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A Strategic Condition Framework for Energy Innovation

Margaret Taylor, K. Sydny Fujita, Jingjing Zhang, Hung-Chia Yang, Sarah Price, and David Jacobowitz

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EXECUTIVE SUMMARY

Building upon previous work in innovation, technology, and economic fields, we propose a conceptual framework to address the interplay dynamics of public policy and the value chains of clean energy technology innovation systems, by focusing on market structural and strategic conditions in relation to the rate and direction of knowledge diffusion within activity-based value chains. Our framework extends beyond socio-technical transition models by considering such nuances as: 1) the implications of geography, 2) the locus of knowledge types, 3) the dynamics of financial and knowledge flow, and 4) emphasizing the importance of both market structure and institutional conditions. At the firm level, we consider dynamics of interactions between suppliers and customers, innovation activities, the competitive environment, and the firm's broader strategic relationship to governance activities and structures; we allow for the fact that each of these aspects of a firm's identity may have a strategically relevant geographic dimension (e.g., service territories, locational concentration of input resources, etc.). We provide a proof-of-concept application of the U.S. utility-scale solar photovoltaic (PV) and onshore wind sectors, including their interactions with the U.S. power market, which we in present in a web-based information platform (Energy I-SPARK, ei-spark.lbl.gov).

1 Introduction

Achieving a sufficient rate of technological advancement in order to address the impacts of impending climate change is an extensive problem that necessitates concerted global action, as framed and debated in a voluminous literature spanning numerous scientific fields of study (see, e.g., Masson-Delmotte et al. 2018). As urged in a 2018 Intergovernmental Panel on Climate Change (IPCC) report, limiting global warming to 1.5°C will require "rapid and unprecedented" changes in all aspects of society over the next decade, to bring about widespread adoption of climate-driven innovation and practices, including dramatic improvements in clean energy technologies. IPCC calculates that meeting this goal will require investments on the order of trillions of dollars per year globally, but they acknowledge that innovation policies targeted specifically to a 1.5°C temperature increase are presently understudied and as compared to the more thoroughly studied target of 2°C (Masson-Delmotte et al. 2018).

1.1 Existing frameworks of innovation

While technological change (and congruent change to procedures and practices) will be of key import to mitigation of climate change, when considered in the environmental economics perspective of policy analysis, it is typically accorded secondary importance in the context of resolving the market failure of incomplete appropriation of returns to research and development (R&D) investment by innovators. Under this "market failure" approach, the process of innovation is usually treated as a "black box," with innovations adopted and diffused in a linear fashion (Rosenberg 1983). We argue that this approach is insufficiently nuanced to address the magnitude of climate issues we currently face. Viewed through another lens, innovation scholars and socio-technical transition researchers have offered insightful conceptual frameworks to help analysts dive deeper into the dynamics of innovation diffusion processes and the interaction of technology within the broader contexts of industry, society, and users, etc. (Sorrell 2017; Geels 2019). While the grand theories of these fields are useful in understanding system transformation dynamics (e.g., the evolution of the U.S. electricity system), these methods are often applied in the context of long-term historical transitions, and significantly, lack causal explanatory and predictive power.

Innovation scholars have approached climate response from various angles by drawing on the toolkits of a variety of fields of study. The precise focus of research questions differs across disciplines. Environmental economists explore how a carbon tax could impact the rate and direction of clean energy technology diffusion (e.g., Nordhaus 1992); innovation economists investigate the dynamics between R&D and innovation (e.g., Romer 1990); scholars of political economy explore the role of power (both market and political) in gaming of system innovation; innovation system and transition scholars ask whether and how institutional and governance conditions spur or limit innovation and transition; social scientists explore the influence of social networks and agency innovation activities and outcome. While all of these branches of questioning can contribute meaningfully to the response to climate change, there remain significant divisions among different schools of tradition in terms of methodologies, focuses, predictive capability, and recommended business or governance actions.

1.2 The value of a meso-level framework

The question remains open: how can we envision the complex array of actors (e.g., firms, governing bodies, individual consumers), products (e.g., energy technologies, their input components, complements or substitutes, etc.), and connections (e.g., up- and down-stream supply stream relationships) in a way that is readily useful to planning activities, but also retains sufficient nuance to provide predictive accuracy in terms of real-world impacts of decision-makers choices? For response to the current climate situation to be effective and timely, we argue a middle ground ("meso-level") framework is needed to allow policymakers, business planners, and researchers to navigate the complex processes of innovation adoption and diffusion, and to purposefully explore policy and research questions critical to realizing a 1.5 °C climate target.

Building upon and drawing from previous work in innovation economics and innovation systems literature, we here describe such a meso-level analytical framework that will provide relevant stakeholders a structure within which to craft responses consistent with pre-existing multi-dimensional innovation systems, e.g., economic, technological, institutional, socio-cultural, etc. (Masson-Delmotte et al. 2018). Specifically, our framework addresses the interplay dynamics of public policy and the global value chains of clean energy technology innovation systems by focusing on both market structural and strategic conditions in relation to the rate and direction of knowledge diffusion. We operationalize our proposed framework in the cases of the U.S. utility-scale solar photovoltaic (PV) and onshore wind sectors, including their interactions with the U.S. power market. At the firm level, we consider dynamics of interactions between suppliers and customers, innovation activities, the competitive environment, and the firm's broader strategic relationship to governance activities and structures; we allow for the fact that each of these aspects of a firm's identity may have a strategically relevant geographic dimension (e.g., service territories, locational concentration of input resources, etc.). At the sector level, we extend the value chain scope to feed clean energy technologies into the power market, which itself encompasses three value chain activities. We also expand the sectoral framing of the U.S. renewable energy industry to the international scale in acknowledgement of today's globalized economy. Our framework provides a high-resolution assessment of innovative firms along the value chain of energy production, generation and supply, as well as capturing relevant facets of wider industry, market structure and institutional environments across the dimensions of time and geography. It allows policy-makers and analysts to track energy innovation dynamics in terms of material, financial, and knowledge flows. We discuss methodological and empirical contributions of our framework below.

Our framework addresses a number of knowledge gaps in the current energy innovation and public policy literature. Methodologically, we pay careful attention to the following aspects that we find inadequately addressed in existing models: 1) the implications of geography, 2) the locus of knowledge types, 3) the dynamics of financial and knowledge flow, and 4) emphasizing the importance of both market structure and institutional conditions. Considering the impacts of geography, we acknowledge that in today's highly globalized economy, it is insufficient to analyze innovation activities strictly within national boundaries; depending on the particular characteristics of innovation, relevant knowledge creation, diffusion, and adoption can span across geographies. Second, as the cost of hardware components of clean energy technologies continues to decrease, we recognize the importance of non-hardware knowledge to realize the full potential of innovation uptake, including developments in software, business practices, project development strategies, as well as mindsets and network configurations relating to the technology use. Our framework treats knowledge in a precise and sophisticated manner that tracks knowledge accumulation, investment in knowledge, and knowledge spillovers across a broad range of industries and activities, including some rarely addressed by innovation studies. Third, most value chain frameworks for the energy sector draw predominantly from engineering knowledge of material flows in a supply chain system, which focuses on the interrelated activities of acquiring inputs and producing output goods or services, rather than on the concordant strategies that influence a firm's competitive advantages surrounding those activities. Our framework also emphasizes the financial and knowledge flows of an energy system in the context of a global innovation value chain. Finally, we view market structure and institutional conditions as equally important influences on innovation; existing literature tends to center on one of these factors, i.e., the emphasis on market structure in the economics of innovation, as compared to the focus on institutional conditions and change in innovation system and transition literature.

Empirically, our framework accounts for the various contextual environments in which energy technologies currently exist. For example, we recognize that today's renewable energy industries have progressed to a large scale, in which a sophisticated system of global value chains with a dynamic set of actors has been established; however, this system is not static and continues to develop over time in response to technological, societal, and policy developments. Industry expectations arise from evolving policy and market environments, such as the uncertainties related to U.S. commitments in the post-Paris Agreement era, global trade trends and tariff impacts, and decreasing costs of PV panel and wind turbine manufacturing, etc. By contrast, previous literature has typically treated clean energy technology as a niche innovation, see, e.g., the recent perspective written by Markard (2018).

We extend the clean energy value chain to feed renewables into the U.S. power market, i.e., we array systems of value-adding production activities into interconnected "start-to-finish" value chains leading from the initial manufacture of technologies to the production and sale of undifferentiated electrons. Through inclusion of the power market, we aim to expand the application of innovation system perspectives across relatively uncharted territory. In addition to providing a scaffold for constructing and exploring future policy questions, we aim to provide insight on existing theories and questions in the innovation policy realm as they apply to the activities included in the example value chains. We use our framework to identify critical research gaps, work to codify universally applicable descriptions of knowledge, and enable causal explanation and the potential for prediction power regarding the impact of market structures, policy instruments, and business environments on innovation. In the process of gathering the information necessary for this proof of concept, we arrive at several interesting findings regarding knowledge types and the potential for market power across industries.

Our paper proceeds as follows: in section 2, we provide a working definition of a framework, and describe how we designed and built the strategic conditions innovation framework, with specific attention to the models and literature from which we drew insight. In section 3, we describe the process of building the framework; we include discussion of the online database we created to house and share our ongoing work. In section 4, we discuss initial findings and insights revealed in the process of constructing our framework. Finally, we conclude in section 5, where we discuss our conclusions, including limitations of our framework and future research directions revealed by our work to date. Additional information is available in the supplemental online materials and in our online data platform (Energy I-SPARK; https://ei-spark.lbl.gov/)

2 Defining and developing a conceptual framework of innovation

2.1 Defining a conceptual framework

Broadly, a conceptual innovation framework is an analytical tool in which a simplified depiction is presented to structure the variations and contexts in the system of innovation and the diffusion of knowledge. It guides analysts to collect, organize and analyze relevant information across the system of innovation. Porter (1991) provides a useful definition, which has been adopted and modified by subsequent researchers (e.g., Geels 2014): "A framework . . . encompasses many variables and seeks to capture much of the complexity… Frameworks identify the relevant variables and the questions which the user must answer in order to develop conclusions tailored to particular industry and company. . . In addition, all the interactions among the variables in the frameworks cannot be rigorously drawn. The frameworks, however, seek to help the analyst to better think through the problem."

An analogy of our interpretation of a conceptual framework is viewing the system of clean energy innovation and diffusion as the process of weaving a tapestry. The conceptual framework refers to the weaving design, an organized structure encompassing the elements of patterns, colors and material. Structural designs, which in this analogy can be represented by the support of a loom, are influenced by factors such as earlier works, values and beliefs, a practical purpose or inspiration, etc. In practice, the framework tapestry is constructed using the threads amassed through "data collection" and woven through the act of "data processing." While the weaving process is ongoing, the conceptual framework provides an organized structure to capture a snapshot of this process, instead of an end result. This helps to reveal key structural elements of the innovation system and their interconnections, their evolving dynamics, and potentially, a lens to future trends. Our proposed framework, however, is more descriptive than normative. As far as system structural evaluation and causal mechanisms are concerned, we aim to provide a discussion platform as a way to inspire and inform research and policy questions relevant to the underlying explanations for structural change.

2.2 Constructing a new meso-level innovation framework

Building from the theoretical discussion of a conceptual framework above, we examined existing frameworks to inform our design. In this section we pay special attention to the lens through which innovation systems were viewed in prior research, as pertains to the firm and its environments. This process can be envisioned as if we are looking into a kaleidoscope, in which the content and patterns are reflected through the angle one chooses to view the tube (i.e., innovation system). We discuss what structural elements matter for innovation, and how they are treated by each framework, such as power dynamics, actor-network, knowledge, geography and the use of value chains.

2.2.1 Different lenses to examine innovation

The foundation of our framework design draws substantially upon pioneering work in the field of economics of innovation (e.g., Porter 1979; Schumpeter 1942), innovation systems (e.g., J. Markard, Hekkert, and Jacobsson 2015), and socio-technical system studies, particularly those addressing the firm-in-industry and a firm's environment (e.g., Geels 2014). We draw substantially from the former two approaches to inform key inter-firm dynamics addressed by our framework.

Within the field of economics of innovation, the Schumpeterian endogenous model emphasized the role of innovation and entrepreneurship for economic growth; it highlighted several important conditions for quality-improving innovation, including R&D, market structure, a country's distance to the technological frontier, its institutional quality or its degree of financial development (Ugur 2016). In other words, the Schumpeterian model views a firm's strategic conditions and an industry's market structure as endogenous factors for innovation. Regarding market structure, Porter's prominent work in competitive dynamics, i.e., Porter's "five forces" (1979), provided a framework for a firm to evaluate its strategic options. Porter's five forces include three forces from 'horizontal' competition--the threat of new entrants, the threat of established rivals, and the threat of substitute products or services --and two forces from 'vertical' competition--the bargaining power of suppliers and the bargaining power of customers. In this framework, a basic value chain unit is comprised of a focal firm, its suppliers and customers, new entrants and established rivals; dynamics of the relationships between these players influence a firm's available competitive strategies.

However, firms do not strictly compete with one another, but have complex interactions that can include collaboration and cooperation. Networks among firms and organizations have been emphasized in ecosystem approaches, which tend to see firms as self-organizing and self-sustaining; these approaches have received increasing attention in the field of management of technology and innovation in recent years (e.g., Teece 2007; Scaringella and Radziwon 2018; Tsujimoto et al. 2018). According to Moore

(1993), “firms should not be seen as a part of an industry, but as a part of an ecosystem where companies cooperate, compete and co-evolve capabilities around a new innovation”. Here, the ecosystem can potentially span across national boundaries, whereas “industries” are often defined within a country or economic zone. As value chain analysis focuses on the process of value creation, the ecosystem approach underlines the value network amongst actors (Battistella et al. 2013). The definitions and inclusion of actors vary across different types of ecosystem approach. While the business ecosystem approach is centered around networks among business players, the innovation ecosystem approach also considers a web of knowledge that shapes the creation and production of innovation (Xu et al. 2018). A central feature distinguishing ecosystem approaches from endogenous technological change models is recognition of the nonlinear complexity of innovation processes; that is, R&D and appropriability of knowledge are not the only concerns relevant to firms’ survival and evolution in their environments.

Innovation system approaches take into account an extensive set of important factors that shape innovation activities, drawing from the fields of evolutionary and institutional economics (e.g., Edquist 1997; Lundvall 1992; Nelson 1993). These approaches focus primarily on the macro level of institutional structures needed to take advantage of innovations for economic growth. The system structure constitutes a web formed by all relevant actors, their relationships (i.e., social networks) and the processes related to producing, distributing and utilizing economically useful knowledge (i.e., learning, institutional conditions, etc.). The innovation performance of organizations (both private and public) is thus conceptualized as dependent on the system structures and the subsystems they operate in (Rinkinen and Harmaakorpi 2018). Depending on the pertinent scope, an innovation system can be analyzed from national, regional, sectoral, or technological levels. As suggested by the names, national and regional innovation system approaches tend to be bounded by a geographical definition. Recent advancements in the field have aimed to enrich the spatial dynamics and complexity of the system (Bergek et al. 2015), including by analyzing technological innovation processes in transnational contexts (e.g., T. Hansen and Coenen 2015; Binz and Truffer 2017). The innovation system approach and value chain analysis have also been viewed in combination, in particular for solar PV technology (Binz, Tang, and Huenteler 2017; Zhang and Gallagher 2016). As innovation increasingly takes place in global networks, a firm’s connectedness to and standing within the global network of its suppliers, competitors, and customers are expected to impact its innovation strategy. Multiple methods are available to represent value chains: the traditional value chain, as viewed by endogenous technological change models, and innovation value chain analysis. Each of these methods tend to be applied in different strands of literature, since global production networks and global innovation networks are generally analyzed separately (Lema, Quadros, and Schmitz 2015). There is value in understanding the linkage and dynamics of both financial and knowledge value chains, with the latter typically including idea generation, idea development and the diffusion of developed concepts (M. Hansen and Birkinshaw 2007). Despite the development of conceptual models, there is generally a paucity of information on the immaterial aspects of knowledge and innovation.

Rather than viewing a firm as a passive participant in its environments, the Triple Embeddedness Framework (Geels 2014) takes the bi-directional viewpoint that firms not only adapt to institutional pressures (i.e., managerial adaptation), but also respond strategically to shape them (i.e., environmental selection). Firms are seen to strive for both social and economic fitness. They “satisfice” rather than “optimize” (i.e., act with bounded rationality), in contrast to the economic efficiency goal assumed in endogenous technological change models. The co-evolution of firm and its environments are argued to be more Lamarckian (“intentional”) than Darwinian (“blind”), which makes the study of causal mechanisms more feasible. In this framing, industries represent a population of firms (core and peripheral firms that hold different degrees of power) in a sector facing similar pressures from its environments. These environments are comprised of three levels, including an industry regime (i.e., formal and informal institutional conditions that create system inertia), an economic environment, and a socio-political environment. The Triple Embeddedness Framework attempts to integrate economic theory with insights from other social sciences and political economy studies. Although it arguably produces a more sophisticated representation of reality, this framework primarily exists as a theory with limited operationalization. We do, however, find that it is useful to broadly conceptualize the contextual environments and strategic conditions firms face, which guide their innovation activities. We also recognize the usefulness of encompassing technological and non-technical innovations, such as changes to user practices and institutional structures, that are typically discussed in socio-technical transitions literature. An important feature of socio-technical approach is adding a social aspect to the technological system, therefore emphasizing transformations in all relevant system elements, including changes in technology, user practices, regulation, industrial networks, related infrastructure, and symbolic meaning or culture (Geels 2002). Due to ontological differences, we primarily adopt broader concepts to guide our conceptualization of firms, rather than concrete aspects of, e.g., the Triple Embeddedness Framework.

2.2.2 Bridging the differences

Recognizing the merits and pitfalls of each perspective, innovation and transition scholars have attempted to combine or bridge frameworks ranging from technical quantitative modeling to endogenous growth theory, to provide a more holistic view on innovation (Romer 1990). For example, Ruttan (1997) claimed that three approaches (i.e., induced technical change, evolutionary theory, and path dependence) should be regarded as components of a more general theory of the sources of technical change. Recently Geels et al. (2016) argued that full integration of the three analytical approaches to innovation (i.e., economic and integrated assessment models, socio-technical transition analysis, and practice-based action research) is not feasible due to their ontological differences, and alternatively sequential and iterative use of these approaches may generate a more nuanced assessment to support policy design and implementation.

The continuous debates surrounding the complex systems of innovation and transition indicate that each perspective potentially grapples with a limited subset of relevant innovation-related processes and outcomes, with respect to current climate change and energy system transformation issues. By varying the lenses through which an innovation is examined, researchers often draw differing insights and conclusions. While it is possible that an entirely new perspective will be necessary to accurately frame innovation in the context of addressing climate change, we find it fruitful to bridge existing approaches into a more general and operational framework, with the hope that we also provide a platform for discussion among innovation scholars in different disciplines, who are currently divided in their views on determinants and scoping for innovation activities, process and outcome. Building upon and drawing from existing lenses, we propose a meso-level analytical framework, encompassing key metrics and interactions, that will provide relevant stakeholders a structure within which to craft policies consistent with pre-existing multi-dimensional innovation systems.

3 Building the strategic conditions framework

Our framework connects an extended (i.e., includes power markets), activity-based value chain with four layers of information, each encompassing a geographic component. We replicate the connectedness of industries and activities that in reality exist throughout the path from technology manufacturing through electricity generation through transmission, distribution, and energy markets (Figure 1). We currently use utility-scale PV solar and on-shore wind in this proof of concept, but our framework could be usefully extended to other electricity generating technologies, as well as energy end-use activities and products. We aim to lay out the groundwork for future analysis of all major electricity generation types and demand-side technological systems, to provide a fine-grained integrated assessment of the ways in which climate and innovation policies interact within each of the value chain steps.

Figure 1 demonstrates the flows of physical products from one step to the next, and also the flows of money, knowledge, and material throughout the value chain (marked as colored arrows). Many of the prominent frameworks used to investigate the processes of innovation and the interplay between policy and innovation consider the emerging clean technologies in comparative isolation, without explicitly examining how these technologies feed into the power market. We expand the value chain system to include electricity generation and further break out its elements, following the exchanges of goods and services, money, and knowledge from the initial manufacture of major energy technology sub-components all the way through to the distribution of electricity to customers. By so doing, we emphasize the interconnectedness of value chain activities, enabling a researcher or policymaker making use of the framework to be cognizant of market structure and other facets of power market activities that may impact the effectiveness of a policy or the implications for a market disruption targeting an upstream value chain step.

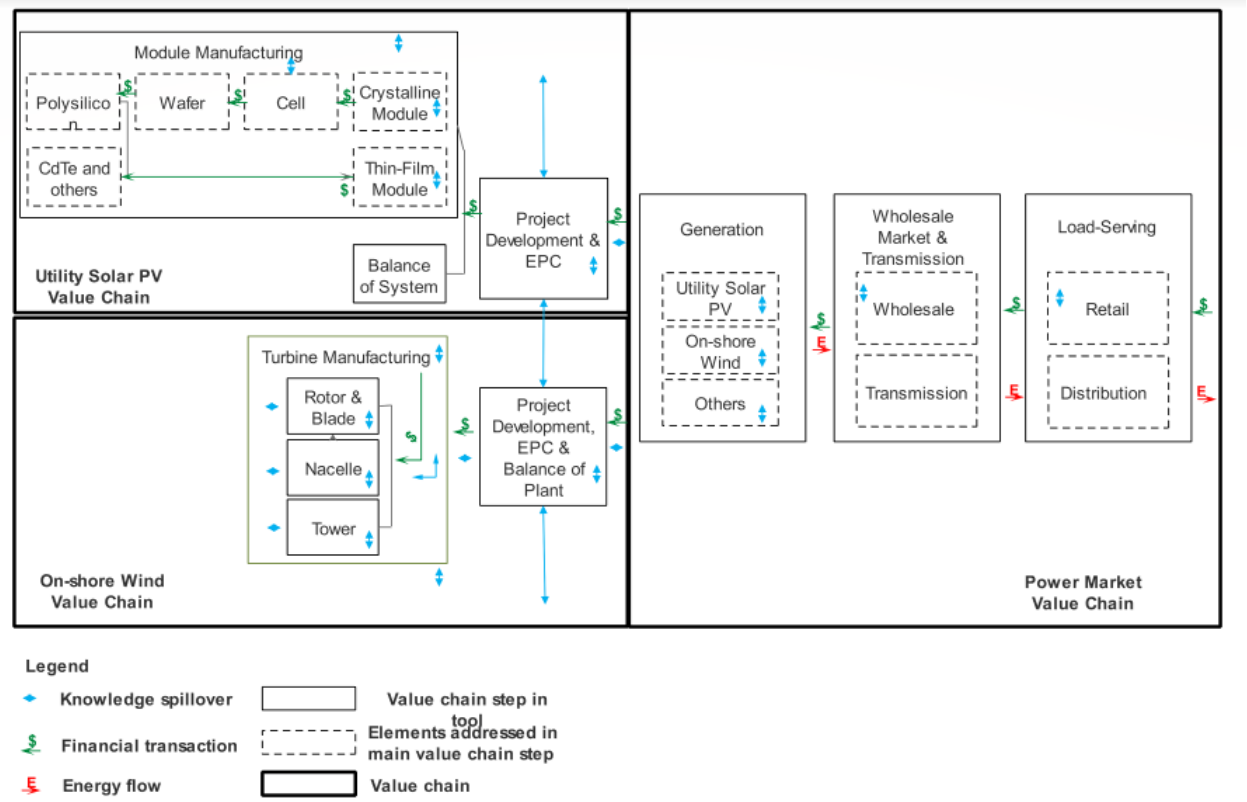

Figure 1. Value chain representation of utility-scale solar PV, onshore wind, and power market

We chose to define value chain steps in terms of activities rather than actors, due to the fact that individual firms may be active in only one step of a value chain or vertically integrated across many; this definition is relevant to describing industries and studying market concentration and dynamics within them. That said, the corresponding actors are easily identifiable as needed in a prospective social network type of analysis. Additionally, some project development and EPC firms work with multiple energy technologies (e.g., wind and solar). Activities may be sequential (e.g., successive manufacturing stages of polysilicon PV modules) or parallel (e.g., concurrent manufacture of wind turbine components), and our symbology reflects these differences. In this iteration, we do not focus on the diversity of electricity customer and end use types, nor on generation that takes place behind the meter (e.g., residential solar PV), though we note that these activities could also be represented by our framework. In order to bound the volume of information required, we also exclude peripheral activities such as the manufacture of transmission infrastructure and construction equipment. While these activities are in fact relevant to a complete picture of the set of energy technology value chains, we leave them veiled for now as we balance the effort of data collection with the value of further detail. Key challenges of defining value chain steps included: how to separate activities, what activities or sectors to leave aggregated, and clarifying connections between activities. In our initial proof-of-concept, we decided to bound the value chain by excluding generic input industries (e.g., glass manufacturing, copper mining), though these could plausibly be analyzed and embedded in the framework as well.

We operationalize our framework in the form of an online information platform, "**Energy I**nnovation, **S**trategy, **P**lanning, **a**nd **R**esearch **K**nowledge for decision-makers, entrepreneurs, and analysts" (Energy I-SPARK). In the current iteration, the Energy I-SPARK platform allows a user to explore the substantial amount of information on these value chains that we have compiled from secondary sources; in the future, we aim to manage this information platform as a repository for primary data.

Information on electricity generation from solar PV and wind is plentiful, but scattered across many resources and specific topic areas. One contribution of our framework proof-of-concept is to organize valuable information about these value chains into four related categories: descriptive information, strategic conditions, knowledge conditions, and innovation outcomes. Underlying this categorization is the notion that the outcomes of innovation are a function of the strategic and knowledge conditions present throughout the value chain. Table 1 gives a brief overview on the four major categories of attributes, with description of the content and indicators included in the framework; we discuss these four categories in greater detail to follow.

The descriptive information section is intended to orient the user within the value chain; it provides a basic snapshot of the selected value chain activity. We include a definition of the technology (or process) of interest, discussion of the primary firms engaged in the step's activities, and discussion of the relationship between the selected activity and the rest of the value chain. While industry experts are likely already familiar with the descriptive information, we include it for other decision makers (e.g., policy analysts) who may not yet have a thorough grounding in each value chain activity.

Under the strategic conditions section, we examine the strategic conditions created by the market and governance environments experienced by the actors within a value chain step. The types of data we categorize as such include: Porter's five forces, as they relate to the value chain step (i.e., industry rivalry, threat of new entrants, threat of substitutes, bargaining power of suppliers, bargaining power of buyers); firm market shares in terms of production and/or revenue and the implied market concentration; firm size in terms of number of employees; metrics of production (e.g., units manufactured, installations completed, etc.). These types of information are included to illustrate the relationships of power and cooperation within the relevant industries, as well as to illuminate a given firm's relative role in the industry. A variety of indicators are included because no single one (e.g., market concentration) can reliably predict the innovative activities of a firm or industry; rather, innovative output appears to be a function of a combination of intersecting factors of strategic and knowledge-related activities. The evolving policy environment is described in relation to other strategic conditions, as rules, incentives, and oversight interact with market dynamics to influence inter-industry relationships and individual firms' business strategies. The influence of geography is also explored, in terms of distribution of jobs as well as in relation to geographically fixed resources (e.g., regions with strong, reliable winds), the choice to locate near firms performing up- or downstream activities versus transporting inputs and output products, and the connection between country or region and commonly applied oversight or incentive mechanisms.

Table 1. Overview of major attributes and content in the framework

Activities		**Attributes**			
		Descriptive Information	**Strategic Conditions**	**Knowledge Conditions**	**Innovation Outcomes**
Utility-Scale Solar PV	Module manufacturing	Broad discussion of the technologies or processes encompassed by the activity, including descriptions of sub-categories of activities and of the array of types of technologies or processes included.	Discussion of Porter's five forces in the context of the activity Overview of geography (global or U.S. context) Overview of governance (laws, incentives, regulations impacting the activity) Quantitative treatment of competition (FFCR, HHI) Information table of top firms involved in the activity (location, revenue, employees, etc.)	Knowledge as a resource (absorptive capacity, R&D input, etc.) Knowledge creation (patents, publications, process development, etc.) Knowledge spillover (tacit knowledge transfer, patent citation, research collaboration, etc.) Overview of geography (global or U.S. context)	Discussion of direction and rate of technological (or process/procedural) change Data table including quantity, cost, and quality attributes over time
	BOS manufacturing				
	Project development/EPC				
Onshore Wind	Turbine manufacturing (rotor blade; nacelle; tower)				
	Project development/EPC/ BOP				
Power Markets	Generation				
	Wholesale marketing and transmission				
	Load service and distribution				

The knowledge conditions section focuses on: 1) investment in knowledge, 2) production of knowledge, and 3) knowledge spillovers relevant to advances in the selected value chain step. It provides discussion of technology and non-technology-based knowledge, patenting (or propensity to forgo patenting) and exclusivity of knowledge, and research and development. After much deliberation, we concluded that these three categories of knowledge-related topics are universally relevant within clean energy value chains, not just to technology manufacturing activities. For example, investment in knowledge may be represented by traditional R&D within a manufacturing activity, and analogously, it may manifest as collaboration with colleges to create training programs within a project development or power market operations activity.

The innovative outcomes section is intended to aid the user in exploring the results of innovative activity (e.g., the direction and rate of technological change or knowledge accumulation) within the selected value chain step; it provides information relating to the dominant design of the technology (or procedure) and to emerging technologies and methods, allowing analysis of incumbents versus new entrants to the industry. We include data on costs, performance, production levels, and other quality attributes when possible; we aim to provide the necessary items of information to construct various experience or learning curves, and also present estimates of these values found in the literature.

We keep an eye to geography throughout, in acknowledgement of the role location and proximity can play in strategic dynamics and the fact that job impacts of policies and changes to technological trajectories may differ regionally. Goods and services (e.g., manufacturing infrastructure, service territories, etc.), money, and knowledge all have geographic centers where they are currently located and routes through which they move from one step of a value chain to another. These factors exhibit varying degrees of geographic "stickiness" (i.e., difficulty in changing location or difficulty in replicating elsewhere). Reasons for locational stickiness include: supportive policies in a state, region, or country (e.g., tax credit, government R&D support, stringency of labor and environmental laws, etc.); proximity to suppliers (particularly if suppliers are "stuck"); path dependency. For instance, the U.S. Great Lakes region has the highest concentration of wind-related manufacturing activity following from the knowledge and facilities of the automobile industry as many of the components in wind turbines are similar to those used in engines and other auto parts (McGinley 2018). Suppliers in the Great Lakes region also benefit from the close proximity to Canada, the industry's largest export market, and the Plains region, where wind energy represents over 80% of all new electric generating capacity installed in the recent years (American Wind Energy Association 2017; McGinley 2018)

We intentionally weave policy throughout our representation of the value chain, recognizing that laws and oversight entities impact the market environment in which these activities take place. Many existing models and frameworks treat policy as a background condition or a potential disruption; our treatment of the existing policy environment as one of many sets of strategic conditions aims to accurately represent policy's role in the fabric of reality, as threads in the structural weave such that changes may have wide-ranging and diverse impacts depending on the nature of value chain interactions. The connection between governance and market structure is particularly pronounced in the power markets value chain, in which the potential for the exercise of market power by utilities holding a monopoly on electricity service is balanced against the oversight of utility commissions. The existence of the potential for power and the regulations and oversight to limit it are all relevant to the incentive to innovate and to the realization of future policy goals.

4 Discussion of findings and insights

While our focus was on laying the theoretical and logical foundation for our strategic conditions framework, we also arrived at several value chain-specific findings worth sharing through the course of developing this proof of concept, as summarized in Table 2. These findings provide an example of the types of research questions that our framework is well-positioned to address. By connecting findings regarding the firm or organization (e.g., locus of knowledge) and its environment (including market structure and governance conditions) to innovation outcomes, we aim to provide decision-makers with the necessary materials to draw insights on: the development of tailored R&D agendas, the stringency of oversight, and policy interactions with different value chain components as technological systems evolve, as well as to enable comparison against the current rate and direction of change. Business actors can evaluate their strategic environments by navigating the market power up and down the value chain and focus on resources and directions needed to stay competitive. Innovation researchers can benefit from this framework's system view of innovation activities (innovation system), investigate questions concerning knowledge spillover (innovation economics) and broader impacts of institutional structure on innovation (socio-technical system studies). Many results are summarized in terms of a low - moderate - high scoring, represented by a white open circle (low, ○), a half-shaded circle (moderate, ◒), or a black fully-shaded circle (high, ●). More discussion and description of these value chain attributes, including the evidence underlying our scoring, can be found in the supporting online material.

To give a concrete example, one can observe an increasing cost trend of non-manufacturing activities in the utility-scale solar PV value chain, and the key type of knowledge and oversight required has also shifted correspondingly which points to a direction and importance of non-technological innovation (See Table 2). However, current innovation studies still heavily rely on a technology focused framing of innovation, where such facets are downplayed or unaccounted for.

We evaluated the strategic conditions in each step of the value chains in order to inform a prediction of the potential for the future exercise of market power by firms engaged in the primary activity of each step, scoring each activity "low," "moderate," or "high" in potential. The exact reasoning for each of our scores differs and is provided in the Supporting Information, but in general, we arrive at a score by evaluating market concentration (e.g., Herfindahl-Hirschman Index – "HHI," four firm concentration ratio – "FFCR," or qualitative assessment provided in previous research), Porter's five forces, and the regulatory environment faced by the firms participating in a value chain activity. Market concentration (represented by the HHI or FFCR) is a common metric used to assess an industry's level of competition, particularly in the case of estimating the impact on competitiveness of a merger between firms. By examining a number of factors that contribute to a firm's competitiveness within an industry and an industry's overall degree of competition, we conclude that market concentration alone does not appear to be a reliable indicator of the degree of industry competition or of the plausibility of future exercise of market power.

Tracking the locus of knowledge across value chain steps, we evaluate the relevance of four categories: people (knowledge in embedded in human resources, e.g., expertise and relationships used by a project developer to successfully match tasks to qualified subcontractors), procedure (knowledge is recorded in procedures and rules, e.g., electricity wholesale market rules), process (knowledge relates to production methods or systems, e.g., change to materials deposition processes in PV module manufacturing), and product (knowledge relates to aspects of the product form and is likely patentable, e.g., change to turbine blade design). The four categories of people, procedure, process, and product exhibit differences in the degree to which knowledge can be retained within a firm, patentability or other form of protectability, and the tendency for knowledge spillovers, which highlights the importance of considering each category to gain a complete picture of the knowledge landscape of a value chain activity.

When reviewing the strategic conditions for value chain activities in the context of governance, we determined that the primary forms of governance experienced within an activity tended to fall into one of three categories: 1) innovation in the activity benefits from the support a grant-providing institutions (e.g., U.S. Department of Energy or Department of Defense R&D funding, etc.), 2) performance of the activity is contingent upon permission of permitting and licensing entities (e.g., city building permits, state licensing of construction companies, transmission interconnection permits, etc.), 3) activity is monitored by an oversight body (e.g., state utility commissions, Federal Energy Regulatory Commission – "FERC", etc.). While other types of law, policy intervention, or oversight may influence a value chain activity directly or indirectly (by which we mean through impacts feeding up or down the value chain from adjacent activities), these three forms were more universally applicable and unambiguous in targeting (as opposed to, e.g., attempting to unravel exactly where the incidence of a renewable portfolio standard is experienced and to what degree), so they are the focus of our proof-of-concept evaluation.

For manufacturing activities within the value chain, "rate of change" can be interpreted as the rate of technological change; for non-manufacturing activities (e.g., project development), we use the term "rate of change" to refer to the pace at which knowledge accumulation leads to procedural innovations that advance the performance of the activity. The discussion process undertaken to come to this framing of rate and direction of change, i.e., that it can logically be applied in an analogous manner to non-technology-centric value chain activities, was in fact a significantly valuable aspect of this research endeavor. For some value chain activities, such as wholesale electricity marketing and transmission, we note variables important to progress in the value chain step even though we do not yet have sufficient data to provide a rate of change score with a satisfactory degree of certainty.

Table 2. Insights from the development of Energy I-SPARK

Value Chain step		Share of Value Chain Cost (%)	Market Structure: Potential for Market Power	Locus of Knowledge				Primary Form of Governance	Rate of change	
				People	Procedure	Product	Process		Key Trend	Rate Code
Utility-Scale Solar PV	Module manufacturing	23.5%	Upstream: ◒ Downstream: ○	○	○	●	●	Grant providing institutions	Shift from polycrystalline silicon to thin film	○
									Increasing efficiency	◒/●
									Decreasing cost	●
	Balance of system	39.6%*	◒/●	○	○	●	●	Grant providing institutions	Decreasing cost	◒/●
	Project development and EPC	36.9%	PD: ◒, EPC: ○	●	●	○	○	Permitting and licensing entities	Dominance of soft costs	◒
									Changes in finance options	●
Onshore Wind	Turbine manufacturing	71.6%	◒	○	◒	●	●	Grant providing institutions	Decreasing cost	○/◒
									Increasing turbine capacity	●
									Increasing rotor diameter and hub height	●
	Project development and EPC	28.4%	◒	●	●	○	○	Permitting and licensing entities	Time to complete project	Uncertain
									Decreasing cost	○/◒
Power Market	Generation	59%	◒/●	●	◒	○	○	Oversight bodies	Shift from IOU/POU to IPPs	○/◒
									Shift to renewables	◒
	Wholesale Marketing and Transmission	13%	○	●	●	◒	◒	Oversight bodies	Evolving market rules	Uncertain
									Improving knowledge of the transmission system	Uncertain
	Load Service and Distribution	28%	●	●	◒	○	○	Oversight bodies	Deregulation / Shift from IOU to other arrangements	○/◒

Notes: Each column of findings is discussed in greater detail in its own section of the Supporting Information. Many results are summarized in terms of a low - moderate - high scoring, represented by a white open circle (low, ○), a half-shaded circle (moderate, ◒), or a black fully-shaded circle (high, ●). Data sources for cost share %: utility scale solar, based on 5 MW PV system with one-axis tracker (Fu et al. 2017)), onshore wind (Mone et al. 2017), power markets (U.S. Energy Information Administration 2018).

5 Conclusions

The sense of urgency to resolve climate change issues has been repeatedly stressed by IPCC and governments at various levels. With the goal of providing a general and flexible platform for generating meaningful policy and research questions, we bridged innovation analytical frameworks from various school of tradition and operationalize it in the context of global clean energy value chain that feed into the U.S. power market. We addressed several knowledge gaps in the existing literature, by connecting key aspects of economics of innovation, ecosystem approaches, and innovation systems approaches.

We combined an array of insights from existing innovation studies into a new generalized framework to inform meaningful research and policy questions, and shed light on future directions for like-minded research. Although we appreciate the complex contributions of prior research, we did not explicitly address several important elements of existing theories and frameworks; these include, for example, the impacts of networks, the implications of political power, and socio-cultural factors such as values, beliefs, social norms and trust, etc. We see potential value to expanding our groundwork to encompass the practices of social network studies, as the actors involved in the global innovation value chain can be readily identified in our current framework. We note that social networks could be treated similarly to the way geography enters our framework, i.e., nested across different segments of value chains. Socio-cultural factors could also be explored in parallel to social network analysis; for example, trust is typically the foundation of forming and maintaining a business or knowledge network. Regarding political power, we also see a parallel to our presentation of market power, especially in the U.S. This is also a topic that is well discussed in political economy and institutional economic sphere, as related to opportunity structure.

Throughout the process of operationalizing the strategic conditions framework for energy innovation, we incorporated insights regarding the concepts and definition used, particularly in terms of relevant timescales, how to define and categorize value chain actors, and the importance of geography in various layers of value chain information. Regarding timescale, utility-scale PV and wind projects usually take multiple years to complete; the single-year data sets generally available thus do not give a complete picture of a project developer’s or EPC’s activities, role in a particular project, or influence in a service region. In general, we found it challenging to precisely identify and attribute the contributions of specific actors (e.g., how to apportion megawatts of PV capacity across project developers when multiple firms have worked on the same project sequentially). Note that this is different than shared ownership of a project, because ownership shares are reported or can be calculated. Regarding geography, we found that defining the “location” of a firm can be a complex problem, as it can be defined as the firm headquarters, headquarters of a parent company, location of R&D facilities, or location of manufacturing facilities. All of these locations can be relevant to different questions regarding the ways in which incentives and knowledge flow in the system of innovation (e.g., contexts of corporate taxes, labor or environmental regulations, etc.).

We aim to extend our framework to include all major electricity generation technologies in the future (e.g., combined cycle natural gas, nuclear, coal, geothermal, etc.), and as a further-reaching goal, to incorporate demand-side technological systems and practices (e.g., residential PV, electric vehicles, efficient appliances, demand response, etc.). We also believe that this framework could be usefully extended to other sustainability-related fields and topics (i.e., energy and pollutant impacts of the transportation sector, etc.). On the data front, we hope to identify information sources covering a longer time series, and more primary than secondary data. We note that the financial flow is particularly challenging to track, as project ownership and sources of finance can be disconnected, and the dynamic shifts rapidly depending on the timing of project stages as well as enabling or blocking mechanisms imposed by the changing governance conditions.

Practically, there are pertinent programs at the federal and state level that can be usefully evaluated via the support of our Energy I-SPARK platform, for instance, tracking the U.S government energy R&D investments such as SUNSHOT and ARPA-E programs. Evaluating these programs or general R&D portfolios in the contexts of global value chain can aid the process of examining the U.S. clean energy innovation activities and policies in a much broader scale, and to enable amplification the innovation-specific policies needed for reaching the 1.5 C degree climate target.

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Supporting Information

S1. Discussion of the Potential for Market Power

Below we discuss the potential for market power within value chain activities based on strategic conditions. In our assessment of the potential for market power, we consider whether the strategic conditions in each value chain step could plausibly result in a future situation of market power, whether or not such a situation has previously arisen in that sector and whether or not the actors within that sector would be likely to act to benefit from such a situation. We take into account such factors as market concentration, barriers to entry, and policies aimed at maintaining competitive behavior or reducing incentives to manipulate price and supply. We address the particular circumstances of each value chain step individually. Our assessment is summarized in table S1 below.

Utility-Scale Solar PV:

- **Module Manufacturing:** Generally, the industries involved in upstream activities in module manufacturing (e.g., silicon processing, wafer manufacturing) are fairly highly concentrated, but involve strong competition largely due to the nondifferentiable nature of the product. Downstream substeps of module manufacturing (e.g., module assembly) have lower barriers to entry and are less capital intensive. Polysilicon processing is capital intensive, contributing to nontrivial barriers to entry; market concentration is moderate to high, while competition between industry actors is moderate. Wafer and cell manufacturing require high technical precision and high capital investment, contributing to barriers to new entrants; however, market concentration in these activities is low to moderate and competition between industry actors is high. Thin-film manufacturing is a relatively new activity within module manufacturing, with moderate market concentration and a moderate level of competition. As the process requires fewer steps than traditional polysilicon module production, initial capital investments are comparatively low, reducing barriers to entry. Thin-film manufacturers also must compete against polysilicon modules, as well as other actors in thin-film manufacturing.
- **Balance of System:** Two key components of the balance of system for a PV project are inverters and racking. Inverter manufacturing is a moderate but increasingly concentrated activity, with a high degree of competition. Racking manufacturing is a highly concentrated activity with a moderate degree of competition. Manufacturers of BOS components sell to a relatively less concentrated industry (project development and EPC), providing the potential to exert market power. Contributing to this potential for market power is the critical nature of BOS components to the PV project as a whole, in combination with the relatively minor share of BOS cost of project total (as compared to module and soft costs).
- **Project Development and EPC:** Market concentration is moderate within the project development activity, with a moderate level of competition. EPC firms tend to serve a

more localized territory, with low market concentration across the U.S. market and a moderate degree of competition within the industry. Dedicated EPC firms must also compete against vertically integrated project developers. Many of the largest project developers (e.g., First Solar, SunEdison) are vertically integrated across EPC, manufacturing, and financing activities as well. Project developers must interface with numerous suppliers and subcontractors in order to complete a PV project. While the expertise and business connections required to perform project development activities present a barrier to entry, the substantial recent growth in demand for PV projects has encouraged some new companies to enter the industry.

Utility-Scale Onshore Wind:

- **Turbine:** Turbine manufacturing is highly concentrated, with the top three manufacturers accounting for on the order of 80% of cumulative and new installed capacity in recent years. However, competition in this activity is high, as the top companies aim to maintain or improve market position relative to one another, and companies compete aggressively on price and quality attributes. The top manufacturers are active across sub-activities within turbine manufacturing (e.g., blades, nacelle), and also face some degree of competition from manufacturers specializing in individual turbine subcomponents, which increases the overall level of competition in the industry. Turbine manufacturers sell into a similarly concentrated industry (project development and EPC), so they do not have a comparative advantage in that respect.
- **Project Development and EPC:** For onshore wind, project development and EPC activities are moderately concentrated, with a high degree of competition between industry participants, particularly between firms specializing in wind EPC. Dedicated EPC firms must also compete against vertically integrated project developers. Competition is largely based on price and reputation. Barriers to entry are fairly high due to the expertise and business connections required to perform project development and EPC activities, especially for large projects.

Power Markets:

- **Generation:** In spite of low market concentration and high competition under normal operating conditions, during periods of mismatch when demand outpaces supply, marginal generators (i.e., those that have the capacity and capability to quickly increase output) have the potential to wield substantial market power. The potential for exercise of market power is generally confined to short time periods (i.e., measured in hours or days), but could plausibly extend to a much longer time frame due to barriers to entry of new generation.
- **Wholesale Marketing and Transmission:** While wholesale markets appear to have high market concentration and little to no competition, ISOs/RTOs are set up such that wholesale market makers have no incentive to influence prices. As the market maker's goal is to efficiently dispatch trades, they have no incentive to attempt to exert market power; in fact, wholesale market makers aim to mitigate potential market power of those

bidding capacity into the market. Outside of ISOs/RTOs, incentives for the exercise of market power are higher. Additionally, under certain circumstances, the owner/operator of a transmission line may have the opportunity and incentive to restrict access to the connection by other entities.

- **Load Service and Distribution:** The investor-owned utility is currently the dominant mechanism of load service and distribution; as these are for-profit entities with a monopoly within their service territories, there is substantial potential for market power. The existence of state utility commissions reflects the economic risk of this potential for the exercise of market power. Regions that allow for electric retail competition have reduced potential for market power in this sector.

Table S1. Potential for the Exercise of Market Power across Value Chain Activities

VC step		Market Concentration*	Market Competition[†]	Potential for Market Power
Utility-Scale Solar PV	Module manufacturing	Medium[‡]	High[‡]	Upstream: ◒ Downstream: ○
	Balance of system	Med and increasing[§]	High[§]	◒/●
	Project development and EPC	PD: Med[§] EPC: Low+[§]	Medium[§] to high[‡]	PD:◒,EPC:○
Onshore Wind	Turbine manufacturing	Medium[‡] to High[§]	High[‡]	◒
	Project development and EPC	Medium[‡]	High[‡]	◒
Power Markets	Generation	Low[‡]	High[§]	◒/●
	Wholesale Marketing and Transmission	High[§]	None to low[§]	ISO/RTO: ○ Other: ◒/●
	Load Service and Distribution	High[§]	None to low[‡]	●

Notes: Open (white, ○) circle represents a "low" scoring, a half-filled circle, ◒, represents "moderate," and a filled-in (black, ●) circle represents "high."

* Most of these rankings come from IBISWorld industry reports. IBISWorld generally uses the four firm concentration ratio to assign industry concentration rankings: "Concentration is considered high if the top players account for more than 70% of industry revenue. Medium is 40% to 70% of industry revenue. Low is less than 40%." For value chain activity steps where no IBISWorld report is available (or if we have more recent data), we assign market concentration rankings as provided by other secondary sources or from our own calculation of the four firm concentration ratio or HHI. We aim to keep these rankings consistent across value chain activities.

[†] IBISWorld industry reports are the primary source for these rankings. Unlike market concentration rankings, industry competition scores are based on qualitative factors within each industry, including prevalence of vertical integration, competition from international sources, impacts of regulation, etc. For value chain activity steps where no IBISWorld report is available, we assign market competition rankings as provided by other secondary sources or from our own interpretation of market conditions. We aim to keep these rankings consistent across value chain activities.

[‡] denotes IBISWorld ranking

[§] author interpretation of compiled data, see Energy I-Spark Strategic Conditions section on this value chain activity for the full details that led to the assignment of this ranking (https://ei-spark.lbl.gov/)

S2. Discussion of Governance across Value Chain Activities

When reviewing the strategic conditions for value chain activities in the context of governance, we determined that the primary forms of governance experienced within an activity tended to fall into one of three categories: 1) innovation in the activity benefits from the support of grant-providing institutions (e.g., Department of Energy or Department of Defense R&D funding, etc.), 2) performance of the activity is contingent upon permission of permitting and licensing entities (e.g., city building permits, state licensing of construction companies, transmission interconnection permits, etc.), 3) activity is monitored by an oversight body (e.g., state utility commissions, FERC, etc.). While other types of law, policy intervention, or oversight may influence a value chain activity directly or indirectly, by which we mean through impacts feeding up or down the value chain from adjacent activities, these three were more universally applicable and unambiguous in targeting (as opposed to, e.g., attempting to unravel exactly where the incidence of a renewable portfolio standard is experienced and to what degree). Our findings are summarized in Table S2. Additional information on the types of governance relevant to each activity is provided in the activity-specific Strategic Conditions sections of Energy I-Spark.

Utility-Scale Solar PV:

- **Module Manufacturing:** The availability of public research and development funding directly impacts the module manufacturing activity (e.g., Department of Energy SunShot Initiative and ARPA-E). Other relevant policies include import tariffs, trade restrictions, loan guarantees, and tax incentives. Environmental and labor policies can influence the country or state in which a firm chooses to locate to perform this activity. Policy support of downstream activities (e.g., feed-in tariffs incentivizing renewable generation) impacts module manufacturing indirectly.

- **Balance of System (BOS):** The availability of public research and development funding directly impacts the balance of system manufacturing activity (e.g., Department of Energy SunShot Initiative and ARPA-E). R&D funding for modules also has an indirect impact on the manufacture of BOS components. Other relevant policies include import tariffs, trade restrictions, loan guarantees, and tax incentives. Environmental and labor policies can influence the country or state in which a firm chooses to locate to perform this activity. Policy support of downstream activities (e.g., feed-in tariffs incentivizing renewable generation) impacts module manufacturing indirectly.
- **Project Development and EPC:** Permits are required at the local, state and federal level to construct and operate the solar project and to sell the electricity produced, including: approval from a local land use board or zoning authority, a building permit, an electrical permit, an interconnection agreement, and possibly a permit from the BLM or the Department of Agriculture's Forest Services. Policy support of downstream activities (e.g., feed-in tariffs incentivizing renewable generation) and upstream activities (e.g., R&D supporting beneficial modifications to modules and BOS) impacts project development and EPC activities indirectly. For a project developer aiming to finance or sell a project, the availability of renewable energy incentives can influence a potential financer or owner (i.e., solar investment tax credit).

Utility-Scale On-Shore Wind:

- **Turbine:** The availability of public research and development funding directly impacts the turbine manufacturing activity. Other relevant policies include import tariffs, trade restrictions, loan guarantees, and tax incentives. Environmental and labor policies can influence the country or state in which a firm chooses to locate to perform this activity. Policy support of downstream activities (e.g., feed-in tariffs incentivizing renewable generation) impacts module manufacturing indirectly.
- **Project Development and EPC:** Permits are required at the local, state and federal level to construct and operate the wind project and to sell the electricity produced, including: approval from a local land use board or zoning authority, a building permit, an electrical permit, an interconnection agreement, and possibly a permit from the BLM or the Department of Agriculture's Forest Services. Policy support of downstream activities (e.g., feed-in tariffs incentivizing renewable generation) and upstream activities (e.g., R&D supporting beneficial modifications to blades) impacts project development and EPC activities indirectly. For a project developer aiming to finance or sell a project, the availability of renewable energy incentives can influence a potential financer or owner (i.e., wind production tax credit).

Power Markets:

- **Generation:** Government oversight impacts the generation activity in many ways. Agencies such as the U.S. Environmental Protection Agency, state environmental agencies and boards (e.g., Department of Fish and Wildlife, Air Resources Board, etc.) and other environmental entities directly regulate power plant air emissions, thermal emissions in rivers, and other environmental impacts of electricity generation. Cap and trade programs (e.g., RGGI for greenhouse gas, Acid Rain Program for SO_2, etc.) force generators to buy and consume emissions credits. Downstream, FERC's oversight of the wholesale market for electricity also impacts generator incentives and behavior. Renewable portfolio standards, investment or production tax credits, and other policies can create incentives to build and operate certain types of generation rather than others.

- **Wholesale Marketing and Transmission:** The wholesale markets in the US operate primarily under the supervision of the Federal Energy Regulatory Commission (FERC), with technical operational standards come from the North American Electric Reliability Corporation (NERC), a nonprofit corporation, that has authority to enforce its standards by way of having been designated as an Electric Reliability Organization (ERO) by FERC. FERC applies rules and tests of market power within wholesale markets to ensure fair competition in the transmission system.
- **Load Service and Distribution:** Traditional investor-owned utilities have to comply with their governing regulatory entities, often called public utility commissions (PUCs), which approve their rate cases. PUCs' authority over utilities can be very broad. They often will set standards for fuel and resource mix, loading order, hedging strategy, and resource adequacy. Publicly-owned utilities are exempt from PUC oversight due to their not-for-profit nature. The Federal Power Act gives states the authority to regulate retail and intrastate electricity markets, but in the case of interstate transactions and wholesale markets there is federal regulation under the Federal Energy Regulatory Commission (FERC).

Table S2. Summary of Governance Across Value Chain Activities

Value Chain Step		**Primary Form of Governance**
Utility-Scale Solar PV	Module manufacturing	Grant providing institutions
	Balance of system	Grant providing institutions
	Project development and EPC	Permitting and licensing entities
Onshore Wind	Turbine manufacturing	Grant providing institutions
	Project development and EPC	Permitting and licensing entities
Power Markets	Generation	Oversight bodies
	Wholesale Marketing and Transmission	Oversight bodies
	Load Service and Distribution	Oversight bodies

S3. Summary of Knowledge Across Value Chain Activities

Below we discuss the ways in which knowledge manifests across value chain activities, drawing particular attention to the locus of knowledge. In table S3 below, we summarize this discussion by noting the relevance to each value chain activity of four categories of knowledge loci: people, procedure, product, and process. The "people" categorization refers to the tacit knowledge of human resources; this type of knowledge stays with a market actor so long as its personnel do. The "process" categorization refers to knowledge embedded in formalized practices and rules, which are maintained by an actor; such a stock of knowledge is not reduced by workforce mobility. The "product" categorization refers to knowledge embedded in technological changes, including but not limited to patented innovations. The "process" categorization refers to knowledge encompassing technology production processes, such as changes to a manufacturing routine that result in a reduction in waste byproducts. The table coding provides our assessment of the relative importance of each type of knowledge to each value chain activity. We note that all types of knowledge are present to some degree in each value chain activity, but the dominant knowledge type differs. Extensive discussions of the ways in which knowledge manifests in the value chain steps are provided in the "Knowledge Conditions" sections of the Energy I-SPARK platform (https://ei-spark.lbl.gov).

Utility-Scale Solar PV:

- **Module Manufacturing:** Knowledge in module manufacturing is centered around aspects of the module and module subcomponent technologies, and is thus largely embedded in technological developments. There is substantial private R&D invested in this sector, as well as some public R&D. Many innovations relevant to modules are patented (or patentable), including panel components themselves and the outputs of source industries (e.g., chemicals, semiconductors). The spillover of knowledge in module manufacturing is expected to be moderate, considering the substantial patenting action undertaken to protect knowledge embedded in technology, but simultaneously, substantial collaborative research across countries and institutions.
- **Balance of System:** Knowledge in PV BOS manufacturing (i.e., inverters and racking) is centered around technological aspects, either of the inverter and racking equipment or of upstream components (e.g., semiconductors), and is largely patented (or patentable). A portion of the substantial R&D investment into solar technologies supports the development of BOS components. The spillover of knowledge in BOS manufacturing is expected to be low to moderate, considering the substantial patenting action undertaken to protect knowledge embedded in technology, but simultaneously, substantial collaborative research across countries and institutions.
- **Project Development and EPC:** Knowledge in PV project development and EPC is centered around financial, operational, and planning procedures, and often takes the form of tacit knowledge embedded in a firm's human resources. Little traditional R&D is available in this value chain activity, except for the case of some firms that are vertically integrated through module manufacturing. Project developers may support the

development of in-house expertise or outside training programs (e.g., community college degrees). The spillover of knowledge in project development and EPC is expected to be moderate to high because new finance models are publicly visible and trained personnel are mobile.

Utility-Scale On-Shore Wind:

- **Turbine:** Knowledge in turbine manufacturing is centered around aspects of the turbine technology, and is thus largely embedded in technological developments. Research and development in wind tends to be government funded rather than corporate funded, though most investment does not take the form of traditional R&D. Many innovations relevant to wind turbines are patented (or patentable), including turbine components themselves, or the products of source and related industries. The spillover of knowledge in wind turbine manufacturing is expected to be low to moderate, considering the substantial patenting action undertaken to protect knowledge embedded in technology, but simultaneously, substantial collaborative research across countries and institutions.
- **Project Development and EPC:** Knowledge in project development and EPC is centered around financial, operational, and planning procedures, and often takes the form of tacit knowledge embedded in a firm's human resources. Little traditional R&D is available in this value chain activity, except for the case of some firms that are vertically integrated through module manufacturing. Project developers may support the development of in-house expertise or outside training programs (e.g., community college degrees). The spillover of knowledge in project development and EPC is expected to be moderate to high because new finance models are publicly visible and trained personnel are mobile.

Power Markets:

- **Generation:** As we have defined the generation activity, knowledge is centered around financial, operational, and planning procedures, and often takes the form of tacit knowledge embedded in a firm's human resources (recall that in the Power Markets section of our value chain, Generation refers to the operation of electricity generating facilities, not to the construction of such facilities). Specifically, knowledge accumulated includes expertise in the capabilities and limitations of the generation assets, insider knowledge regarding how the electric system as a whole works, understanding of the dynamics of fuel markets and electricity wholesale and retail markets. Patentable knowledge in this value chain step largely takes the form of software developed by outside firms or in some instances, through in-house capabilities. Traditional forms of investment are generally not relevant to this step, and significant knowledge spillover can occur as personnel move between firms.
- **Wholesale Marketing and Transmission:** Knowledge in wholesale marketing is centered around operations, planning procedures, and market optimization. While it often takes the form of tacit knowledge embedded in human resources, market rules and business practices are formalized into procedures maintained by ISOs/RTOs. Little

traditional R&D is available in this value chain activity, and much of the investment in knowledge aims to improve the tracking and modeling of markets and transmission networks. Transmission, economic, tariff, and business practice information is made publicly available. Much of the operational knowledge is specific to each ISO/RTO. Computer models and programs used for market optimization are proprietary, and generally developed by outside parties.

- **Load Service and Distribution:** Knowledge in load service and distribution is centered around finance, operations, and planning procedures, specifically including expertise regarding load patterns, the transmission system, the distribution system, rate structures, billing and metering, and interactions with the wholesale market and generation resources. While there is little traditional R&D, investment in research occurs through EPRI; the results of such research are shared within the industry. In some cases, an oversight body (utility commission or board) may require an IOU or POU to fund research through an electricity surcharge. Utilities may choose to provide data to academic researchers. In this value chain step, the preservation of operational knowledge is generally more important than preventing spillover.

Table S3. Summary of Knowledge across Value Chain Activities

VC step		Locus of Knowledge			
		People	Procedure	Product	Process
Utility-Scale Solar PV	Module manufacturing	○	○	●	●
	Balance of system	○	○	●	●
	Project development and EPC	●	●	○	○
Onshore Wind	Turbine manufacturing	○	◒	●	●
	Project development and EPC	●	●	○	○
Power Markets	Generation	●	◒	○	○
	Wholesale Marketing and Transmission	●	●	◒	◒
	Load Service and Distribution	●	◒	○	○

Notes: Open (white) circle represents a "low" scoring, a half-filled circle represents "moderate," and a filled-in (black) circle represents "high."

S4. Summary of Rate of Change Across Value Chains

Below we discuss the rate of change across value chain activities based on our findings regarding innovation outcomes. For manufacturing activities within the value chain, "rate of change" can be interpreted as the rate of technological change; for non-manufacturing activities (e.g., project development), we use the term "rate of change" to refer to the pace at which knowledge accumulation leads to procedural innovations that advance the performance of the activity. In our assessment of the rate of change, we draw from the material presented in the "Innovation Outcomes" section of EI-Spark for each value chain step (https://ei-spark.lbl.gov). We address the particular circumstances of each value chain step individually. Our assessment is summarized in table S4 below.

Utility-Scale Solar PV:

- **Module Manufacturing:** PV cells can be categorized into first (mono- and polycrystalline silicon), second (thin-film), or third (in development, including organic and dye-sensitized) generation technologies; in recent years, the total installed capacity of second-generation PV cells has increased, but the installed capacity of polycrystalline silicon cells has increased at a faster pace, leading to little change in the relative total installed capacity of second-generation PV technologies. While some new PV technologies have entered the market with lower-than-market-average efficiency (e.g., organic solar cells), efficiency has increased significantly overall and within each technology type over the past two decades [1]. Between 2009 and 2017, PV solar modules have experienced an 81% reduction in prices, with learning rates in the range of 18-22% [2].
- **Balance of System:** BOS manufacturers can significantly reduce their costs through modularization, preassembly, standardization, and automation, techniques that are commonly utilized in mature industries. It is estimated that utility-scale PV system costs can be reduced by up to 20% from 2015 to 2025 following a trend towards more modular, scalable power plant development [3].
- **Project Development and EPC:** The soft cost share of utility scale PV projects has increased from about 30% in 2010-2011 to about 37% in 2016-2017; this does not mean that soft costs have grown absolutely, rather that soft costs are falling at a lower rate than the costs of hardware [4]. Dominant financing methods for utility-scale PV have changed dramatically over time, and new options are continuing to emerge and evolve. Over the period of 2004 to 2016, the share of new renewable projects funded through project financing grew from 16% to 52% [5]. Emerging finance methods include "yieldcos," master limited partnerships, and green bonds, among numerous others.

Utility-Scale On-Shore Wind:

- **Turbine:** The average capacity rating of a wind turbine installed in 2017 was 2.32 MW, an increase of nearly 29% from 1.80 MW in 2010. The average turbine installed in 2017 grew slightly to 86 meters in hub height and stretched to 113 meters in rotor diameter, an increase of 34% as compared to average turbine installations in 2010 [6]. The cost of onshore wind has fallen significantly over the last several decades, with the LCOE of wind power suggesting a learning rate of 10-19%; part of the fall in wind energy cost is attributable to turbine cost [7]. Towers and nacelles are predicted to each account for one quarter of the potential for future reductions in wind LCOE [3].

- **Project Development, EPC, and BOP:** The cost of onshore wind has fallen significantly over the last several decades, with the LCOE of wind power suggesting a learning rate of 10-19%; much of this reduction in wind energy cost is attributable to turbine component costs, but a sizable portion is due to decreases in soft costs [7]. Best practices are predicted to account for one quarter of the potential for future reductions in wind LCOE [3]. Siting, permitting, and financing a project can take several years; this timeline can be reduced by, e.g., standardized permitting practices [8].

Power Markets:

- **Generation:** Traditional vertically integrated investor-owned or publicly-owned utilities owned and operated the vast majority of generation capacity before deregulation, and still dominate in many parts of the U.S.; however, considering the whole U.S., independent power producer generation as a percent of total grew from 25% in 2001 to 40% in 2017 [9]. There is a noticeable shift from coal and natural gas generation to renewables; in 2017, approximately 1.3% and 6.7% of U.S. generation came from utility-scale solar and wind, respectively, up from substantially below 1% and 2.3% in 2010 [10].
- **Wholesale Marketing and Transmission:** Market rules evolve with experience to encourage straightforward participation in wholesale markets without making it possible for an individual participant to obtain and exercise market power; rules are incorporated into systems to automatically detect and mitigate exercise of market power. Knowledge of the current state of transmission system improves with more and better telemetry and state estimation (e.g., phasor measurement unit). As the cost of telemetry decreases, there may be less reliance on state estimation, which is itself improving over time.
- **Load Service and Distribution:** The core activity of an LSE is to aggregate load on behalf of many customers and make appropriate arrangements in wholesale markets to meet that load, while also for procuring various capacity reservations as necessary to guarantee reliable operation of the system. These activities were historically performed by vertically integrated investor-owned utilities, but now a substantial share of load service and/or distribution is performed by publicly-owned utilities, community choice aggregators, or other arrangements (IOUs account for 60% of annual electricity sales as of 2016) [11].

Table S4. Rate of Change across Value Chain Activities

VC step		Key Trends	Rate of Change Coding	Notes
Utility-Scale Solar PV	Module manufacturing	Shift from polycrystalline silicon to thin film	○	In recent years, the total installed capacity of second generation PV cells has increased, but the installed capacity of polycrystalline silicon cells has increased at a faster pace, leading to little change in the relative total installed capacity of second generation PV technologies
		Increasing efficiency	◒ to ●	While some new PV technologies have entered the market with lower efficiency, efficiency has increased significantly overall and within each technology type over the past two decades [1]
		Decreasing cost	●	More than 80% decrease in price (per watt) between 2009 and 2017; learning rates in the range of 18-22% [12]
	Balance of system	Decreasing cost	◒ to ●	It is estimated that utility-scale PV system costs can be reduced by up to 20% from 2015 to 2025 following a trend towards more modular, scalable power plant development.
	Project development and EPC	Dominance of soft costs	◒	Soft cost share of utility scale PV projects has increased from about 30% in 2010/11 to about 37% in 2016/17.
		Changes in finance options	●	Dominant financing methods have changed dramatically over time, and new options are continuing to emerge and evolve.
Onshore Wind	Turbine manufacturing	Decreasing cost	○ to ◒	LCOE suggests 10-19% learning rate for wind energy [7]. Towers and nacelles are predicted to each account for one quarter of the potential for future reductions in wind LCOE [3].
		Increasing turbine capacity	●	The average capacity rating of a wind turbine installed in 2017 was 2.32 MW, an increase of nearly 29% from 1.80 MW in 2010 [6].
		Increasing rotor diameter and hub height	●	The average turbine installed in 2017 grew slightly to 86 meters in hub height and stretched to 113 meters in rotor diameter, an increase of 34% as compared to average turbine installations in 2010 [6].
	Project development and EPC	Time to complete project	Uncertain	Siting, permitting, and financing a project can take several years; this timeline can be reduced by, e.g., standardized permitting practices [8].
		Decreasing cost	○ to ◒	LCOE suggests 10-19% learning rate for wind energy [7]. Best practices are predicted to account for one quarter of the potential for future reductions in wind LCOE [3].

Table S4 (continued). Rate of Change across Value Chain Activities

VC step	Key Trends	Rate of Change Coding	Notes	VC step
Power Markets	Generation	Shift from IOU/POU to IPPs	○ to ◒	Independent power producer generation as a percent of U.S. total grew from 25% in 2001 to 40% in 2017 [9].
		Shift to renewables	◒	In 2017, approximately 1.3% and 6.7% of U.S. generation came from utility-scale solar and wind, respectively, up from substantially below 1% and 2.3% in 2010 [10].
	Wholesale Marketing and Transmission	Evolving market rules	Uncertain	Market rules evolve with experience to encourage straightforward participation in wholesale markets without making it possible for an individual participant to obtain and exercise market power; rules are incorporated into systems to automatically detect and mitigate exercise of market power.
		Improving knowledge of the transmission system	Uncertain	Knowledge of the current state of transmission system improves with more and better telemetry and state estimation (e.g., phasor measurement unit). As the cost of telemetry decreases, there may be less reliance on state estimation, which is itself improving.
	Load Service and Distribution	Deregulation / Shift from IOU to other arrangements	○ to ◒	While historically performed by vertically integrated investor-owned utilities, a substantial share of load service and/or distribution is now performed by publicly-owned utilities, community choice aggregators, or other arrangements.

Notes: Open (white, ○) circle represents a "low" scoring, a half-filled (◒) circle represents "moderate," and a filled-in (black, ●) circle represents "high."

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