cleantech investors are more likely to finance climate-tech solutions in part because of the likelihood of an exit, i.e., that others will step up to acquire an innovative technology or firm. Corporations also have many channels through which to scout for innovations, from being limited partners in funds to corporate venture arms. For example, the energy and petrochemical company Shell partnered with the National Renewable Energy Laboratory to establish the "Shell GameChanger" incubator at the laboratory. The incubator provides non-dilutive funding to start-ups working on long-duration energy storage.

According to our interviews, corporate limited partnerships in venture capital funds have several effects: they act as built-in exits; help start-ups navigate regulatory, financial, and business environments; and enable rapid deployment of technologies. When market participants, corporate venture capitalists, and corporations are tied into policy decisions, they can leverage their investments and corporate R&D by working with policy makers. As product integrators (e.g., incorporating batteries into automobiles), they can set product specifications for start-ups. Corporations help with engineering risk by making introductions to manufacturing and construction partners, which helps start-ups go from pilot to scale; by providing commercial testing sites or other resources for pilot activities to gather data; and by suggesting other market applications for an invention.

New corporate investors

Traditionally, the automotive industry, electronics industry, and oil and gas industry have played a critical role in furthering corporate investment in clean energy. Now other sectors, such as utilities and insurance, are entering the field by establishing corporate venture funds and taking on the role of limited partners in venture capital funds.

Utilities are taking an interest in clean energy start-ups and corporate investment, motivated by the desire to decarbonize, decentralize, and digitize the power grid. Those goals are prompted by a number of factors such as state-level greenhouse gas reduction goals; mandates for procurement of energy storage; reliability threats resulting from climate change; a desire to reduce expansion costs while serving growing energy demands; and external threats such as threats to cybersecurity. A network of 53 utilities has joined a fund called Energy Impact Partners to invest in a better energy future. Like other emerging venture capital funds, Energy Impact Partners has a unique niche and offers what they describe as a proven investment model for utilities.

> *"Utilities are investing in start-ups too" (Accelerator)*
>
> *"Utilities are changing innovation culture within a highly regulated monopoly business (monopoly)" (Venture arm of investor-owned energy companies)*

Insurance companies look to early-stage, hard technology startups to establish new business lines by investigating new risks associated with breakthrough technologies. Our interviewee from this sector stated that, by working with early-stage companies, an insurance firm can learn, at the development stage, the risks associated with the technology so that the insurer can have an insurance plan ready to address those risks by the time the technology is deployed. Some insurance companies have been rolling out risk-transfer mechanisms for energy technologies. For energy storage in particular, insurance companies can offer performance warranties covering electrical energy storage systems for 10 to 15 years or more. In addition to supporting investor confidence in energy storage, the coverage protects investors and project owners against potential bankruptcy and technical under-performance. The coverage also enables financiers to invest in long timelines and helps new energy storage technologies get to market.

> *"We [corporate venture wing of an insurance company] are rolling out insurance covers for high-risk technologies by working closely with early stage companies such that they can attract later stage investments with these insurance covers." (Insurance company)*

Interactions between government and corporate investors

To retain venture capital interest in cleantech, the government has increased its role and now provides extensive risk minimization and funding opportunities so that technologies for which risk has been minimized can move on and obtain later-stage funding from investors. In California, for example, state governments are engaging with corporate investors either directly or through intermediary trade organizations such as the California Energy Storage Alliance. The state engages with companies to see whether there are barriers to deploying the technologies the companies have invested in or want to invest in. This enables the state government to establish new, or modify existing, policies to benefit start-ups based on firsthand information from investors and send signals to them at various stages. By working with corporate investors, the state government can disseminate information about supportive policies, which has the additional benefit of potentially attracting employment opportunities to the state.

"So the more signals we can send to the VCs, one of the models, I think, that gets cited often is what happens in kind of the pharmaceutical industry with the FDA. You know, there's every time they get FDA approval at the various stages, it's a signal to the VCs, that these companies are investable, and we've tried to really set up something with CalSEED and bridge and ramp to try to articulate the same thing to the VCs." (Government entity)

Boundary-spanning (cross-cutting) organizations

Distinct from public and private stakeholders, cross-cutting stakeholders span boundaries, linking several other organizations.

Accelerators and incubators are good examples of boundary spanning organizations. Currently, most accelerator/incubator models are funded by governments, corporate entities, or universities. According to PitchBook data, for all start-ups from 2000-2020 listed under energy and cleantech/climate tech, 9% were either presently or formerly backed by an accelerator/incubator. The support services provided by accelerator and incubator programs have increased many-fold to include business advice, marketing and design support, public relations support, investor meeting preparation and introductions, networking events and channel partners, office space, and laboratory space. Accelerator programs are now partnering with other resources within the innovation system, such as boot camp programs and national laboratories, to enhance the value of services. For example, the California Sustainable Energy Entrepreneur Development (CalSEED) program offers business development services by covering costs to attend Cleantech Open.

Accelerators are marketing platforms that promote deal flow for member partners, both corporate and institutional investors. Increasingly, accelerators and incubators also educate state legislators about the needs and capabilities of the entrepreneurial systems to which they are connected. According to our interview, Elemental Excelerator in Hawaii was started to help the State of Hawaii meet its energy goals. The founder of Elemental Excelerator was instrumental in working on some of the policy frameworks that laid the groundwork for Hawaii's renewable energy goals as well.

Accelerators/Incubators act as "boots on the ground" for the California Energy Commission to understand the innovation needs and outcomes of different regions within a particular state (CalSEED and CalTestBed interview). The state essentially appointed a lead organization to an innovation cluster to coordinate programs and resources within that region and essentially create programs for entrepreneurs to get access to a wide spectrum of incubator services such as testing facilities, access to business mentors, access to investors and venture capitalists (CEC Erik interview). Hence, in this manner accelerators can coordinate government programs (CalTestBed interview), provide funding agencies unique insights, and ensure that start-ups have easy access to municipal resources/bodies through them (Regional incubator)

In the battery space, trade associations are important boundary-spanning organizations. For example, in California, the California Energy Storage Alliance acts as a liaison between private industry and regulatory bodies, speaking as a unified voice for the industry in response to policy changes that may affect energy storage. According to our interviews, California Energy Storage Alliance works to expand and advance the energy storage market by creating market conditions that allow for energy storage procurement opportunities. This is accomplished both through policy work and by creating venues for buyers to meet technology solution providers and developers. New Energy Nexus is another important regional boundary-spanner organization that coordinates activities among state governments, start-ups, corporate firms, and accelerator programs to deploy and manage entrepreneurship programs such as CalSEED, CalTestBed, Free Electrons, PowerLab, and LG Battery Challenge.

> *"Our primary service is to provide money and leverage guidance of New Energy Nexus and Cleantech Open. We help them build out their scope of work, financial management systems and introduce them to the network at New Energy Nexus. We provide coaching, business development, leadership development to get them to the next stage. The awardees go through an accelerator program through Cleantech Open (strong relations with Cleantech Open)." (Government funded accelerator)*

Finally, national laboratories can serve as testing facilities, techno-economic modeling consultants, and research centers for corporate and financial investors. Examples include "Cyclotron Road" at Lawrence Berkeley National Laboratory, which support entrepreneurial scientists and engineers from around the world and provide them funding, mentorship, and networking opportunities in the Berkeley research ecosystem. For battery technology specifically, Argonne national laboratory provide testing facilities for innovation at the pre-manufacturing stage.

> *"If an innovation is not as advanced to demand a manufacturing cluster, clients can use national lab scale-up facilities such as the Materials Engineering Research Facility (MERF) at Argonne National Lab - which takes a battery chemistry, from the milligram level (typical for laboratory research) to the kilogram, or 100-kilogram level - for pre-manufacturing R&D."*
> *(One of DOE's energy storage research center)*

3.3 Access to resources

Research and development investments

Traditional measures, such as R&D expenditures, integration of information and communications technologies, and human capital, are the key measures of innovation inputs. In the U.S., DOE, the Department of Defense, and National Science Foundation are the three major federal funding agencies. As mentioned, energy storage can be applied in many different areas, and energy storage research often intersects with research in other domains. At DOE, multiple offices are involved in funding storage-related research, including the Offices of Electricity, Energy Efficiency and Renewable Energy, Nuclear Energy, Fossil Energy, Science, Technology transitions, ARPA-E, and the DOE Loan Program. Specifically, DOE's ARPA-E program has funded many electric vehicle and grid-tied storage projects, including batteries, automotive controls, and efficient electric vehicle chargers, as well as a $30-million long-duration storage program announced in 2018.

Because energy storage has many applications, it is difficult to estimate energy storage R&D. In 2015, the Office of Management and Budget conducted a formal interagency “crosscut” and estimated that approximately $300 million was spent on energy storage RD&D in that year (D. M. Hart, 2019). Federal government R&D for energy storage and other power technologies has been decreasing in the past decade (from $113 million in 2010 to $46 million in 2019). Storage R&D also appears to be minimal compared to other clean energy technology R&D, see

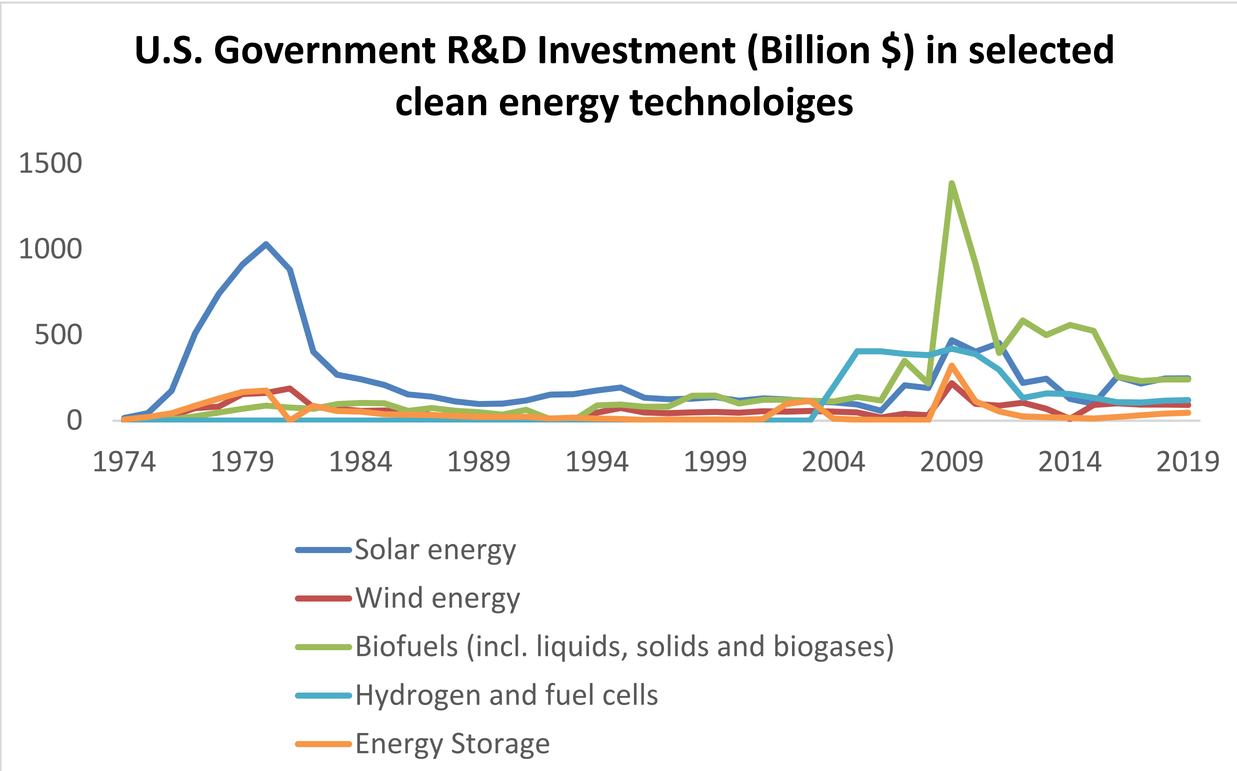


Figure 10. In the private R&D space, it is worth noting that most U.S. battery innovation activities are carried out by small- and medium-sized companies, in contrast to the large and very large companies doing this work in Japan and the Republic of Korea (International Energy Agency and European Patent Office, 2020).

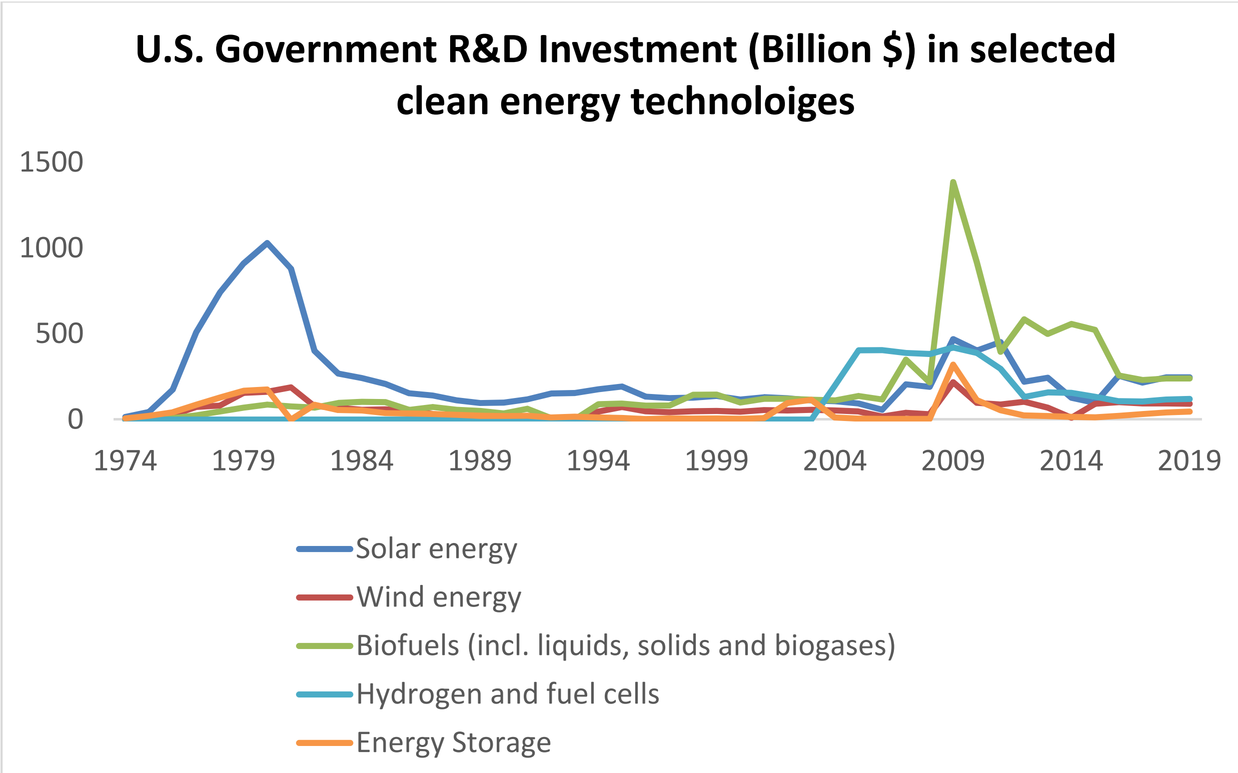


Figure 10 Trends in U.S. government R&D on energy technologies

From a commercialization perspective, energy storage capital investment have been steadily increasing in the U.S. (see ***Figure 11*** and ***Figure 12***). The capital invested received a boost in 2019, largely from key players such as automakers, government funding providers, and climate funds. These funding sources indicate the increasing maturity and bankability [8] of the industry. Storage also plays into some of the major concerns that states have regarding the effects of climate change on their existing energy infrastructure. As focus shifts to grid reliability and resilience, electric vehicles, demand-response mechanisms, and in-front-of-the-meter storage, investments in this sector will continue to rise. Many of our interviewees suggested that they believe diverse technologies will co-exist in the future, whether those are lithium-ion, hydrogen fuel-cell, or flow batteries, primarily because of the geographical diversity and the various services battery offers.

Despite this positive investment trend, we believe that battery storage innovations are still in need of policy support and investments from large institutional actors. According to our interviews, battery chemistry is difficult for companies and corporate venture capitalists to support because fund sizes are typically hundreds of millions of dollars which is highly risky for private venture capitalists.

[8] Bankability" refers to how credible traditional lenders consider a storage project's overall economic viability to be.

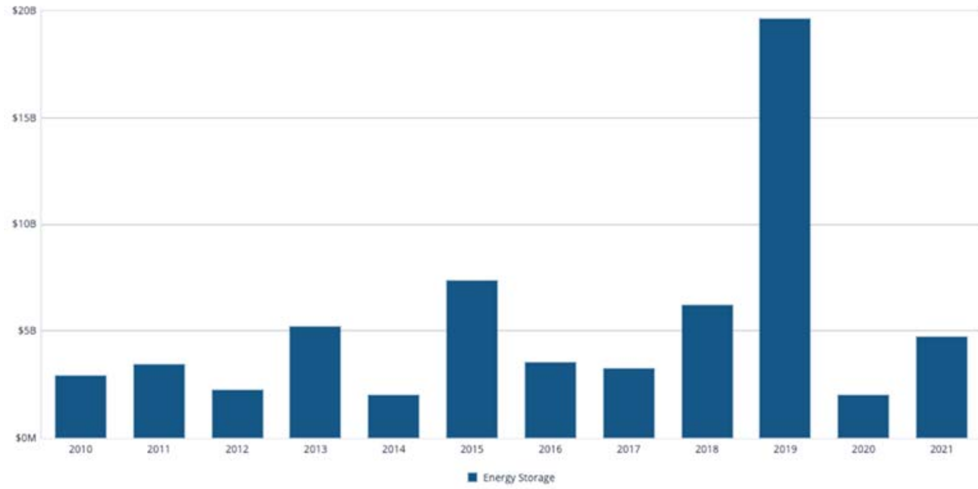


Figure 11 Energy storage capital investment in the U.S.

Source: PitchBook

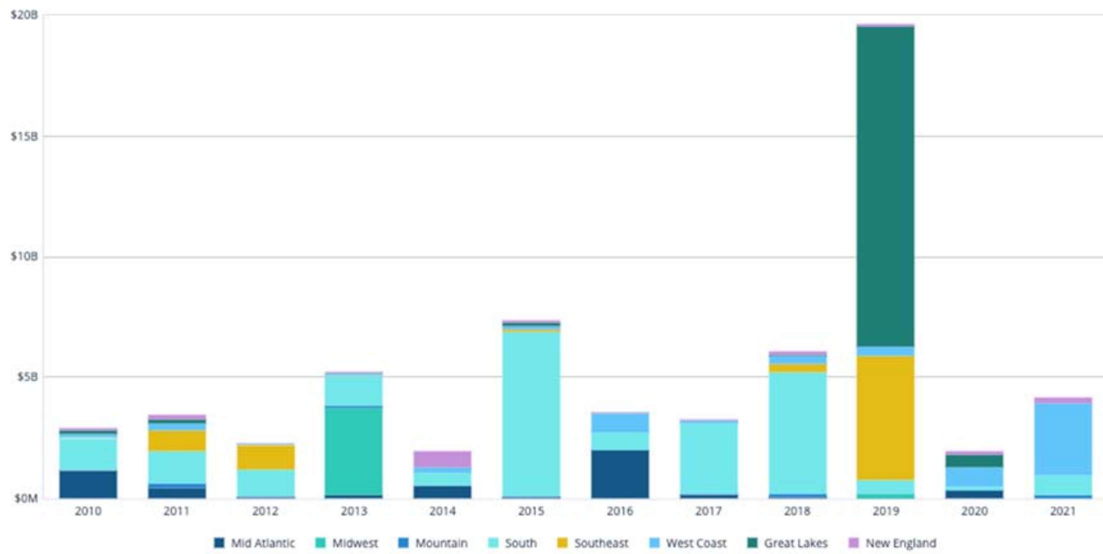


Figure 12 Energy Storage capital invested by U.S. regions

Source: PitchBook

Human resources

The expertise needed to advance battery storage innovation includes both scientific and engineering forces as well the knowledge of those who work in all parts of the value chain.

Regarding scientific workforce, a survey conducted by the National Center for Science and Engineering Statistics documented that the number of scientific and engineering researchers (include graduate students, postdoctoral appointees, and doctorate-holding non-faculty researchers) increased from 342,230 in 1980 to 662,882, and that, in 2018, more than half of those researchers were not U.S. citizens. The U.S. has relied on highly skilled immigrants to support its innovation system to a greater degree than many other nations have done. One study showed that nearly 40% of all the engineering and technology firms founded in California and New Jersey between 1995 and 2005 were funded by foreign-born immigrants (Atkinson, 2020).

In the academic fields pertinent to battery storage, there were about 118,916 researchers in 2018. These fields include chemistry; materials science; physics; chemical engineering; electrical, electronics, and communications engineering; engineering mechanics, physics, and science; metallurgical and materials engineering; and mining engineering (see ***Figure 13)***. Among these areas, fields such as material science and mining engineering have the lowest number of scientific workforces.

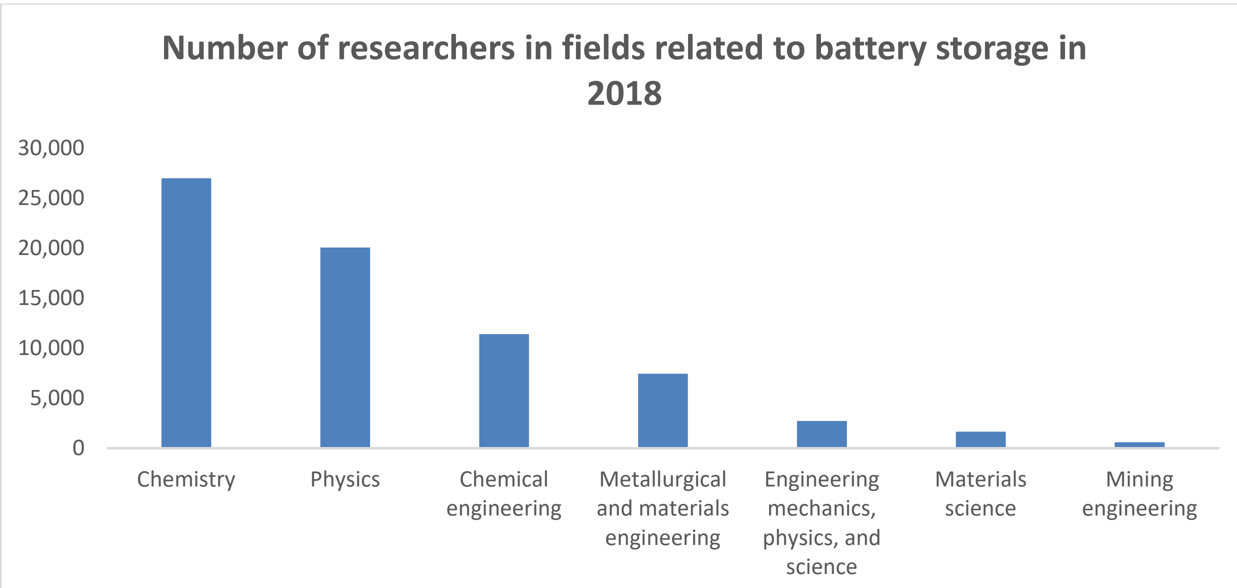


Figure 13 Number of researchers in fields related to battery storage in 2018
Source: (National Center for Science and Engineering Statistics, 2018)

In addition to scientific workforce, approximately 65,900 workers were employed in the battery storage industry in 2019, according to the U.S. Energy and Employment Report (Energy Futures Initiative, 2020). Most of these jobs were in California and Arizona, including engineering and construction (31,776 workers), manufacturing (2,614 workers), wholesale trade and distribution (7920 workers), professional services (11,813 workers), and other services (1,205 workers). The battery job market is expected to grow as the industry scales up. One study predicts that the industry could employ millions of workers by 2050, about 330,000 of which will be in North America (Ram, Aghahosseini, & Breyer, 2020). ***Figure 14*** shows employment by detailed grid and storage technologies.

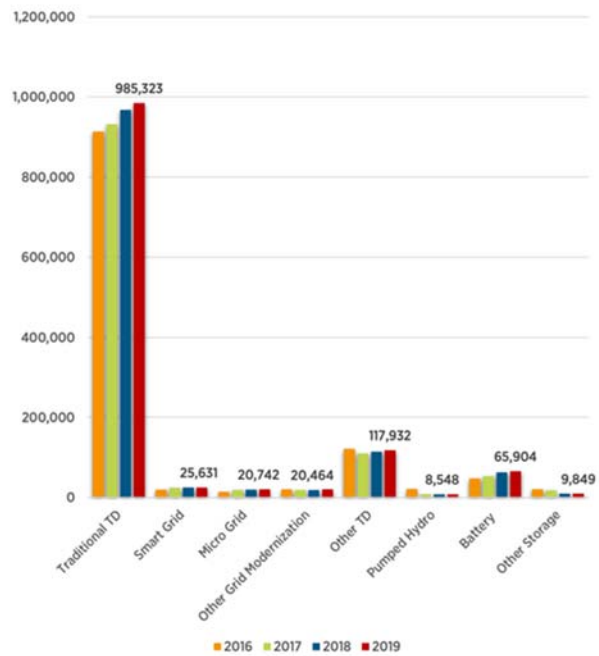


Figure 14 Employment by detailed grid and storage technologies.
Source: (Energy Futures Initiative, 2020)

3.4 Institutional environments

Institutions that are part of the battery storage innovation system have evolved as the technology has matured. The subsections below describe institutional environments for battery storage technology broken down into the "innovate," "make," "deploy" stages of technology development.

Initial innovation stage: research and development policy

Storage R&D needs should be understood in the context of the services and applications that storage supports, including electric vehicles, demand-side management, grid reliability, and resiliency. This is because the requirements for the energy intensity, duration, charging cycle, and operational maintenance for batteries for all of these applications are different. For example, energy intensity is more important for electric vehicles because it must match the performance and costs of internal combustion engine vehicles (International Energy Agency and European Patent Office, 2020)(IEA and EPO, 2020). By contrast, duration is important for utility-scale battery storage where, in some cases, it is cheaper to install flow batteries than stack up many LIBs. These varying needs and requirements may be part of the reason that storage R&D programs are found in many different DOE offices, making it hard, as mentioned earlier, to estimate the amount of R&D invested in battery storage.

Researchers (Breakthrough Energy et al., 2019) and our interviewees have pointed out that the fuel-based organization structure is not a good fit for battery storage. A recent effort that calls for a concerted action to advance storage R&D is DOE's "Energy Storage Grand Challenge", which is a cross-cutting program to address a set of issues as it pertains to storage development, commercialization, and manufacturing. Besides coordination within DOE offices, DOE also worked with the Departments of Commerce, Defense, and State to launch the Federal Consortium for Advanced Batteries in 2020. The organizational restructuring is an important step to coordinate federal actions to advance battery technology and establish a secure domestic supply chain.

In addition to the amount of R&D needed to advance next-generation battery technologies, a widely used R&D approach is to develop programs based on the technological readiness level (TRL) of candidate materials, components, or devices. According to DOE, TRL is a metric used to assess maturity of a technology. TRL is scored on a scale from 1-9. The higher the number, the closer the technology is to commercialization. Based on TRL, R&D efforts vary among storage technologies, ranging from TRL 1-2 for Li-Air electric vehicle batteries to TRL 1-4 for solid state batteries and TRL for 9 LIBs. R&D programs have been designed to support energy technologies at various TRL. For example, ARPA-E typically funds high-risk, high-reward energy technologies and might not take TRL into account when picking its investments, though most ideas tend to fall into low TRL categories. On the other hand, the office of energy efficiency and renewable energy funds research across a variety of TRL, especially those ideas that go beyond the basic technology research (TRL 1-2).

Finally, an important storage R&D focus area relates to supply chain issues and manufacturing capacity. The U.S. has been struggling to meet critical demand for LIB materials such as cobalt, lithium, and nickel. In 2019, the U.S. relied on imports for more than 50% of needed supplies of cobalt, more than 25% of needed supplies of lithium, and more than 57% of needed supplies of nickel (DOE). R&D efforts to support a domestic battery supply chain have focused on: (1) finding alternative materials and battery chemistry to reduce reliance on current LIB materials; and (2) researching methods to reduce, recycle, and recover critical materials in LIBs. This included establishing DOE's LIB recycling center (ReCell Center), and California's Lithium Recovery Initiative. Our interviewees confirmed that supply chain issues will dictate R&D directions in battery storage in the near future.

Manufacturing stage: mining and manufacturing policies

Regarding battery manufacturing, there is a general lack of federal level policies. As the U.S. has deployed more storage and electric vehicles during the past 10 years, the nation has, as noted above, had to rely increasingly on imports of critical materials for battery manufacturing. In response to energy security concerns, DOE included, in the Energy Storage Grand Challenge roadmap, the goal of developing and domestically manufacturing energy storage technologies that can meet all U.S. market demands by 2030. However, building domestic manufacturing for batteries will require years of sustained industrial planning.

For LIBs, DOE identified manufacturing challenges that include, advance processing and recycling to diversify critical materials sourcing, lower manufacturing costs through advanced anode, cathode, electrolyte, and chemistries, improve safety performance, and accelerate manufacturing scale.

To reduce the dependency on critical material (such as cobalt, nickel, and lithium), DOE has focused on three areas: support low-cobalt battery R&D, established battery recycling R&D center called ReCell in 2019, and announced the Battery Recycling Prize, a $5.5-million phased prize competition to incentivize American entrepreneurs to recycle old LIBs. It is estimated that recycled material could potentially provide one-third of U.S. cathode material needs for LIBs by 2030 (Howell, Khazdozian, Porse, & Gillard, 2020). Besides recycling, in California officials have spent years exploiting lithium resources. The state passed Assembly Bill 1657 (Garcia), Chapter 271, 2020 (AB 1657), which authorizes CEC to convene a Blue-Ribbon Commission on Lithium Extraction in California (the “Lithium Valley Commission”). The commission is charged with reviewing, investigating, and analyzing issues and potential incentives relevant to lithium extraction and use in the state. The vision of lithium valley is to build the full supply chain in California.

The U.S. policy support for manufacturing scale-up has been rather absent in the past few years. This is in contrast with the generous financial incentives provided for battery manufacturers in China and Europe. Manufacturing incentives such as “advanced technology vehicles manufacturing loan program (2008), and IRS Section 48C Advanced Energy Manufacturing Tax Credit (2009) are no longer available. Instead, trade policy was pursued against foreign imports. According to BNEF, tariffs are a prominent protectionist measure although they often fail to “bring manufacturing home”. To position the U.S. be the global leader in battery innovation and manufacturing production, all levels of government approaches will be needed, including ease of regulatory burden, target setting, purchasing power, R&D, tax, subsidies, trade, and investment policies.

Deployment stage: technology transition programs and market demand policies

Demand-side policy is critical to spur battery innovation. This has been demonstrated in Europe and China, where aggressive national EV targets together with generous subsidies had pushed for a rapid growth of battery related patents in the past decade. In the U.S., most federal and state storage policies are aimed at the demand side of the value chain, to motivate consumers and utilities to implement new battery technologies by means of direct financial incentives, tax incentives, and non-binding storage targets. However, research (Graham, Belton, & Xia, 2020) and interviews have pointed out that more progressive and coordinated demand-side policies are much needed. Below is a quote that summarizes the cascade effects of demand policy with innovation and manufacturing.

> *“But where the biggest market is, is where the batteries are likely to be made. They're heavy objects, you don't want to ship them across the ocean, if you don't have to. The biggest market right now is in China, there's no doubt just because of its population. And so it's natural that businesses would want to locate their manufacturing there. Well, when you have the manufacturing in a certain place, very often, that's where the innovation occurs, because it's close to the need, you want to make the battery better at the factory. And so innovation is very often driven by how can I change my manufacturing process to get a better battery. So that means the market ultimately certainly encourages both manufacturing and innovation to be local. So one policy that you might think would be sensible is to increase the market for batteries in the States. And you would do that by increasing the market for EV. So you would want to have incentives for EVs as we have now, but maybe more incentives. So the market would come here, the manufacturing would come here and innovation would come here. And that I think would have a big effect, it would not necessarily have a direct effect on funding for*

R&D, although R&D is recognized in Washington as a very important feature of the battery business. I think that there's a potential that the effect could be rather large over the next five to ten years. Because that's sort of the time it takes to shift a market, you can't shift the market in less time than that. So over the long term, if the government sticks to this, to encourage the lead in energy storage returning to the US, we might expect that those policies would come into effect and indirectly, in some cases directly affect battery R&D." (One of DOE's energy storage research center)

Figure 15 presents the results of our analysis of the institutional environment for battery storage in the U.S. In general, most regulations are concentrated downstream to direct market rules. At the state level, regulations are more diverse in California, which has attempted to address issues that arise at different stages of the development of an innovative technology, including direct and indirect storage relevant regulations that aim to support research, spur demand, and improve supply chain security. We discuss institutional environments at both federal and state levels with more details below.

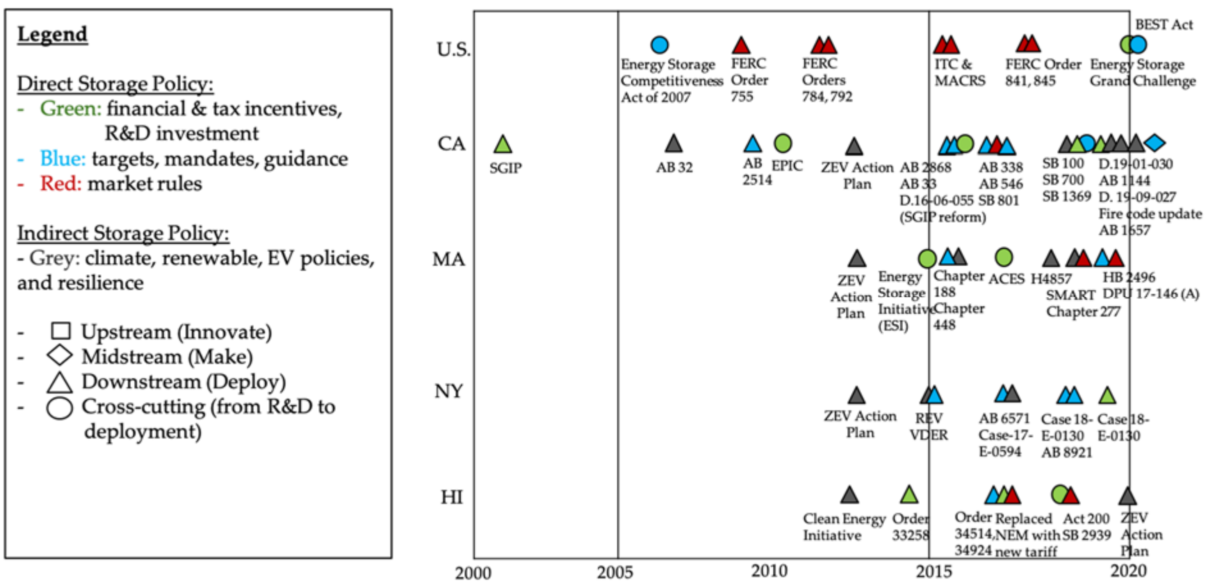


Figure 15 Institutional environment for battery storage in the U.S.

At the federal level, there is a focus on inter-regional market rules for storage to enter wholesale market. The most recent Federal Energy Regulatory Commission Order 845 makes the definition of energy storage more inclusive to account for electricity storage. This will enable electricity storage stakeholders to capitalize on energy storage subsidies and financial incentives available now and in the future.

To bridge the gap between laboratory ideas and commercialization, DOE's office of technology transitions provides a range of programs and market analysis to support each innovation development and diffusion processes. Example programs include coordination of technology commercialization fund, InnovationXLab Showcase, and Energy I-Corps entrepreneurship program. These programs are critical to reap the pay-offs of R&D investments at the national labs. One of our interviewees from the Berkeley Lab claimed that technology licensing is around 10% because manufacturing moved out of the US and transfer policies were cumbersome.

Other federal departments include the U.S. Department of Transportation (USDOT) and the U.S. Environmental Protection Agency (USEPA) regulate end-of-life LIBs handling and safety, because they are so volatile. For example, USDOT regulate lithium battery transport and packaging through its Pipeline and Hazardous Materials Safety Administration (PHMSA), and USEPA require lithium battery owner and facility operators prepare material safety data sheet (MSDS) for LIBs.

At the regional level, four states stand out for battery deployment: California, Hawaii, New York, and Massachusetts, all of which have proposed net zero carbon emissions targets up to date.

California has been a national leader in clean technology innovation and the front runner in developing and implementing storage solutions through financial incentives and Assembly Bill 2514, which requires that California meet a 1,325-MW storage mandate by 2020. California has also been active in amending legislation with updates and adopting additional regulations. The most recently passed legislation, SB 1369, "Energy: Green Electrolytic Hydrogen," demonstrates California's progressive approach, looking beyond LIBs. In addition, California has introduced rebates for clean vehicles, and the new EV mandate require all new cars and passenger trucks sold in the state be zero-emission vehicles by 2035, as well as targets for plug-in electric vehicle chargers and hydrogen fueling stations to support expected growth. California's large share of small-scale energy storage capacity can be attributed to the state's Self-Generation Incentive Program (SGIP), which provides financial incentives for installing customer-sited distributed generation. Battery storage deployment has also been prompted by recent wildfires and the wide deployment of solar PV systems. Storage has piggybacked on solar too. If the storage portion of a solar-plus-storage system is charged by solar power, it is eligible for the U.S. Investment Tax Credit. As quoted below, the policy drivers for California's successful clean energy and storage deployment can be attributed to a range of climate mitigation and resilience policies, and technology specific mandates.

Important policy drivers are SB 100 (electricity system be carbon neutral by 2045) and SB 32 (reduce greenhouse gas emissions by 80% by 2050.). SB 32 is first priority and SB 100 is second. Others are SB 350 which requires that utilities procure 50% of their electricity generation from renewable resources by 2030 and improve the energy efficiency of end users by 50%; Governor Brown's executive order calls for 5 million zero emission vehicles on the road by 2025; and CPUC's energy storage procurement mandate for utilities. – A government entity

Massachusetts state bill H 4857 (2018) established an energy storage deployment target of 1,000 megawatt-hours by 2025 and an expanded state renewable portfolio standard that increases the annual renewables growth rate since 2003. According to the *Massachusetts Energy Storage Policy* (2019), "H 4857 created the Clean Peak Standard for the state (the first of its kind in the nation), which requires retail suppliers to provide a minimum percentage of retail sales during seasonal peak periods from eligible renewable, energy storage, and demand response resources". Massachusetts executive directives relevant to energy storage include the Energy Storage Initiative, started in 2015; the Advancing Commonwealth Energy Storage Program (ACES), created in 2017, and the Solar Massachusetts Renewable Target Incentive Program (SMART), created in 2018; In addition, EV rebate program (MOR-EV) was renewed in 2020. All of these programs aim to scale up storage deployment and incentivize solar-plus-storage development. In early 2021, Massachusetts passed a new legislation that set the state on a net zero carbon emission path by 2050 and increased the renewable portfolio standard up to 40% by 2030, further signifying the role of energy storage for the state's clean energy transition in the coming decades.

In 2019, New York passed S6599, which mandates that 70 percent of the state's electricity must come from renewable energy by 2030, and 100 percent of the state's electricity supply must be emissions free by 2050. The New York State Energy Storage Roadmap, developed in 2018, provides guidance to help New York achieve its 1,500 MW target for energy storage by 2025 and it is now updated to 3,000 MW by 2030. Among the small distribution-level batteries, the biggest drive is the Value of Distributed Energy Resources (VDER) tariff which covering about 18% of the project cost on average (Greentech). Other policies that motivated large storage deployment are, for example, an environmental rule tightening nitrogen oxide (NOx) emissions from power plants. New York's indirect storage policy also include adopting California's ZEV program and offering a range of financial incentives for EV purchase, lease, and charging infrastructure.

Hawaii is another state with a progressive energy storage market. Hawaii's isolated geographical location makes standard energy sources such as coal and petroleum difficult to import, so standard rates for energy are already more expensive than on the mainland U.S. Because of this limitation, combined with a pressing need for energy security, Hawaii has established progressive policies that support combined renewable energy and storage, these include, offering rebates for solar plus storage, replacing net metering with rate structure to drive adoption of behind-the-meter storage, and applying performance-based instead of cost-of-service regulation for utilities (The Hawaii Public Utilities Commission, 2020). Unlike other states, the main driver behind Hawaii's increasing adoption of storage can be attributed to economic viability rather than mandate. Up to date, Hawaii does not have a storage mandate and just recently joined other states in commitment to zero-emission vehicles in 2020.

Cross-cutting climate and resilience policies

Because of wildfire concerns, investor-owned utilities in California executed "public safety power shutoffs" in 2019, cutting power to more than 1.1 million households during weather conditions deemed to elevate the risk of fires caused by utility infrastructure. Many households experienced more than one outage. If "public safety" outages continue to occur at the same or an increased frequency, standby generators or even solar-plus-storage will likely start to be of more interest to California residents. Solar-plus-storage is the most environmentally attractive back-up option for individual customer sites, but it faces many hurdles, including cost and installation. To address the economic barrier, in 2019 California revised its SGIP to include a subsidy aimed specifically at bringing more distributed solar and energy storage to people at highest risk of having their power shut off by utilities. In 2020, the state further updated the California fire code by doubling the allowance for energy storage system capacity.

3.5 Business environments

In this section we discuss U.S. business activities related to the global battery value chain. The battery value chain is complex and competitive. Battery components require continual replacement and raise numerous human, material resource, economic, and business considerations. ***Figure 16*** depicts the links in the battery storage industry value chain.

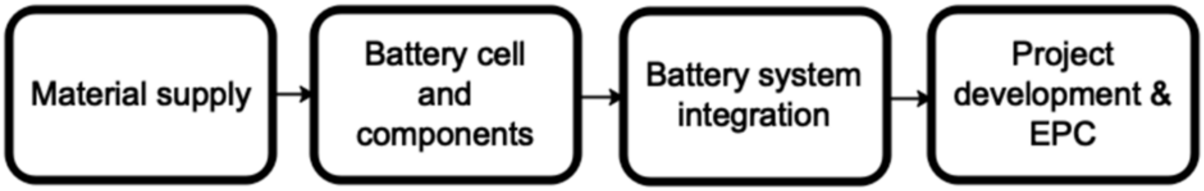


Figure 16 Battery storage value chain

Because most battery demand is for electric vehicle applications, car manufacturers have been heavily involved in battery manufacturing and have had significant impact on battery requirements. One of the large players, Tesla, has become one of the most vertically integrated companies. Currently, Tesla battery suppliers include CATL and LG Chem. Tesla also produces batteries at its Nevada Gigafactory, in partnership with Panasonic.

> *"If you are raising money for a battery company, and you do it successfully, you will no doubt the majority of your investment will come from entities within the current supply chain for the automotive industry. We have investments from original equipment manufacturers (OEMs) such as Hyundai, Ford, and BMW. We view those relationships as really critical. And the reason for that is, our end product is a cell that goes into a vehicle. You know, to go back to first principles, in engineering, you really cannot do anything until you have a set of requirements. And we as a start-up [are] not in a position to provide requirements for a battery for use in a vehicle; that must come from an auto OEM. And so having partnerships with auto OEMs, at a very, very early stage is really, really critical. Because they own integration, so they acquire cells, they then design modules, packs, thermal management systems, etc. And all of those help to define the requirements of the battery system. So without involvement from an OEMs, we would really be dead in the water, so to speak. (battery manufacturer)*

Material supply

A secure supply of critical material is one of the top concerns for producing energy storage technologies. As noted earlier, LIBs require cobalt and lithium, whose production is heavily concentrated in a few countries whereas the U.S. has limited domestic production of both. From 2014 through 2016, an average of 53% of global mined cobalt production came from the Democratic Republic of Congo where there are ethical and humanitarian issues associated with its production. An average of 47% of global cobalt refining took place in China during the same period. More than 80% of global lithium production comes from Australia, Chile, and Argentina (Jaskula, 2020), and only 2% from the U.S.. Even though the U.S. does not have a sufficient domestic supply of cobalt, it does have large potential for domestic lithium sources. It was recently estimated that the Salton Sea area of California could produce 600,000 tons of lithium a year, which is almost eight times last year's global production (Adler & Benson, 2020). If successfully and sustainably obtained, a lithium supply from the Salton Sea area could significantly boost the U.S.'s supply. Meanwhile, battery recycling remains the most viable route to a domestic supply. As the industry continues to innovate battery chemistry and strives to develop cobalt-free batteries, it is technically possible to ease material supply chain issues. See ***Figure 17*** for a representation of the global supply of raw materials for LIBs.

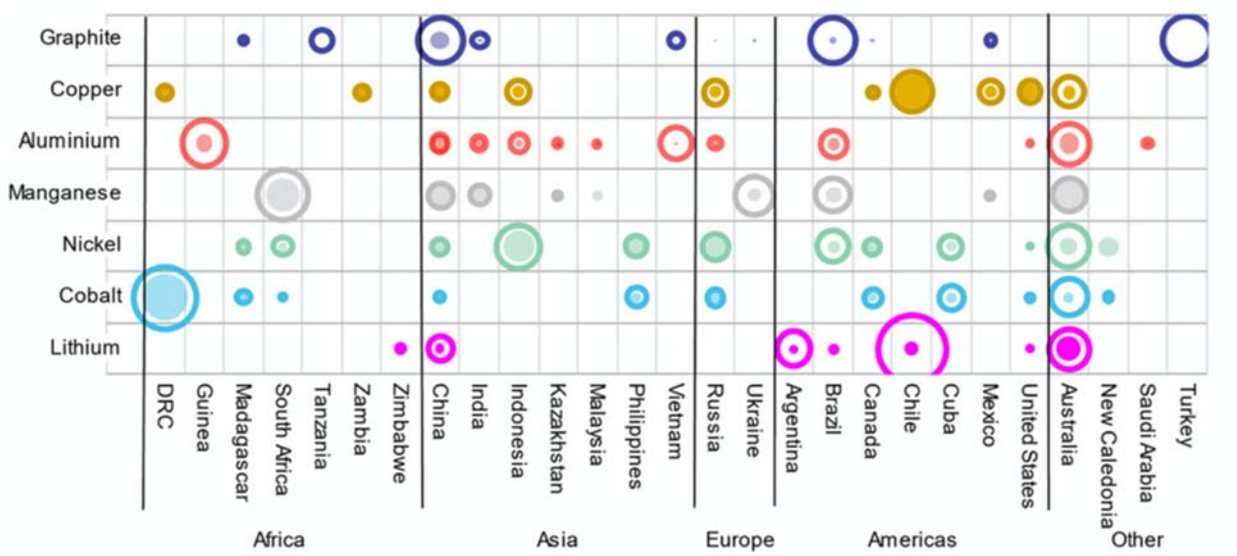
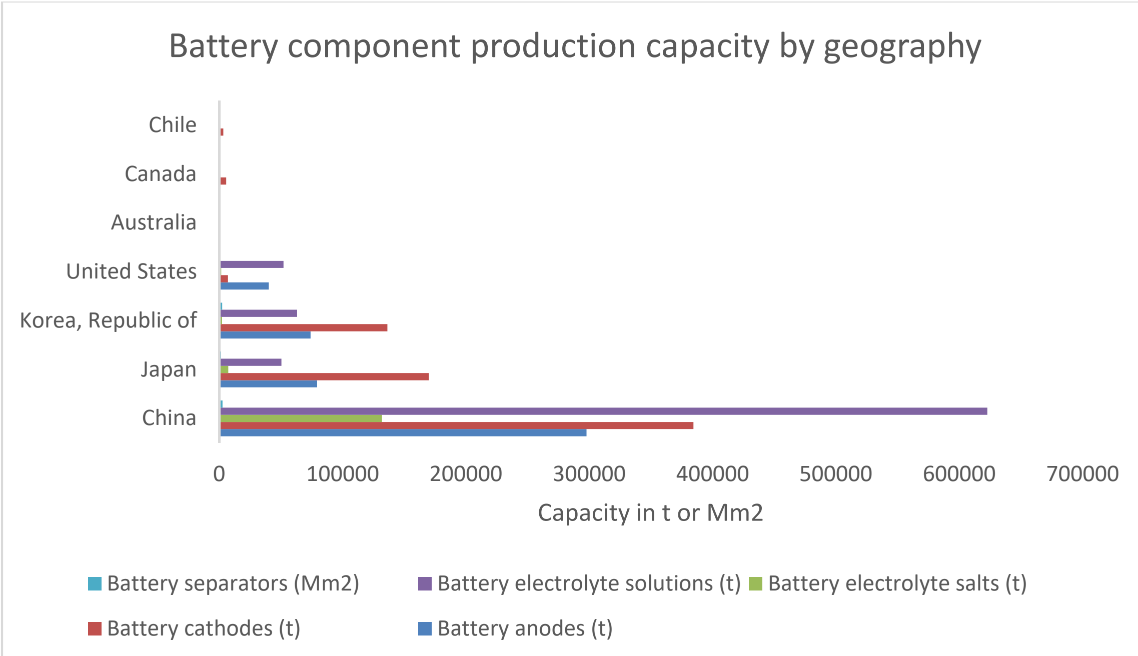


Figure 17 Global LIB material supply by geography and mineral types

Note: the solid spheres represent production, the outer circle represents the total reserves. Size of spheres and circles denote proportionally of the resource between countries. Source: BNEF

Battery components

China is a clear leader in LIBs component manufacturing even though the country's domestic raw material production is not particularly abundant. According to BNEF, China's success results from its large domestic battery demand (72 gigawatt-hours), and control of 80% of the world's raw material refining, 77% of the world's cell capacity, and 60% of the world's component manufacturing. U.S. manufacturers' ability to capture values in the midstream is constrained in part by the lack of critical material and higher U.S. labor costs, and in part by the lack of investments in raw materials, logistical issues, lack of manufacturing workforce and incentives, and relatively insufficient battery and electric vehicle policies. Beyond Tesla, most battery components firms in the U.S. tend to be in early stages of development. Many of these small firms face challenges in scaling up their operations. These challenges will require large capital investments to resolve and might lead the firms to set up their manufacturing outside the U.S. An exception is the completion of Tesla's acquisition of Maxwell Technologies in May 2019 (BNEF, 2019d). ***Figure 18*** shows the geographical distribution of LIBs component production.



Source: BNEF

Figure 18 Battery component production capacity by geography

System integration and project development

The three main types of U.S. battery storage project developers are the automobile industry, utilities, and solar companies.

The battery cell manufacturing market in the U.S. has been highly concentrated. Our analysis shows that since 2011 the market concentration of battery cell manufacturing remains moderate to high, with a HHI score[9] ranging between 2000 to 6000 depending on the year.

For battery system providers, the SGIP data shows that it is also dominated by a few large players, see ***Figure 19*** and ***Figure 20***. Tesla and LG Chem are the leading battery providers in the California residential storage market. Based on California SGIP data, the major installers are also the main developers: SunRun, Tesla, Swell, Petersen-Dean and Sullivan Power. A couple hundred other firms have registered as system developers and installers (BNEF, 2019b).

[9] "HHI" means the Herfindahl–Hirschman Index, a commonly used measure of market concentration. The agencies generally consider markets in which the HHI is between 1,500 and 2,500 points to be moderately concentrated, and consider markets in which the HHI is in excess of 2,500 points to be highly concentrated. See https://www.justice.gov/atr/herfindahl-hirschman-index

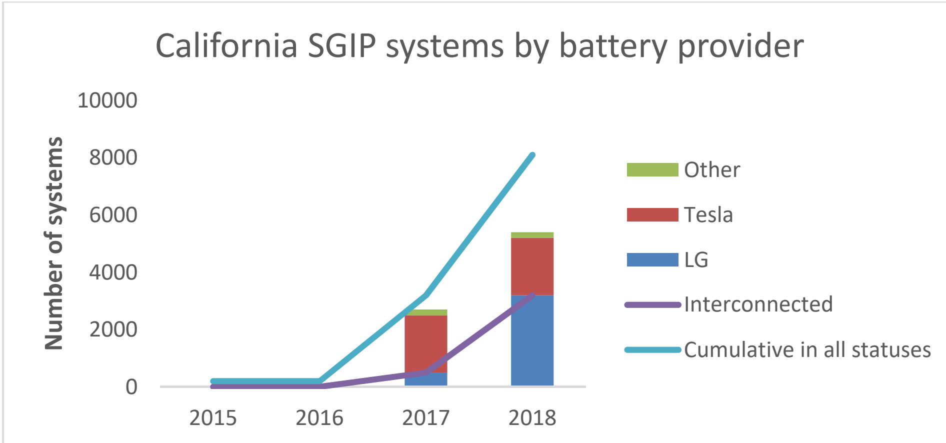


Figure 19 California SGIP systems by battery provider

Source: (BNEF, 2019b)

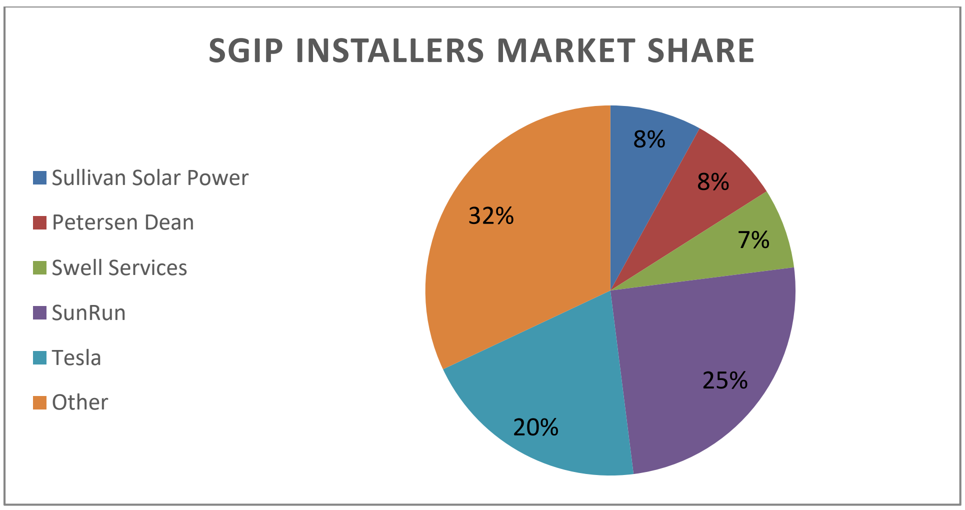


Figure 20 California SGIP installers market share

Source: (BNEF, 2019b)

Increasing solar PV deployment has significant implications for battery storage. Today, solar-plus-storage has become increasing popular, especially in California's residential storage market. A majority of the top solar developers have incorporated storage into their business strategy and have either deployed storage alongside PV or are pursuing hybrid installations. The combined solution makes solar more attractive than a PV system alone, and storage is able to piggyback on the solar investment tax credit. Utilities in California are also beginning to implement residential time-of-use rates that could have a favorable impact on solar-plus-storage economics. The new rate structure charges off-peak prices during most solar hours and peak prices when the sun goes down. Similar to solar industry, which has seen higher soft costs [10] in the past few years, soft costs associate with storage installation and development

[10] Soft costs include permitting, financing, and installing solar or storage systems, as well as the expenses companies incur to acquire new customers, pay suppliers, and cover their bottom line (DOE).

will also be more significant. Studies suggested that increasing competition can be expected for companies that can make significant improvements in storage system soft costs and EPC. From a regulatory perspective, the existing guides for permitting solar PV systems can also help streamline storage permitting processes.

Utilities have shown increasing interest in energy storage, according to information obtained in our interviews, this is in part because they are trying to capture value that has been lost to retail start-ups and are responding to increasing competition in the power sector. Utilities have been slowly adjusting to storage on the grid and have been pushed to accommodate the technology because of pressure from adoption of electric vehicles by consumers with residential solar systems. However, there are still significant obstacles to increasing utility-scale energy storage. These include concerns about the fire safety of LIBs, uncertainty about the next generation of long-duration battery technologies, and the ownership issues associated with storage assets.

3.6 Summary and Conclusions

Two broad lessons drawn from our analysis are that 1) the roles of actors in the innovation systems supporting development of clean energy technologies adapt and evolve as a particular technology matures and 2) institutional support is critical in every phase of development of a new clean technology and every link in the value chain.

Adaptation: the evolution of actors in the innovation system

As clean energy technologies have matured, their innovation systems have become more strategic and adaptive. The roles of public and private actors have shifted, and new corporate and government actors have entered the system, demonstrating the importance of institutions. Accelerator programs have emerged, and non-traditional actors, such as banks and insurance companies, have entered the system. The traditional triple helix of government, university, and industry actors making up the innovation system has evolved and expanded. Changes in one of the agents in the system forces others to evolve.

This evolution has had significant impacts on the clean energy sector, in particular for technologies like battery storage that rely on hardware innovation. The U.S. R&D structure is known for its heavy reliance on the private sector. As policy makers have continued to create guidance and incentives to encourage private investment in battery storage innovations, some state governments have stepped up to address gaps in the private funding process, such as by supporting the creation of intermediary organizations to facilitate knowledge flow and addressing industry segments that have not captured the attention of venture capital. This is particularly true in California, which has introduced an innovation system initiative to address the gaps left by the private sector since 2013. The state has created numerous intermediary organizations to support innovation development at various stages, from providing testbeds and start-up education and funding to offering networking opportunities.

Meanwhile, the majority of the investor community has shifted from funding early-stage development to funding innovations in later stages, following the bursting of the venture capital bubble between 2006 and 2011. At the same time, corporate venture capital has begun engaging with start-ups by providing R&D and exit strategies. What was once a sector of investments characterized by a lack of exits has now attracted the attention of the automotive industry, oil and gas companies, utilities, and insurance companies. Compared to private venture capital, corporate venture capital not only has large investment capability but also many channels through which to scout innovations and easier access to customers.

The clean energy innovation system is also characterized by an increasing number of accelerators and intermediary organizations organized by government, industry, universities, and research institutes. These include professional associations, public funding coordinators, regional innovation clusters, insurance companies, test bed facilities, accelerator programs initiated by federal and state governments, and corporate and private venture capital.

System building: institutional support through the stages of innovation and across industry segments

An effective innovation system is not only adaptive to the environments that emerge during various stages of the development of a technological innovation but also includes specific institutional support that spans the links in the value chain. Our case study of battery storage demonstrates the importance of system building from both government and firm actors. At the federal level, long-term R&D policy and market rules have been essential but more aggressive demand-side polices may still be needed. At the local level, various states have developed clear storage mandates, electric vehicle deployment targets, incentives, and climate policies to push demand. There is, however, a lack of support from the federal government, in particular for R&D. Compared with other clean energy technologies, public R&D in storage technologies is much less. Even though LIBs have reached a level of industry maturity, increased federal support is probably needed to continue diversify storage innovations and address supply chain issues. Patent activities (International Energy Agency and European Patent Office, 2020) show that U.S. is less competitive in battery storage knowledge generation compared to the leading countries, such as Japan and South Korea. Because most battery innovation activities are conducted by small and medium enterprises, financial support will be necessary for scale-up.

Institutional supports are particularly strong in California. In addition to effective downstream market pull policies influenced by the state’s aggressive climate agenda, the state has also introduced systemic policies that address climate resilience issues. These policies, which have been spurred by recent wildfires and power outages, include updating building and fire codes to accommodate larger energy storage capacity, clarifying the role of battery storage, mandating PV for new homes, and providing generous incentives for vulnerable communities to install combined PV and storage. Policy analysis also shows that California has actively engaged with upstream R&D policy and with mid-stream manufacturing policies by initiating the “Lithium Valley Commission.” Effective institutional support should strive to address issues arise during various stages of the development of a technological innovation, from R&D to manufacturing and market demand.

Most federal and state policies aim to foster battery storage downstream demand, and most firms’ activities mimic this aim. The U.S. battery storage industry is characterized by a few big players in the demand sector, including the electric vehicle and energy industry, and has not been able to fully capture upstream and mid-stream industrial segment value. This indicates the importance of supporting knowledge and financial resources needed for materials recovery and manufacturing capacity, as well as finding alternative science and technologies that will not be constrained by the current supply chain issues. To address these concerns, DOE initiated the Energy Storage Grand Challenge program in 2020, which has been applauded by research and industry stakeholders. We expect new federal policies to be enacted over the next few years to firm up the role of energy storage in energy transitions and climate resilience in the U.S.

Finally, we note that the relationship between competition and innovation is extremely complex. From a public policy perspective, it might not be most effective to simply increase or decrease industry competition. Rather, studies (Moen, Tvedten, & Wold, 2018) have shown that for firms in an industry that experiences rapid changes in production technology, the innovation pressure will most likely be high and represent significant challenges to resources. Therefore, access to production-related technology knowledge and innovation funding mechanisms will be particularly important.

This study is a scoping work to understand the high-level system structure of the battery storage innovation system as an example of how the innovation system supporting developments of new energy technologies evolves over time and alongside the maturation of the technology. Future research could flesh out this understanding by characterizing policy and business activities for each stage of development of a cleantech innovation and each industry segment. Existing policies should be revisited and new policies proposed that are targeted and adaptive to the future battery innovation system, which will almost certainly be different from what we see today.

The framework used in this report enables us to analyze innovation policy gaps by examining actors and their activities during the phases of development of an innovation (over time) and in different industrial segments. We believe this framework can be applied to the development of innovations in other clean energy technology areas, enabling us to answer questions regarding who can best diffuse and scale up innovations, and when and how to do so.

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