Structuring Knowledge on Policies to Redirect and Accelerate Technological Change in Low-Carbon Technologies: The Cases of Wind and Photovoltaic Power

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Abstract

Stabilizing the climate will require a politically and economically sustainable transition of the electric power system to much lower emitting generation technologies that can meet the aspirations of a growing global population. The goal of this report is to synthesize the known empirical understanding of the interplay between current policies and innovation in renewable energy technology, with a particular focus on power generated by the wind and by solar photovoltaics (PV). To structure this knowledge, we provide a mapping between the practical, tangible aspects of the wind and PV industries and the observed variables of importance to different theories and strains of the innovation literature. This mapping provides a framework with which we illustrate the first and second-order investment effects of current wind and PV power-relevant policies on technological change. We focus in particular in this report on applying this framework to better understand the innovation effects of two specific policies – feed-in-tariffs and a cap-and-trade program – in the European context. The report concludes with reflections on what our current level of knowledge makes clear and leaves open about how to most effectively accelerate and redirect technological change for climate stabilization.

1. Introduction

Stabilizing the climate will require a politically and economically sustainable transition of the electric power system to much lower emitting generation technologies that can meet the aspirations of a growing global population. Figure 1 illustrates why fostering innovation is important to accomplishing this transition. If today's marginal cost of abating the carbon-equivalent emissions that contribute to global climate change is represented by the curve to the left (the MAC curve), the curve to the right (the MAC' curve) represents what that curve could look like with the necessary rate and direction of innovation. But the existing industries and actors that comprise the electric power sector are less likely to invest the full set of resources required to shift the first curve to the second curve due to market barriers and failures like the negative externality of pollution, the appropriability problem associated with research and development (R&D), and the natural monopoly of the transmission and distribution of electric power. In addition, the phenomenon of innovation is noted for its non-linearity and uncertainty of outcomes. In short, it is not a simple matter to shift the electric power sector to the MAC' curve that stabilizes the climate in the 40 or so years that most climate models suggest we have until the emissions of developed countries should be reduced by 80%+. Policy on this important public problem needs to be informed by an understanding of the interplay of public policy and the motivations and procedures of the actors that comprise the supply chains of new technologies which substitute and complement pre-existing technologies in the electric power sector.

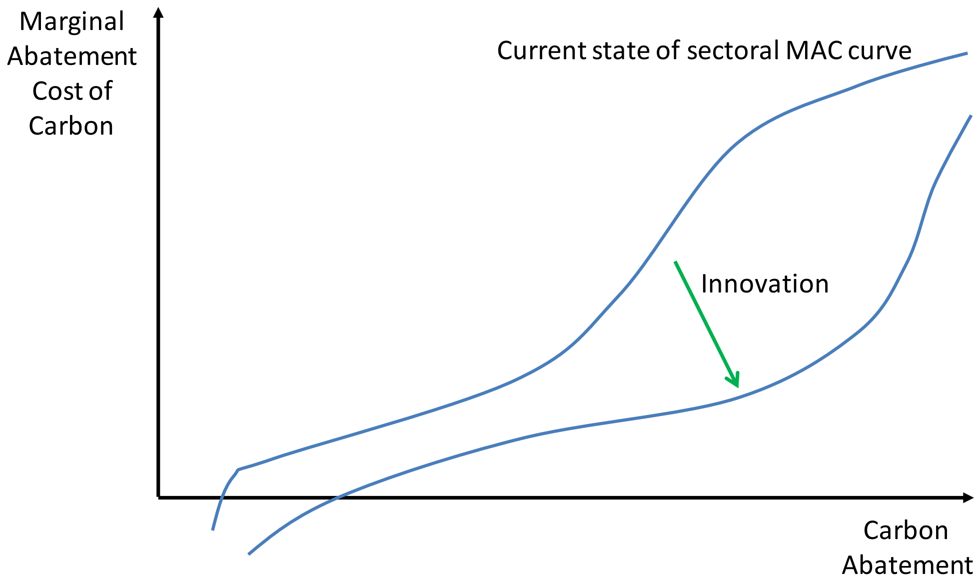

Figure 1: Representation of the effect of innovation on changing the electric power sector's marginal abatement cost of carbon

With the atmospheric concentration of carbon dioxide reaching 400 parts per million this year, a level not seen in millions of years (The Economist 2013), it is an opportune time to systematically reflect on what is known and not known about the interplay of current policies and innovation in renewable energy technology. The goal of this report is to synthesize the current empirical understanding of this policy-innovation interplay , with a particular focus on wind power and solar power (by this we mean solar photovoltaics, or PV), the most developed generation approaches to use resource inputs that are near-zero emitting and widely distributed.[1] Wind and PV power have received considerable policy support to reach their current levels of cost, performance, and global diffusion, which can be considered snapshots of rapidly changing industries. Today's wind and PV power generation currently represent less than 8% of global energy, although ~ 30 countries currently get 20% or more of their total electricity generation from renewables such as these.[2] Particularly noteworthy has been the European experience (the German experience is especially noteworthy) with policy and wind and PV power, which will be a special focus of this report.

Synthesizing knowledge on the effects of policy on innovation in such a way that it is usable in applied contexts presents challenges. For example, it is important when thinking about this topic to recall that both policy and technological change are dynamic in nature (i.e., they change over time). Without this insight, policy decision-making can be misled. For example, forgetting dynamics on the technology side can make it appear that a technology will be successful when a given levelized cost of electricity (LCOE) for that technology is reached, when in actuality, the LCOE competitiveness target may change as the incumbent technology changes over time (see the famous example in the management literature of continued innovations in sailboats, even after steamships eclipsed them commercially). Meanwhile, forgetting dynamics on the policy side can make it appear that a policy

[1] We make the assumption here that hydro-power has basically reached maximum capacity and that the materials to make nuclear power are not widely distributed.

[2] The 8% and 20% numbers come from the REN21 Global Futures Report, where they represent "modern renwables," including wind and PV power as well as hydropower, biomass power and heat, and geothermal.

instrument is stronger for innovation than it really is. For example, the world's most successful cap-and-trade program – which controlled emissions of sulfur dioxide in the U.S. – was not designed with elements that could be adjusted based on developments in the science or in the compliance technologies, and this diminished the ability of the policy to induce innovation (Taylor 2012).

There are also a number of commonly-held beliefs regarding the policy-innovation interaction, and not all of these have empirical support. For example, cap-and-trade programs are not particularly "good for innovation," as most people understand that phrase, which goes against conventional wisdom about this instrument as well as a dominant thread of the economics literature that can be characterized as statically-oriented (Rogge, Schneider et al. 2011; Schmidt, Schneider et al. 2012; Taylor 2012). Similarly, many people believe that "crossing the valley of death" of a lack of investment to bring a technology from pilot to commercial scale is the main barrier faced by most clean energy technologies, but this is not necessarily relevant to prominent climate-relevant technologies like PV power. Additionally, many believe that innovation in clean technologies will lead directly to new economic development, although the level of new jobs – as opposed to substitute jobs – that clean technologies provide is not easily measured or consistent across technologies. On a related topic, many believe that all manufacturing related to PV has shifted to China, when the geographic realities of the industry are more complex.

Some of these "myths" of the policy-innovation interaction in low carbon technologies may exist because of related heuristics – "rules of thumb" approaches to problem solving – that do not always provide optimal results (e.g., assuming perfect competition and perfect information in order to quantitatively model greenhouse gas emissions and translate them into carbon prices that will optimally drive innovation). Others may come about because researchers in policy and innovation for climate change mitigation do not fully appreciate closely related literature streams (Kemp and Pontoglio 2011).

In this report, we try to clear up much of the confusion about what is known and not known about policy and innovation in wind and PV power in order to help guide policy and research. The approach we take is to first, build a detailed understanding of the dependent variable of technological change, as decomposed into three levels. These levels are: (1) the level of the industrial sector (i.e., the electric power sector); (2) the level of technology (i.e., the underlying goods and services in the supply chain involved in building and using wind and PV power generation equipment with today's performance attributes); and (3) the level of actors (i.e., the firms, individuals, etc. engaged in these supply chains and some of the innovation-relevant theories that apply to them, given their attributes). We also consider an additional dimension of geography in this section in order to round out our understanding. Note that these levels can also be seen as coinciding with the major aspects of innovation identified as far back as the writings of Josef Schumpeter, with the sector level the level at which we can observe the diffusion of renewable energy, the technology level the level at which we can observe the outcomes of innovation in renewable energy (i.e., cost, performance, knowledge), and the actor level the level at which we observe the innovative activities of organizations and individuals involved in the supply chain of renewable energy. Figure 2 presents a birds-eye view of our framework.

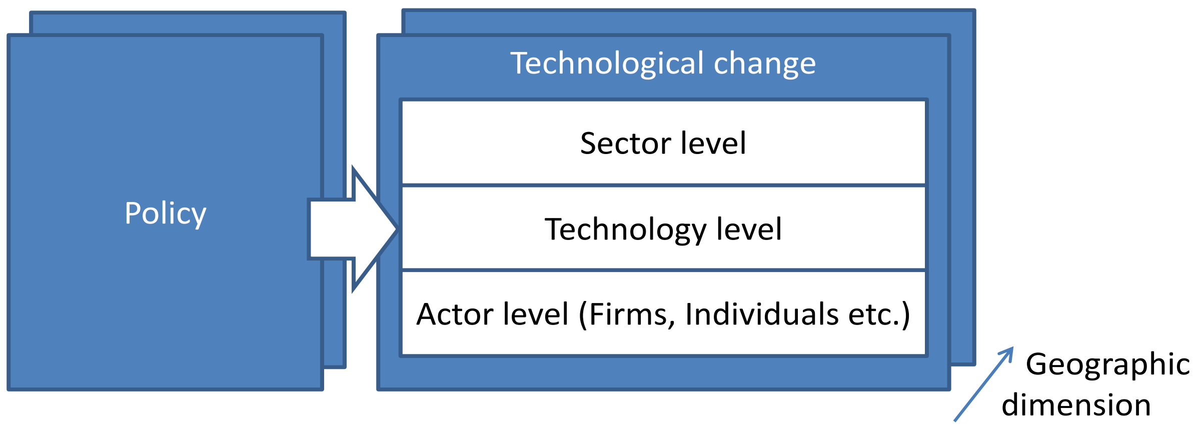

Figure 2: Overview of our framework to systematically reflect on what is known and not known about the effect of policy on technological change in wind and PV power

We believe that this mapping between practical, tangible aspects of the wind and PV industries and observed variables of importance to different theories and strains of the innovation literature, broadly defined, provides a useful way to help policy-makers, policy stakeholders, and researchers communicate as to the needs for new knowledge to inform next generation renewable energy policy design. For this reason, the second section of this report provides an expansive treatment of our Figure 2 framework. This framework also makes it easier for us to illustrate the first and second-order effects on technological change of current wind and PV power-relevant policies – our independent variables of greatest interest – which we do broadly in the third section of the report. We then use our framework in the fourth section of the report in order to help us structure a more detailed treatment of the effects of two specific policies – feed-in-tariffs and a cap-and-trade program – in the European context. The report concludes with reflections on what our current level of knowledge makes clear and leaves open about how to most effectively accelerate and redirect technological change for climate stabilization.

2. Dependent variable: technological change

In this section, we elaborate on each of the levels of technological change in Figure 2, as well as on the geographic dimension of these levels. To guide the discussion, we refer to a common illustrative approach in each section, which draws from the supply chain concept an emphasis on the system of organizations and resource flows involved in moving a product from a raw material to an end use.

2.1 Sector level

At the industrial sector level of Figure 2, we discuss the electric power sector, which operates technologies that generate electricity and delivers reliable power to meet the demand of end-users, but also emits significant amounts of carbon dioxide. This is, therefore, the sector that policy-makers are trying to change and that renewable energy technologies like wind and PV power affect.

2.1.1 Chevrons

Figure 3, below, depicts our vision of the power sector, which we illustrate through the use of "chevrons," or inverted v-shapes, to represent the major organizations and actions involved in the chain of steps involved in supplying electricity to an end-user. Two chevrons are completely embedded in this illustration of the power sector, two chevrons are partially embedded in the power sector, and three others are fully contained outside of the sector, but are crucially relevant to the electricity generation supply chain. Here we define these chevrons in more detail.

Power Generation: This chevron represents traditional generators of power in most electricity systems, whether they generate electricity from one or more “technologies” such as coal-fired power plants, natural gas turbines, etc. The value added by this supply chain step is the transformation of chemical, physical or thermal energy in to electrical energy, which is then fed into the grid. Besides electricity generation, power generation needs to actively support the stability of the transmission and distribution grid (see below). Note the modification of the power generation chevron in this figure to indicate that it is the major source of the climate-relevant emissions that policy-makers are particularly interested in addressing.

Transmission & Distribution: This chevron represents the function of transporting electricity from a (typically centralized) electricity source to the (typically decentralized) load on a regional or national level using fixed infrastructure such as power lines and associated devices (capacitors, inductors, switchgear, transformers etc.), which are collectively known as the “grid.” Electricity grids typically operate at different levels with different voltages (e.g., 380-220 kV at the transmission level, 10-30 kV at the distribution level and 120-230V at the residential level). One important role of the transmission and distribution process is also to keep the grid stable. The two most important parameters for stability are frequency (60 Hz in the US and 50 Hz in Europe) and voltage (at the residential level, 120 V in the US and 230 V in Europe). In order to keep these parameters stable, it is important that the supply of electricity generated exactly matches supply to supply. To this end, reserve capacities are needed, which provide both active power (which stabilizes the frequency), and reactive power (which stabilizes the voltage). While some of this reserve capacity is provided by the “spinning reserve” (the large rotating masses of the generators of large steam turbine power plants) up to 30 second, primary, secondary and tertiary reserve is provided by additional reserve capacity (e.g., in form of fast starting “peaking plants”). Transmission and distribution system operators are typically considered natural monopolies, with implications which we will discuss below.

Finance: This chevron represents the function of supplying monetary resources to invest in different aspects of the power sector.

BOP: This chevron represents “balance of plant,” which includes the architect and engineering firms, etc. that help to build/install and sometimes maintain the technologies used to generate power.

Fuel: This chevron represents the chain of organizations and actions involved in bringing a fuel source to the power sector to be used as an input in the generation of electricity. Although this chevron is most relevant for fossil fuels like coal and natural gas – where it primarily resides in industrial sectors related to mining – as a concept, this chevron is also potentially useful in conceptualizing the supply chain for nuclear power.

Technology: This chevron represents the chain of organizations and actions involved in supplying component technologies to the power sector. These component technologies include, but are not limited to, generation technologies like wind and PV power. This chevron will be expanded upon in more detail in section 2.2. Note that technology is mainly provided by other industrial sectors.

End Use: This rectangle represents the consumers of electricity, whether residential, commercial, industrial, or other. Note that end users are not represented by a chevron, as electricity does not continue to flow past the end-user in our vision of the electric power sector.

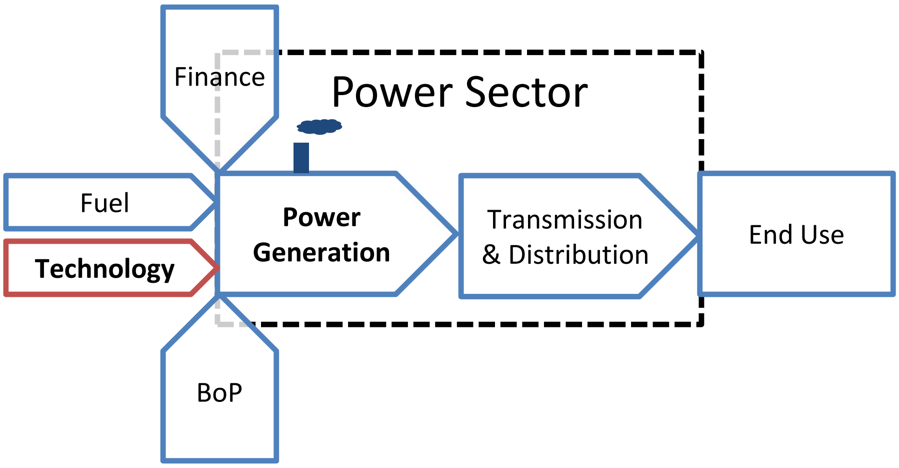

Figure 3: The sectoral level of technological change. This figure depicts the basic supply chain of the power sector, which is the industrial sector that is affected by the development of wind and PV power.

2.1.2 The Chevrons in Context

In Figure 3, where one chevron touches another, a transaction takes place. Many of these are standard market transactions, where a product or service – which carries within it embedded knowledge – moves from one chevron to the next, and money flows in the opposite direction (although in the case of the finance chevron's contact with the electric power sector, money flows from one chevron to the next in the form of investment, but later flows back in the form of returns on that investment).

The point at which the power generation chevron meets the transmission and distribution (T&D) chevron represents the *wholesale market* for electricity, where transactions often take place on spot and futures markets organized by electricity exchanges. Many buyers and sellers meet and trade (and re-trade) certain amounts of electric energy. The point at which the T&D chevron meets the end-use chevron represents the *retail market*, i.e., the market where end-users buy their electricity, which is a non-differentiable good to them thanks to the actions of the T&D system. Long-term delivery contracts often exist in the retail market, which is heavily influenced by the monopolistic structures of T&D.

Note that the connection between the technology and power generation chevrons is the point at which a new technology can out-compete another technology and diffuse into the electric power sector in order to begin operations. It is therefore the decision point that is most directly relevant to most policies focused on the deployment of renewable energy.

2.1.3 Characteristics of the electric power sector

Several characteristics of the electric power sector are important to understand when reflecting on its relationship to the innovation literature. First, the power sector is one of the classic examples given when defining the condition of a "natural monopoly." This is a form of imperfect competition, which is one of the three main market failures that mainstream economic analysis widely accepts as justifying public intervention in a private industry (another is the pollution externality mentioned in the description of the power generation chevron, above).[3] In a natural monopoly, it is theoretically most economically efficient to have a single producer of a good because that producer's per-unit costs decrease as it increases output; meanwhile, the barriers to entry for new firms are very high. In the U.S., the natural monopoly condition of the power sector has long justified regulation of the utilities that generate and help transmit and distribute power in the electric power sector, in particular to protect consumers from exorbitant energy prices. In other nations, however, the power sector was traditionally publicly owned, although recent decades of privatization have changed this to a varying extent, depending on the nation and even the locality.[4] Note that the importance of the power sector to national security has also played a role in decisions of regulation and ownership over time. Regarding the innovation literature, the stream of work that followed on Schumpeter (1942) is directly relevant to innovation under conditions of market power, such as natural monopolies.

Second, as Figure 3 makes clear, the technologies that are used by power generators are typically provided by firms that supply, but do not operate, these technologies. This makes the power sector a classic example of a "supplier-driven sector" (Pavitt 1984). Several key theories in the recent innovation literature appear to be relevant to this attribute of the sector, in which technological change is re-directed and accelerated by the diffusion of new technologies. One is that product innovation typically takes place outside the sector (as will be discussed below), while process innovation takes place inside the sector. Another is that the power generators have the key selection function for technologies (Nelson and Winter 1982; Anderson and Tushman 1990). Regarding the process innovations that occur inside the power sector, note that that power generation technologies are subject to learning feedbacks (Sagar and van der Zwaan 2006) and economies of increasing returns (Arthur 1989; Unruh 2000), which implies that there is potential for strong cost reductions in technologies once they have been purchased.

Third, the technologies used in the power sector are typically very costly, requiring large investments with long lifetimes. This is a source of inertia in the sector, as it builds to a general lock-in into existing technologies. It is also an indication of why finance is so important to the sector, as investments cannot be covered by cash flows.

2.2 Technology level

At the technology level of Figure 2, we begin to discuss wind and PV power more specifically. Here, the focus is on the technologies we see today, with their current characteristics of cost, performance, market share, etc. We also discuss some noteworthy aspects of their evolution, particularly as these define trends and technical challenges that matter to the future of these technologies.

2.2.1 Trends and general characteristics of wind and PV power

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[3] These three main market failures – or scenarios in which the pursuit of rational self-interest leads to instances in which some market participants are made worse off, unlike the ideal Pareto efficient condition – can be boiled down to imperfect markets and goods with either externalities (such as carbon emissions) or non-excludable attributes.

[4] Socio-political factors are also likely to be highly relevant in the power sector for the reason that power plants can be considered complex "open assembled" systems, characterized by high uncertainty (Tushman & Rosenkopf).

Figure 4 shows the broad trend in global wind turbine prices (Figure 4a) and PV module average selling prices (Figure 4b) over time, as charted against capacity growth. Note that both of these technologies have dropped notably in price over a relatively short period of time, and at roughly similar rates, although PV power has exhibited a steeper decline. The current levelized costs of electricity (LCOE) of these two renewable energy technologies differ, however, with wind power less expensive than PV power and more widely deployed geographically. Note that in the earliest days, the predominant use of PV was for remote power applications like satellites and buoys, and later consumer products like calculators, rather than residential, commercial, or industrial PV power generation. Today, besides remaining a product, like calculators, rather than a process, like a wind turbine, PV power has another distinguishing characteristic that is important to mention here. This characteristic is the modular nature of PV power, with factory-produced "building blocks" being used to comprise both small and large systems.

Figure 4: (a) The trend in global wind turbine prices graphed against the cumulative capacity of MW of electricity generated by wind turbines, with key dates highlighted. (b) The trend in global PV module average prices graphed against the cumulative production volume of modules, given according to MW and decomposed between crystal-silicon and cadmium telluride. Key dates are also highlighted in this figure. (IRENA 2013; IRENA 2013)

2.2.2 Wind

2.2.2.1 Chevrons and their context

Figure 5 depicts the "technology level" of technological change in wind power, emphasizing the basic supply chain involved in the creation and ultimate diffusion of power generated from the wind. Here, the "chevrons" should be read as representing the flow of goods or services in wind power technology.

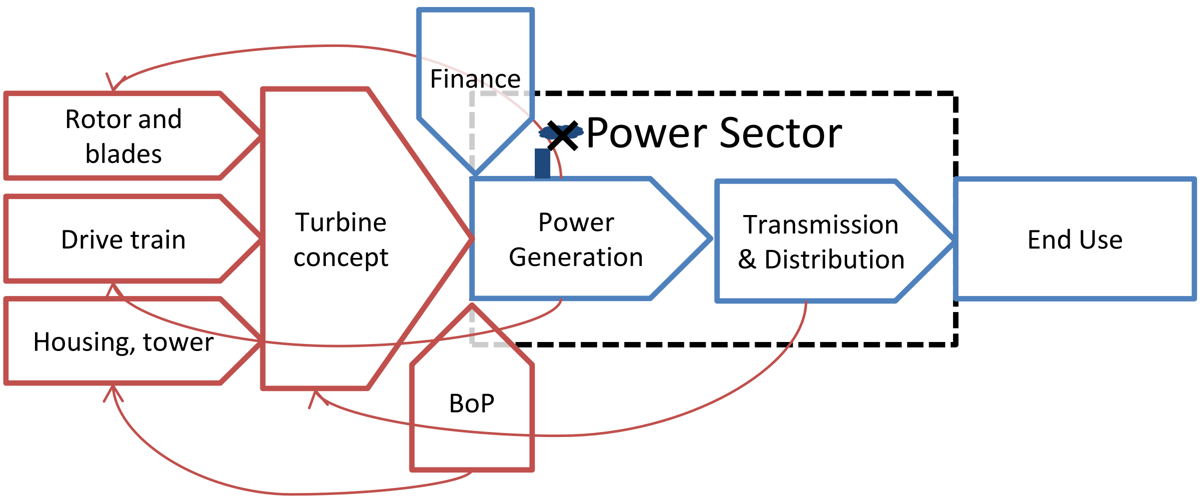

Figure 5. The technology level of technological change in wind power. This figure depicts the basic supply chain involved in the creation and ultimate diffusion of power generated from the wind.

Note that knowledge is embedded in these goods and services. At the contact points in Figure 5, knowledge flows in the direction of the chevron. But instead of money necessarily flowing back, as in the power sector illustration above, it is more useful at the technology level to think instead about knowledge feedbacks flowing along the red arrows in non-linear ways and incorporating such things as various forms of "learning" (i.e., learning-by-doing, learning-by-using, etc.) (Hünteler, Hoffmann et al. 2012). Of course, knowledge can be considered an attribute of actors as well as an embedded characteristic of technologies, and is thus something we will discuss at the actor-level, below. Also at the actor level, we will revisit the topic of money flows between chevrons, since characteristics of actors such as their degree of vertical integration (or the incorporation of more than one chevron within a single firm) will influence such money flows.

Here we define the wind power chevrons in Figure 5 in more detail. Note that we do not define the rectangle of end use here, as it was defined in the power sector previously.

Rotor and blades: This chevron represents the production of the rotor and blades for the wind turbine, as well as the control system for these artifacts. These are core components used in transforming wind energy into rotary energy.

Drive train: This chevron represents the production of the drive train and the control system for the drive train. These are the core components involved in transforming rotary energy into electric power.

Housing, tower: This chevron represents the production of all the components that are important to the physical structure of the wind turbine (e.g., the tower and the nacelle which houses the drive train). These components are not directly involved in generating power, but they are important to the reliability and productivity of the turbine.

Turbine concept: This chevron represents the processes through which the components are assembled, tested, and disassembled for shipment to the construction site for the turbine.

Balance of plant: This chevron represents the several services involved in siting, assembling, and erecting a wind turbine, typically in a wind farm. Note that this step can involve significant optimization.

Finance: This chevron represents the project finance for the wind installation (i.e., the equity and debt). It also includes corporate finance for manufacturers.

Power generation: The power generation chevron in this figure is no longer producing carbon emissions, but it has to cope with the intermittency of power generation from wind power. Note that wind intermittency often, but not always, follows a daily and seasonal pattern; it is also related to weather conditions. Therefore, an important aspect of this chevron involves the planning requirements associated with tasks such as predicting energy production for day-ahead markets.

Transmission and distribution: An important aspect of this chevron involves the load balancing requirements associated with the limited dispatchability of wind energy.

2.2.2.2 Characteristics of wind power technology

The cost and performance attributes of the wind power technology that we observe today – with an increased ratio of energy yield to installed capacity, and associated reductions in the LCOE – came about at the rates depicted above in Figure 4 through a combination of private and public forces that drove the technology in specific directions.[5] The primary direction of innovation has been toward increasing the amount of energy (kWh) that can be harvested through the technology. As Figure 6 shows, this has mainly come about through a focus on increasing turbine size, as increased size makes it possible to capture the greater wind potentials that come at greater heights, where there are less obstructions. This trend is the predominant one in the commercial marketplace, although there are also less developed, alternative approaches to capturing unobstructed wind energy, such as designing turbines to be located offshore and in the air.

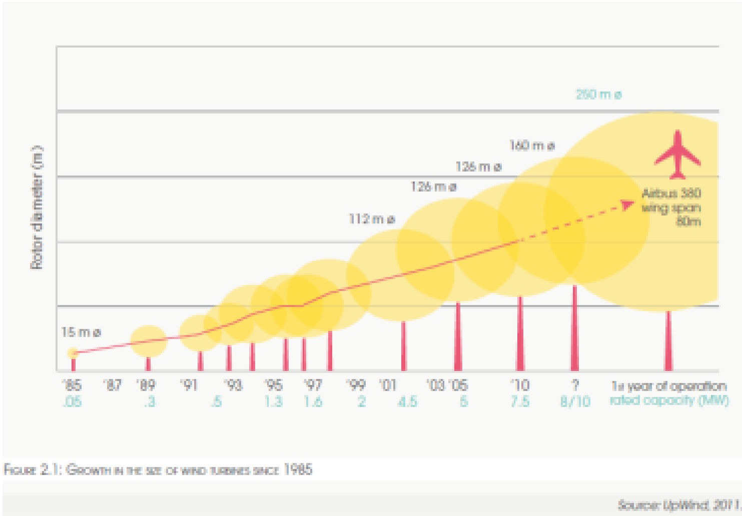

Figure 6: Growth of turbine size over time

The main innovation challenge for increasing turbine size has been effectively operating an integrated mix of components and subsystems like control systems under turbulent wind conditions at different geographies, given that the relevant physical variables sometimes exhibit quadratic and cubic relationships with turbine size. Although a dominant design has emerged – horizontal axis, three-blade, upwind, pitch-controlled turbines – this has occurred incrementally and hand-in-hand with new knowledge from large-scale, long-running demonstrations (small pilot plants provide insufficient information) at different geographies, as well as with related improvements in computer simulation.[6] Thus, significant knowledge feedbacks from operating experience (Hünteler, Hoffmann et al. 2012) have played an important role in the development of wind power, particularly as they have improved the so-called "lower levels of the product hierarchy" (Murmann and Frenken 2006), or components and subsystems (Hünteler, Ossenbrink et al. 2013).

A second important direction of innovation in wind power is toward lower costs and the related goals of less intermittency and down-time). Today, wind power technology has not only the cost advantage that accrues from a dominant design, but it has a further cost advantage in that much of the equipment involved in producing, integrating, and installing wind turbine components is standardized (e.g. welding, etc.), with few key exceptions (Hünteler, Hoffmann et al. 2012). Skilled labor, on the other hand, plays an important role in the wind power supply chain, with associated

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[5] Note that the LCOE has stabilized over the past decade or so.

[6] There is still some variation in turbine design, however. For example, some turbine drive trains have gears (e.g., Vestas) and some do not. Of those that do not have gears, some have a permanent magnet (e.g., Siemens) while others have a separate excitation generator (e.g., Enercon).

costs. Manufacture of wind turbines can be characterized as handwork, despite a growing trend to pre-assembly and modularization, and installation also involves skilled craft knowledge, primarily drawn from the construction industry. Note that turbine size interacts with modularization and installation in important ways. Modularization helps keep costs down, but because pre-assembled parts must be moved to wind sites through the existing transportation system (e.g., highway bridges, truck beds, train cars, etc.), there are limitations to how far the modularization trend can go. Meanwhile, turbine size poses important construction challenges for installation that require specialized – rather than less expensive, generic – knowledge (i.e., trained labor) and equipment. One way installation costs have been kept down, however, is to send teams of trained installers from wind project to wind project, thereby ensuring as efficient a knowledge transfer between locations as possible.

Note that a range of other important innovations has helped the wind power industry mature, even if the specific innovations involved were not primarily directed toward one of the major goals of the industry. Most of these innovations affect either the balance of plant or its integration into the existing power sector, including: wind mapping (which the public sector has played a particularly important role in supporting); better project siting; improved installation equipment (e.g., cranes); moderated environmental (e.g., noise, avian, spectrum, etc.) impacts; and better grid-integration (e.g., frequency mismatch issues with too-slow pitch control, ramping, etc.). This latter topic is very important to the future of wind power technology, and a likely future trend is that wind power will become more closely integrated with advanced storage, further increasing the "openness" and complexity of wind power as a technological system and opening up new opportunities for learning.

2.2.3 PV

There is still much laboratory research on different PV chemistries and configurations, and for this reason we are unwilling to say that a dominant design has yet emerged in PV power. However, as crystalline silicon PV modules have a global market share of PV production today of 80%, our focus in this section is on the technology level supply chain for this type of PV power (see Figure 7). Again, note that knowledge is embedded in the goods and services in this supply chain, and the primary flow of that knowledge is in the direction of the chevrons. The red arrows represent non-linear knowledge flows, including various forms of "learning" (i.e., learning-by-doing, learning-by-using, etc.). The actor-level discussion of PV will discuss knowledge, money flows, and concepts like vertical integration, or the incorporation of more than one chevron within a firm.

Here we define the PV power chevrons in more detail. Note that we do not define the rectangle of end use here, as it was defined in the power sector above.

Silicon: This chevron represents the production of the silicon, which is the basic material for the semiconductor needed to transform light into electric power. This process involves high energy consumption.

Ingot: This chevron represents the production of the crystal ingot via crystal growth processes – which involve specialized equipment and high energy consumption.

Wafer: This chevron represents the process of cutting the ingot into very thin slices (wafers). An important aspect of the wafer production is to reduce the loss of material.

Cell: This chevron represents all the processes which transform the wafer into a cell able to transform sunlight into electricity, including doping, coating and wiring.

Module: This chevron represents the production of the module in which several cells are connected and assembled into a module structure including the glass cover, back cover and framing.

Equipment: This chevron represents the variety of equipment used in each of the supply chain steps it is connected to. For silicon this is mainly reactor equipment; for ingots, this is primarily crystal growth equipment; for wafers this is mainly saws; for cells, this is primarily automated specialized production lines.

Finance: This chevron represents the finance of PV installations (i.e., the equity and debt, in the case of large scale installations based on a project finance structure), as well as corporate finance (of manufacturers) and venture capital.

Balance of Plant: This chevron represents the installation of PV modules (e.g., roof-top mounted) and the inverters which transform direct current into alternating current.

Power generation: The power generation chevron in this figure no longer produces carbon emissions. The intermittency of power generation from PV follows a daily and seasonal pattern and is also related to weather conditions.

Transmission and distribution: An important aspect of this chevron involves the connection and integration of distributed PV generation capacity, as well as load balancing requirements associated with the typical non-dispatchability of PV energy.

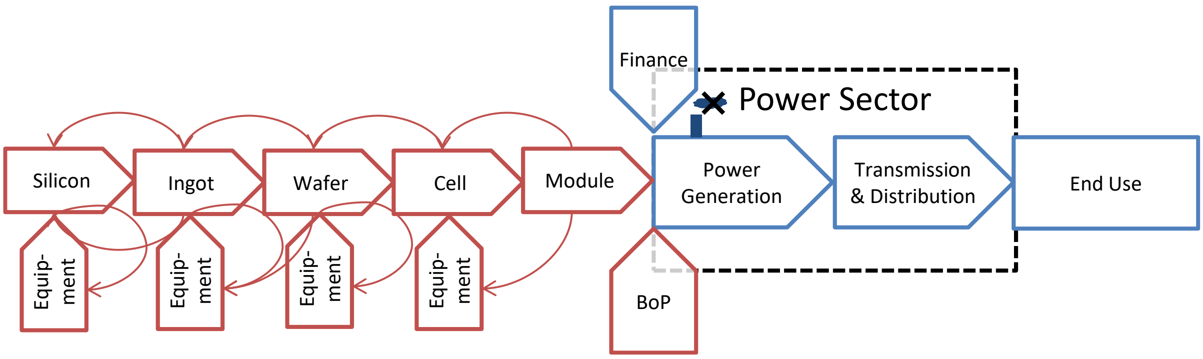

Figure 7. The technology level of technological change in PV power. This figure depicts the basic supply chain involved in the creation and ultimate diffusion of power generated from PV.

2.2.3.2 Characteristics of PV power technology

The primary direction of innovation in PV power technology is toward reduced costs per wattage. The results have been quite successful, as evidenced in the rate of cost improvements shown in Figure 4, although PV power still has higher LCOE than wind power and conventional power sources in most areas. Cost reductions have primarily resulted from many improvements along each step of the PV power supply chain (which tends to be vertically integrated, as we will discuss in the actor section below). These include savings in material inputs (e.g., reducing the amount of energy used to produce poly-silicon through the use of new production processes and equipment like the fluidized bed reactor; reducing material losses in wafer production through innovations like sawing, etc.) to mass production techniques that have helped commoditize PV cells. These production improvements have left the cost of BOP, including inverters and installation, to be an increasingly significant aspect of the cost of PV power, a fact that is beginning to receive more research attention (see, e.g., Seel, Barbose et al. 2013 on varying permitting costs in different municipalities). Note that the type of innovation involved in rooftop installation tends to be tacit and/or craft knowledge which resides with small actors and is not always easy to transfer; (Taylor 2008) discusses some of the attempts the California government has made in the past to better pass knowledge along to installers of solar systems.

An important secondary direction of innovation in PV power has long been toward greater efficiency PV cells (which allow the same area to generate more electricity, thereby making PV power more cost competitive. As we mentioned at the beginning of this section, a number of PV chemistries and configurations are in early stages of development. It was for this reason that we did not feel that we could declare that there is currently a dominant design for PV power, as in the case of wind power, despite the dominance of crystal-silicon PV in the global market (crystal-silicon PV represented 87% of the global market in 2010) (IRENA 2013).[7]

Note that a clearly foreseeable future direction for innovation in PV power is for integration of large-scale PV with storage. This has the potential to move PV power from a commodity product to a more complex, open system that might benefit from additional demonstration in order to capture operating knowledge.

2.2.4 Summary/synthesis

Wind power and PV power differ in many ways. As we discussed above, they differ in their relevant supply chains, which progress from input materials to component production to component integration into products, and finally to installation and integration through interaction with the power sector.[8] Note that these supply chains can be thought of as collapsing into the "technology" level in Figure 2. Wind and PV power also differ on several other dimensions, such as: (a) distance from the existing technology in the power sector and the potentially related degree to which new processes and underlying manufacturing equipment had to be created (e.g., more new machinery was required for the development of PV power than wind power technology); (b) level of technological maturity and potentially associated dominant design (e.g., wind power is more mature and a dominant design is more evident); (c) their directions of innovation (e.g., turbine size for wind, with demonstration projects particularly important; production cost for PV, with supply chain improvements particularly important); (d) the nature of the learning feedbacks between supply chain steps; (e) scales in use (e.g., PV power is very modular, with even large plants rather small compared to conventional power generation technologies); and (f) merit dimensions like intermittency, dispatchability, timing of the fuel source's peak, etc. Note that the merit dimension discussion ties directly to work by Anderson & Tushman (1990) which implies that new "interface" technologies which address issues like intermittency are predicted to be needed in wind and PV power as grid integration becomes a more important direction for innovation for both, with their growing scale of diffusion.

Table 1 provides a snapshot of how competitive Wind and PV currently are in the U.S. and Europe. Note that while electricity generated from wind is typically compared to the wholesale price of conventionally-generated electricity from new natural gas-fired combined cycle plants, PV is often compared to the retail price of that conventionally-generated electricity.

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[7] An important competing design is thin-film photovoltaics.

[8] PV power can be thought of as having a more serial (or linear) supply chain than wind power, which appears to have more parallel features.

Table 1: Cost of Wind, PV in comparison with prices and marginal baseline.

	USA	Europe
LCOE Wind (2010)	0.07-0.11 USD/kWh[1]	0.08-0.14 USD/kWh[1]
LCOE PV (2010)	0.17 USD/kWh[2]	0.2-0.26 USD/kWh[2]
Retail prices (av., household)	0.12 (0.075-0.398) USD/kWh[3, 4]	0.24 (0.12-0.39) USD/kWh[5]
Wholesale prices (av.)	0.03-0.12 USD/kWh[4]	0.07 USD/kWh[6]
Marginal baseline*	0.05-0.07 USD/kWh[4]	0.07-0.095 USD/kWh[2]

*LCOE of new natural gas-fired combined cycle plant

Sources: [1](IRENA 2013), [2](Peters, Schmidt et al. 2011), [3](IRENA 2013), [4](EIA 2013) [5](Eurostat 2013), [6](EC 2012)

2.3 Actor level

This section discusses the actor level of Figure 2. It is here that we provide sketches of the major organizations that work within the wind and PV supply chain and are thus crucial to understanding the relevant processes of innovation, such as formal invention and induced learning (Taylor and Fujita 2013), as well as the effects of policies designed to change power sector emissions. In this section we discuss some of the attributes of these actors that are particularly relevant to understanding the baseline incentives for innovation in wind and PV technology without policy intervention. The attributes we focus on here are both external to (i.e., in the competitive environment of) and internal to (i.e., in the organizational behavior of) the firm. Note that although we name some important firms in the wind and PV power supply chain at various points in this section, we do not attempt to be comprehensive about identifying specific firms. We conclude this section with a brief treatment of some of the innovation literature that we find relevant to actors in wind and PV power, attempting to link this literature to the actor attributes discussed here wherever possible.

In discussing the actor level of technological change, we use visual cues that are either embedded in or cross-over the existing chevrons laid out in the technology level discussion above. Actors are represented by small colored boxes, with the colors identifying relevant actor types. If a typical actor spans more than one chevron in its operations (and is thus considered to be “vertically integrated”), this fact is identified by connecting relevant colored boxes with lines of the same color. The level of competition associated with a given chevron is represented by a larger number of boxes in that chevron.

2.3.2 Wind Power

2.3.2.1 Illustrating the actor level of technological change

Here we briefly sketch some of the attributes of the major actors in wind power, as illustrated in Figure 8, below.

(1) Manufacturers: These actors manufacture turbines and/or their components and sub-systems. As the level of vertical integration is high in the wind industry, many turbine manufacturers also produce important components and sub-systems themselves (e.g., Enercon of Germany covers 85% of the supply chain). The current trend is toward less vertical integration, however, so there is a growing role for smaller manufacturing firms that focus only on the production of certain components (e.g., the blade manufacturer LM Wind Power of Denmark).

(2) Equipment/service providers: The primary role for actors that provide equipment and services in the wind power industry is in the area of site-specific BOP (e.g., siting, permitting, commissioning, etc.), which is relatively complex, given the typical erection of wind turbines in groups known as wind farms. Given the high level of vertical integration in the wind industry, as discussed above, it is not surprising that many of the engineering, procurement, and construction (EPC) services required for BOP are handled primarily by the turbine manufacturers and project developers. However, there is a role for specialist EPC firms (e.g., WKN of Germany). A secondary role for equipment and service providers, given the high degree of vertical integration in the wind power industry, as discussed above, is the supply of specialized equipment that bridges from adjunct industries (e.g., Renk of Germany providing gearings).

(3) Incumbent technology users (i.e., the power sector): The relatively large investments needed to develop wind farms is at the same order of magnitude as conventional power generation technologies, and incumbent technology users of generating equipment (i.e., existing utilities) often own these wind farms. Three attributes that these actors are typically characterized as having are worth mentioning here, as they are relevant to their innovative capabilities: (a) they typically operate under conditions of regulation or sometimes public ownership, given their traditional natural monopoly status and importance to national security, and the issue of whether they can pass their investment costs through to end users can vary, based on these conditions; (b) they are known for risk aversion, given the primacy of their traditional goal of reliable power; and (c) they have been criticized for not conducting enough R&D, perhaps because of the absence of competition in the industry (see, for example, the origin of the U.S. Electric Power Research Institute as an R&D consortia for the sector, as a result of an administrative law judge's order that the industry conduct more R&D, in the aftermath of a notorious blackout in the 1960s)

(4) Financiers: There are two major types of independent financial actors in wind power installations, and one major financial actor in wind power production. [9] For wind farm investments, as alluded to above, project developers often supply equity, with either a business model of build-own-operate (BOO) or build-own-transfer (BOT); these investors are typically new entrants in the wind industry. Meanwhile, local and regional banks service debt for wind installations; these investors have low risk appetites but long time frames, which suit the rather long payback periods observed in the industry. Regarding wind production facilities, corporate finance is the major investor type; these investors, which often work with industrial banks, typically have somewhat greater risk tolerance than local banks and institutional investors, but they also have shorter time frames for investment payoffs.

(5) New technology users: Although, as mentioned above, traditional utilities often own wind farms, there are also new entrants that operate, invest, and generate power from wind energy.

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[9] For new designs/sub-technologies, venture capital (VC) is also important, but the dominant design of the three-blade turbine is not very VC dependent.

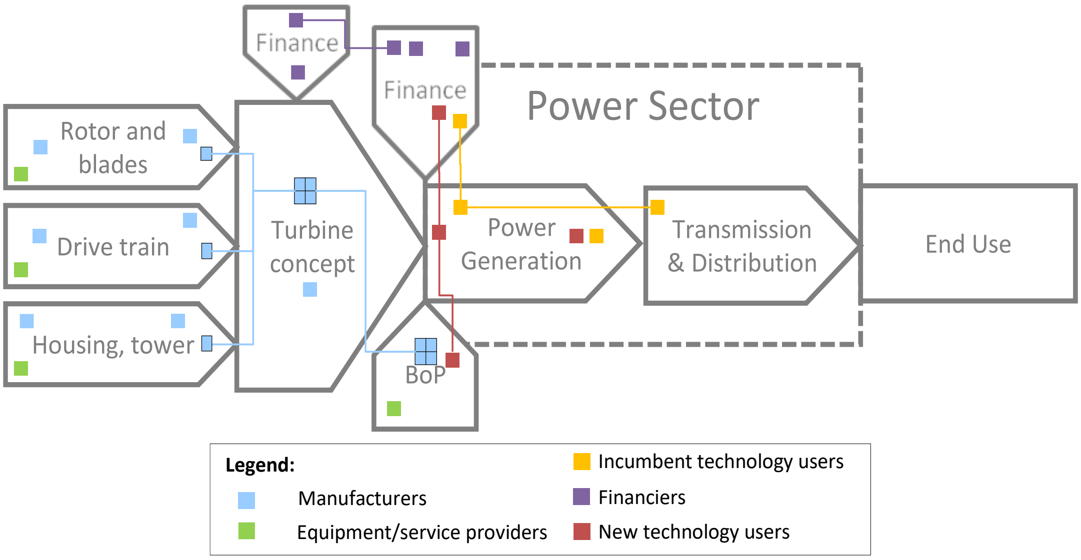


Figure 8: Actor level of wind power supply chain

2.3.3 PV Power

2.3.3.1 Illustrating the actor level of technological change

Here we briefly sketch some of the attributes of the major actors in PV power, as illustrated in Figure 9, below.

(1) Manufacturers: The manufacturers of crystal-silicon PV are often highly vertically integrated.[10] The production of the wafer, cell, and often, the module, is typically done by the same firm, while some firms are even fully integrated (e.g., REC, of Norway, produces the silicon itself). Competition is also very high in the PV power industry. While some of the firms are established players in the electronics industry (e.g., Kyocera or Sharp, of Japan), most firms were founded over the last decade and focus only on PV (e.g. Solarworld of Germany, Jingli of China).

(2) Equipment/service providers: In PV power, suppliers of production equipment are important. These firms are typically players in the machinery industry (e.g., Meyer Burger, of Switzerland, which provides equipment for wafer, cell, and module production). BOP is mainly covered by local installers who are active as electricians or roofers. They plan and install the solar plant and procure the equipment needed for system integration (inverters, etc.).

(3) Incumbent technology users (i.e., the power sector): The modularity of PV power facilitates decentralized power generation and the emergence of new technology users. As PV power scales up, in part through policies that require end-user production to be purchased by incumbent actors in the power sector or that subsidize end-user production, incumbent technology users can experience both technical and business pressures.

(4) Financiers: Here we focus on three roles of finance in the PV power supply chain for crystal-silicon PV: finance for new technology user installations (e.g., rooftop PV), finance for larger PV plants, and finance of production facilities. Rooftop PV installation finance is typically done by

[10] This trend also holds for thin-film PV, with the leading thin-film PV firm, First Solar, even developing and manufacturing its own production equipment.

the end user (equity) and local banks (debt). These investors typically have long time frames, which match the rather long payback periods involved, although they are also typically risk averse. Larger PV plant installation finance is typically done by project developers (equity), that either have a build-own-operate (BOO) or a build-own-transfer (BOT) business model. Finally, investment in production facilities is typically done through corporate finance, sometimes in conjunction with industrial banks. However, since the new chemistries and configurations that are currently in early-stage development are likely to matter to PV power in the future, we must mention the importance of venture capital (VC) in financing these alternatives. VC investors are known for their large risk appetites and short payback time frames (5 years or less).

(5) New technology users: As mentioned above, the modular nature of PV and its relatively small size facilitates decentralized power generation and the emergence of new power producers in the power sector, which were formerly only the end-users of electricity. These new users include households which install PV on their rooftops, and thereby generate power as “prosumers,” a term that represents the hybrid nature of their relationship to the power sector, given that they sometimes consume their PV-generated power and sometimes feed that power back into the electricity grid (note that, typically, prosumers receive electricity from the grid during times of under-supply from their PV plants, e.g., during the night, so they are currently not fully independent of the existing power sector). For larger PV installations, it is often project developers that operate these plants.

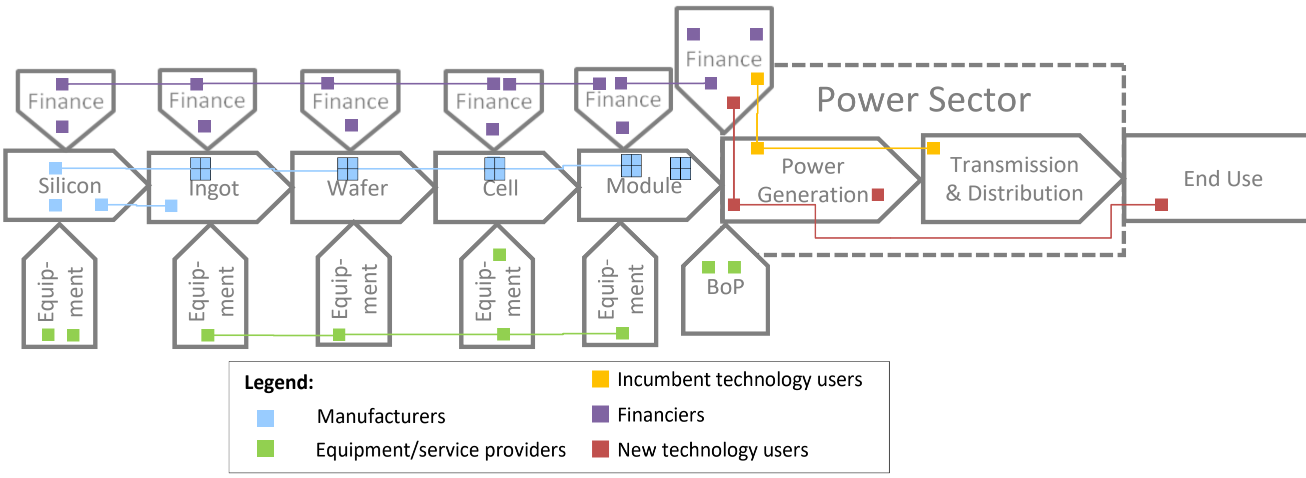


Figure 9: Actor level of the PV power supply chain

2.3.4 Summary/synthesis

Here, we summarize some of the more important attributes of the actor-level of wind and PV power, from the perspective of existing policies and innovation theories, as they cluster around two concepts: market structure and firm heterogeneity. Below, we briefly introduce some of the key innovation theories that we think have relevance for a deeper understanding of likely policy effects of innovation on these actors.

Market structure is a concept that connotes two concepts: the level of vertical integration in an industry, as well as the level of competition in that industry. It is thus, less a concept relating to specific firms as it is to market conditions. In the description of the leading actors involved in Figure 8 and Figure 9, above, we see vertical integration playing an important role in whether there is a role for new entrants in specialized components, which might distinguish themselves with regard to cost or quality. Vertical integration is common in both the wind power and PV power industries.

Firm heterogeneity is another important concept to think about at the actor level of a technology. Our approach in visualizing relevant supply chains is helpful in understanding the ways the relevant actors differ from each other both within a supply chain and across supply chains for wind and PV power. For example, different financial actors play roles in different aspects of the PV and wind power supply chain, and can be distinguished by their levels of risk aversion, as well as their payoff timeframes. The emergence of prosumers in PV power technology (but not wind power), however, is a particularly interesting aspect of the level of heterogeneity in this industry. It is difficult to fully conceive of these actors as new entrants, since they still play one of their incumbent functions in the original electric power sector as end users, but the alteration of their functionality and the pressure their emergence exerts on incumbent transmission and distribution, as well as power generation actors, is a particularly important for policy in PV, but not wind power. Note that another important dimension of firm heterogeneity that typically matters for business policy and innovation theory is firm size; we did not go into this variable in detail here, but it matters to understanding the effects of policy instruments, including those instruments that focus on reducing the tax burdens of firms.

Finally, firm heterogeneity is an important concept to keep in mind when considering how to characterize the types of innovative activities undertaken in the wind and PV power supply chains. Relevant activities include: formal R&D directed toward commercialization; the honing and transferring of craft and tacit knowledge; the establishment of more efficient production lines and processes by management, as opposed to laborers on production lines within actor organizations (for more on the distinction between such "induced" versus "autonomous" learning, see Taylor and Fujita 2013); and the potential importance of end users as a source of innovation, drawing on the work of (von Hippel 1976; Von Hippel 1986).

2.3.5 Relevant theories

To better understand the actors, their sense making of their business environment, and the factors that drive their investment and innovation decisions, it is useful to visit relevant theoretical management literature. We consider the following theories as specifically helpful in order to better understand the effects of policies on the innovating actors:

Cognitive theory (Weick 1979; Dutton and Jackson 1987) and specifically the *attention based view* of the firm (Ocasio 1997) are helpful in order to analyze whether a policy is able to attract the attention of the relevant decision makers within an organization (typically decision makers are confronted with a myriad of changes in their business environment) and make them reconsider their strategic investment and innovation decisions (Schmidt, Schneider et al. 2012). How they interpret the role of the respective policy for their organization and which the decision then take is strongly dependent on their mental frames (Kaplan and Tripsas 2008). One theoretical question that is also relevant to policy makers is: can policy change these mental frames and/or attract entrants with different mental frames to an extent that initiates paradigmatic shifts within the power sector?

Besides the cognition of the decision maker the potential pay-off structure of an adoption or innovation, i.e. to which probability and extent the investment will pay off, will affect the decision of a manager. On the one hand, this depends on the policy and the regulatory environment. On the other hand, it also has to do with the situation of the firm in its market environment. *Porter's five forces* (Porter 1980) are a useful concept to structure the business environment of a firm and its decision making. The five forces include (1) industry internal competition (compare the symbols for the firms in our chevron figure), (2) the bargaining power of suppliers (which in our chevron figure affects the transaction between the focus chevron and the chevron left to it), (3) the bargaining power of the customers (which in our chevron figure affects the transaction between the focus chevron and the chevron right to it), (4) the threat of new entrants (in our chevron figure represented by the red firm symbols; note that new entrants also may encompass actors from adjacent industries), and (5) the threat of substitute products (in Section 3 we will merge the Wind and PV supply chain figures and also introduce the conventional technologies). Policy makers should be aware of these effects, when designing policies, as the same policy might have very different effects in different market environments[11].

While the above factors all relate to an organization's environment, another important factor for the innovation/adoption decision of an organization relates to its internal resources and capabilities. Firms are very heterogeneous actors (Nelson 1991). Important factors that affect the innovation decision are: the firms technology portfolio (Christensen and Rosenbloom 1995), its value chain position (user or producer of technology) (Lundvall 1985), and its size (Schumpeter 1942). Also its technological capabilities (Teece, Pisano et al. 1997) and other dynamic capabilities (Teece and Pisano 1994) as they will affect its ability to innovate/adapt to changes to the competitive environment as brought on by policy or other measures. For policy makers, these factors are important, as they affect the stringency levels and the timing of a policy instrument.

2.4 Geographic dimension

This section briefly discusses the geographic dimension of each of the technological change levels discussed above. When discussing these geographic dimensions, we will be incorporating knowledge that is pertinent to localities (e.g., local PV installers), nations (e.g., national power sectors), regions (e.g., regional transmission grids), and the globe (e.g., multinational firms). Note that chevrons at each level can have varying degrees of geographic depth.

2.4.1 Sector level

The most relevant geography for the power generation chevron is provinces/federal states or national regions (e.g., the U.S. or India), to nations (e.g., France). It is rather seldom that power generation encompasses various nations. The transmission and distribution supply chain step is additionally often transnational (e.g., in Europe with its closely linked transmission grid). Consequently, relocating power generation into other nations (or regions) , e.g., in order to avoid regulation, is only possible, if the transmission grid allows.

2.4.2 Technology level

The relevance of different regional levels for technology differ (a) by technology and (b) by supply chain step. While components and sub-systems are sometimes sourced globally, their modularity in terms of size affects geographies: PV's high modularity allows it to be shipped almost anywhere which is one reasons that allowed China's PV industry to emerge mainly on exports (Peters et al 2012). in contrast, the often large components of Wind often impact geographies. In case new

[11] Let us give an example of how market forces can dominate the innovative effect of a policy: A power generator in a monopoly market structure translates into very low bargaining power of the customer. If the power generator is able to pass through a cost stemming from regulation (e.g., a carbon tax) to the end consumer, the likelihood of that firm to become innovative is much lower than in a market with strong competition and high bargaining power of the customer. In a monopoly, the policy (e.g. Tax) would need to be designed in a way that the costs can't be passed through in order to generate effects.

markets for wind open up (e.g., through a new support policy), it is often production of the large components (tower, blades) which is first built up in these markets. For finance geography matters at the national level and in terms of investment risk profiles and currency exchange rates (Waissbein et al. 2013). The BoP/installation is per definition bound to a specific locality.
Note, as natural resources, capital markets, the baseline energy mix and other factors vary strongly across geographies, also the LCOEs of renewables and competitiveness with conventional technologies vary heavily across geographies (see e.g., Peters, Schmidt et al. 2011; Schmidt, Born et al. 2012; Waissbein, Glemarec et al. 2013).

2.4.3 Actor level

Geography at the actor level refers to the scope of action of an actor. In general, the range of actors' geographical scope can vary from very local (e.g., household end-consumers or prosumers) via national (e.g., national grid operators) to global (e.g., MNC supplying components or materials). Wind turbine manufacturers typically started as national or even local firms and – if successful – become MNCs. PV companies are often more locally bound but serve international markets (see 2.4.2). Installation/BoP in PV is typically done by local firms (especially for small scale installations such as roof top mounted PV), which results in major differences in BoP costs across geographies(Seel, Barbose et al. 2013). Installation of Wind is partly global (installer teams are sent around the world) and over time becomes local with growing market size.

3. Policy effects on technological change

In this section, we apply our visualization technique in order to synthesize knowledge about the effects on technological change for wind and PV power of various prominent policy instruments that either mitigate carbon emissions or directly incentivize renewable energy. We primarily select the policy instruments for examination from the most prominent international organization dedicated to renewable energy policy (International Renewable Energy Organization, "IRENA"). We employ many of the definitions IRENA has developed in Table 2, which also provides some example geographies in which the instrument is employed. But we also pause to reflect on the theoretical economic purposes of these policies, as derived from their historical context, as these purposes re the typical metric of the success of the policy. Figure 10 then illustrates the point of application of each policy within the wind, PV, and conventional generation technology supply chains, and illustrates the first- and second-order investment effects these policies have on innovation in such a way that we make the pattern of effects across instruments visible. Finally, we provide a table that summarizes the major effects illustrated in Figure 10 and provides a selection of relevant references to the empirical literature on policy and clean energy innovation.

Table 2: Policy instrument definitions and exemplary geographies

Instrument	Definition	Exemplary Geographies (Sources: DSiRE, REN 21)
Carbon tax	A tax levied on emissions sources based on the amount of carbon emitted and the needed level of reduction.	Norway, British Columbia

Carbon emissions trading	A cap is set on the quantity of permissible emissions and “allowances” are distributed to emissions sources that collectively sum to the cap. If sources can reduce emissions cheaply on a relative basis against sources with different marginal abatement costs, they can sell excess allowances at whatever price the market will bear. (Taylor 2012)	European Union, California, Northeast States of U.S., Australia
Renewable obligations/renewable portfolio standards	Obligates designated parties to meet minimum (often gradually increasing) renewable energy targets, generally expressed as percentages of total supplies or as an amount of renewable energy capacity, with costs potentially born by consumers through pass-through (based on IRENA 2012). Depending on design, tradable certificates can be used to meet obligations.	California and other U.S. States, Sweden, China
Feed-in tariffs (FITs)[12]	Guarantees renewable energy supplies priority access and dispatch, and sets a price varying by technology per unit delivered during a specified number of years. In fixed FITs, the price is fixed, in premium FITs, renewable energy supplies are guaranteed an additional payment on top of their energy market price or end-use value. (based on IRENA 2012)	60+ countries (30+ of which are high income) (REN 21). Most prominent Germany, Denmark, China
Net metering	Allows a two-way flow of electricity between the electricity distribution grid and customers with their own generation. The meter flows backwards when power is fed into the grid, with power compensated at the retail rate during the ‘netting’ cycle regardless of whether instantaneous customer generation exceeds customer demand. (based on IRENA 2012)	Most U.S. States, Japan, Denmark, Italy, China
Investment tax credits	Provides the investor or owner of qualifying property with an annual income tax credit based on the amount of money invested in that facility during the relevant year. Allows investments in renewable energy to be fully or partially deducted	U.S., Austria, Belgium, France, Germany, Canada*

[12] A related instrument is tendering/bidding. In this, public authorities organize tenders for a given quota of renewable energy supplies or supply capacities, and remunerates winning bids at prices mostly above standard market levels. (IRENA 2012)

	from tax obligations or income. (based on IRENA 2012)	
Production tax credits	Provides the investor or owner of qualifying property with an annual income tax credit based on the amount of energy that it generates during the relevant year. Allows investments in renewable energy to be fully or partially deducted from tax obligations or income. (based on IRENA 2012)	U.S., Austria, Belgium, France, Germany, Canada*
Public funding – R&D	Public authorities support the supply of new knowledge in a renewable energy technology by investing in research and development. This R&D can be performed either by public, private, or some combination of public and private actors. (Taylor 2012)	Most high income countries, including U.S. and Germany; also China**
Public funding – Loan guarantees	Risk-sharing mechanism aimed at mobilizing domestic lending from commercial banks for renewable energy companies and projects that have high perceived credit (i.e., repayment) risk. Typically a guarantee is partial, that is, it covers a portion of the outstanding loan principal with 50 - 80% being common. (based on IRENA 2012)	Most high income countries, including U.S. and Germany; also China**

* = REN 21 does not distinguish between investment and production tax credits in its tables.

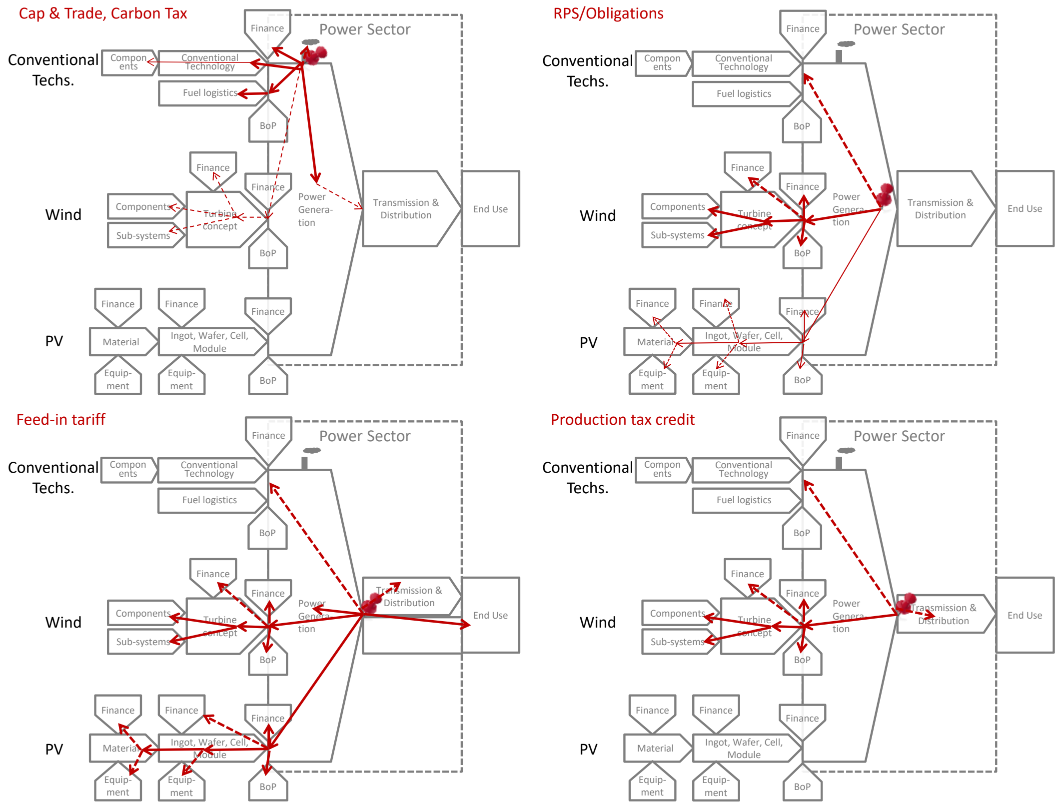
** = REN 21 does not distinguish between public funding types

The theoretical focus of the policy instruments in Table 2 are primarily focused on correcting three market failures. Carbon emissions trading and carbon taxes are both designed to internalize the cost of the negative externality of carbon dioxide pollution. R&D funding is designed to help defray the reluctance of firms to innovate due to the imperfect appropriability of the returns to their innovations. But what is important to note is that many of the renewable energy-oriented policy instruments in this table – including renewable portfolio standards, production tax credits, investment tax credits, feed-in-tariffs, and net metering -- all have major historical and theoretical bases not in those market failures, but in the market failure of imperfect competition. Investment tax credits and production tax credits both emerged in the Public Utility Regulatory Policy Act of 1978 in the U.S., which was particularly focused on creating a role for independent power producers in the electric power sector, thus helping to break up the monopoly power of the utilities. In Germany, the feed-in-tariff instrument the nation is particularly famous for was explicitly based on breaking up the existing power sector regime. Harnessing the power of policy to foster innovation renewable energy technologies was not as primary a concern as this goal of breaking up monopolistic practices, or even as great a goal as supporting industrial policy/economic development (and in the case of Germany, supporting geographic equity).

Figure 10 is our attempt to visualize the first order and second order investment effects of these policy instruments on technological change in wind and PV power. We place a visual “pin” in this figure on the point of application of the policy within the actor supply chain – either inside a chevron or at an intersection point between chevrons – that we think is most directly relevant to the instrument, given these theoretical considerations. We use a solid arrow to depict the first order investment effects of the policy on innovation and a dashed arrow to represent the second order investment effects. The strength of the effects, whether first- or second-order, is represented by the thickness of the arrow.

Please note that in Figure 10 we include the conventional technologies, which are characterized by an additional chevron: the fuel logistics, representing the supply chain of the fuel including mining, refining and transport.

In interpreting the pictures in Figure 10, we want to stress that although our visualization style highlights the actors in the supply chain, as we feel it is these actors that receive financial incentives or are responsible for meeting legal obligations, etc., it is important to remember that any effects that policy has on the innovative activities conducted by the actors will be observed over the course of time on the improvements in cost and performance at the technology level, as well as on the diffusion of technologies observed at the sectoral level. We also want to note that details of policy design matter to the types of observed effects in Figure 10. In our description of some of these effects in Table 3, we draw heavily from work started in Kemp (1997) on the design features of policy instruments (e.g.,policy stringency, policy flexibility and neutrality between technologies, predictability, timing, etc.



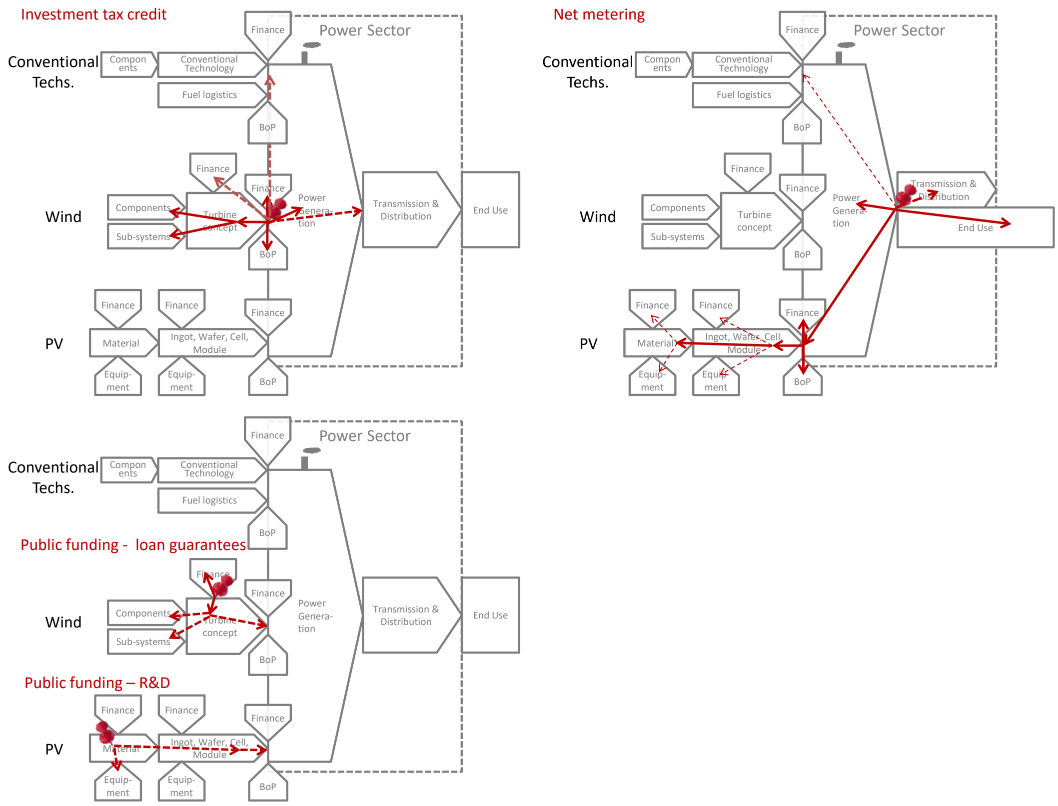


Figure 10: Illustration of the different effects of selected policy instruments on innovation across the supply chain

Table 3: Summary of effects of policy on technological change and related literature

Instrument	Effects	Selected Empirical Literature
Carbon Tax Cap-and-Trade	Point of application of policy • At the power generation chevron where it regulates power generators based on emissions 1st order effects • Organizational change (operational strategies, e.g., merit order, units that do trading) • Investments in conventional technologies (e.g. retrofits) 2nd order effects • Primarily incremental innovation in coal plant efficiency • Theoretically, a very high carbon price could trigger demand for the wind power due to the typical favorable LCOE comparison with PV power	• (Taylor 2012) • (Schmidt, Schneider et al. 2012) • (Rogge, Schneider et al. 2011) • (Rogge and Hoffmann 2010)
Renewable obligations/ Renewable portfolio standards	• Point of application of policy At the power generation chevron it regulates the power generators based on their generation mix 1st order effects • Demand for wind power increases and production capacity responds	• Taylor et al (2006) • (Mignon and Bergek 2012) • (Butler and Neuhoff 2008)

	• Demand for large PV plants may also increase depending on tech-specific design • The entry of new power generators is favored when trading is allowed 2nd order effects • Learning and financial feedbacks can improve the components, concept, and BOP • Lasting demand can trigger upstream investments in new production equipment	
Feed-in-tariff (FiT)	• Point of application of policy At the grid feed-in transaction point it changes the incentive structure of electricity markets 1st order effects • If designed in a tech-specific way, drive demand of wind and PV • • Due to their de-risking side effect, they typically attract new financial actors (including venture capitalists), which can fund invention and diffusion of wind and PV • In the case of PV, FITs have the potential to transform end-users into producers (see, e.g., “prosumers”) • 2nd order effects: • If demand increasing, investment into new production capacity and innovations in manufacturing equipment • If new capacity of (variable) renewables large enough, the amount of electricity generated can change the wholesale market and affect the operation of conventional plants and the grid • Learning and financial feedbacks can improve the components, concept, and BOP	• (Hoppmann, Peters et al. 2013) • (Waissbein, Glemarec et al. 2013) • (Bürer and Wüstenhagen 2009) • (Butler and Neuhoff 2008) • (Johnstone, Haščič et al. 2010)
Production tax credits (PTC)	Point of application of policy • At the grid feed-in transaction point by supplying tax credits for each kWh supplied to the grid 1st order effects • Typically drive demand of large Wind parks (due to transaction costs, see section 4) 2nd order effects • If demand increasing, investment into new production capacity and innovations in manufacturing equipment	• (Bürer and Wüstenhagen, 2009 • (Johnstone, Haščič et al. 2010)

	• Learning and financial feedbacks can improve the components, concept, and BOP • If new capacity of (variable) renewables large enough, the amount of electricity generated can change the wholesale market and affect the operation of conventional plantsand the grid	
Investment Tax Credit	Point of application of policy • At the transaction point where wind and PV equipment is purchased, financed, and installed 1st order effects • Increases the demand for wind and PV capacity and incentivizes new power generators to enter the market 2nd order effects • Learning and financial feedbacks can improve the components, concept, and BOP	• (Taylor 2008) • Taylor et al (2006) • Taylor et al (2007)
Net metering	• Point of application of policy At the transaction of end-user purchase of power 1st order effects • Changes the consumption incentives of end-users • The only instrument where transmission & distribution, power generation, and end-users have to meet (whereas in FITs they can but do not have to meet) • In the case of PV, FITs always transform end-users into producers (see, e.g., “prosumers”) 2nd order effects • Learning and financial feedbacks can improve the components, concept, and BOP	• (Taylor 2008)
Public funding – R&D	• Point of application of policy At any inventive actor in the supply chain 1st order effects • Improvement of component, product or process for which research support has been granted 2nd order effects • Innovative outcome may lead to performance or cost improvements and hence a diffusion across the value chain	• Taylor and Bush conference paper
Public Funding – Loan Guarantee	• Point of application of policyAt the provision of finance throughout the supply chain by changing the incentive schemes of capital markets (in Figure 10, wind turbine manufacturers) 1st order effects • Directly affects either the R&D or the production investment decision of the receiving actor	• (Waissbein, Glemarec et al. 2013)

	• Affects the financier by increasing their willingness to lend 2nd order effects • Investments will lead to invention and eventually to diffusion of the technology	

What has not been touched upon in Table 3 is the role of geography. Policies might be local, national or international and their effects might also differ across geographies. For example, the German feed-in-tariff triggered a lot of investments into production capacity and innovation globally (Peters, Schneider et al. 2011). The role of geography depends on the type, but also the design, of the policy instrument.

In future research, differentiating policies on the basis of their effects on the acceleration and redirection of technological change (as graphically done in Figure 10) might also be helpful for understanding the interaction effects of the multiple policies that co-exist under real-world conditions (see research on interaction effects by Sorrell and Sijm 2003; Sijm 2005; Fischer and Preonas 2010).

4. Framework in practice

In order to show how our framework can be used to analyze the effects of policy on technological change, we discuss here the effects of Feed-in tariffs (FiTs) and the EU Emissions trading scheme (EU-ETS) on wind and PV power.

Feed-in tariffs (FiTs)

Globally, many countries have introduced feed-in tariffs for wind power (37 countries, according to REN21.org) and PV (35 countries). In the EU, the FiTs of Germany and Denmark are the longest running for wind, and the FiT of Germany is the longest running for PV. These FiTs have had a strong influence on technological change in the power sector within these countries, but also globally.

Wind

According to our framework, technological change at the sector level takes place in the form of the diffusion of new technologies. The FiTs of Germany and Denmark resulted in a strong increase of the diffusion of wind power. In Denmark, the share of Wind in electricity generation has reached 28% in 2011, which equals an average annual growth rate (AAGR) of 8.5% over the last ten years (ObservER 2012). In Germany, wind reached an 8% share in 2011 and a AAGR of 16.7% over the past decade. While these are average numbers, on a windy weekend day (with low electricity demand) wind can cover much higher shares in both countries. Due to the increased shares of wind power, the operation of the transmission and distribution grids has to be adjusted. This has to do with the fact that the windy sites and hence the Wind turbines are often not located in proximity to the load centers – e.g., the windiest parts of Germany are in the North, while the load centers are mainly in the West and South. Additionally the variability of Wind has to be counterbalanced by the grid operator, in order to keep the grid parameters (frequency and voltage) stable. Despite some changes in the grid infrastructure, e.g. adding FACTs devices (Flexible Alternating Current Transmission Systems) which make the grid more flexible. Wind power now has to be able to be taken off the grid quickly in order to avoid grid instabilities. However, further technologies, counter-balancing the intermittency of wind, such as storage, currently come at high costs. Policy support has solely focused on the generation technologies and neglected the support of these technologies, which might ultimately be necessary to integrate very large shares of renewables (Source: own interviews). However, some technological developments that support the system integration have taken place, e.g. in form of lasers that anticipate wind speed changes mounted to the turbines and thereby increase the predictability of the variable wind resource. Another interesting aspect of system integration has to do with the German nuclear phase-out. Wind is typically not capable to provide "millisecond reserve" for frequency regulation (nor is PV capable of doing so). So the owners of the nuclear plants that have been shut down now use the spinning reserve of the electric generators of these plants in combination with a small electric motor, to provide millisecond reserve. These innovations are triggered by the grid code and grid operating rules which were affected by the larger shares of wind (and PV) through the FiT.

On the technology level, technological change can be seen as the outcome of innovation in form of new knowledge , products and processes. Lewis and Wiser (2007) find that FiTs "have historically offered the most successful foundation for domestic wind manufacturing" (p. 1853). This is especially important as there "is a clear relationship between a manufacturer's success in its home country market and its eventual success in the global wind power market" (p. 1844). In fact, the turbine design that became dominant over time – horizontal, three blades, pitch-controlled – was heavily influenced by the Danish and German developments. Denmark, where the feed-in tariff was introduced in 1991[13] (previously, the policy support mainly consisted in investment subsidies and production tax credits), is the leader in the global wind industry. The Danish wind industry started with small turbines and scaled them up over time. This allowed many feedback from the use-phase of the technology (Hünteler, Hoffmann et al. 2012). In Germany, a first FiT was also established in 1991 and substantially reformed in 2000. An important factor in both countries was the stability of the policy support leading to continuous stable/increasing annual demand (Lewis and Wiser 2007).

The impact of the FiTs on innovation is ambiguous. While Johnstone et al. (2010) find negative effects of these instruments on innovation (measured via patents), Hünteler (2011) shows that FiTs increase innovation but rather of incremental nature. This is supported by a new analysis by Hünteler et al. (2013), which shows that currently enacted demand pull policies like FiTs are not able to support radically new turbine designs but rather support the emergence of a dominant design and thereby carry the danger of early lock-in into this design.

On the actor level, the FiTs had important effects in both countries. The German FiT provides a guaranteed tariff over 20 years, thereby fully covering both market access and price risk[14] (Waissbein, Glemarec et al. 2013). In Denmark, the design changed several times between a FiT (with guaranteed tariffs) and a FiT premium (paid on top of the variable electricity price), fully covering market access and partly covering price risk. Due to this risk coverage, investors were willing to invest in these new technologies. It was mainly new actors, like farmers, new wind project developers and

[13] The Danish government replaced the FiT premium with a RPS in 2000 and a FiT-premium in 2003 but returned to a FiT in 2009 (www.ens.dk).

[14] The access risk, i.e., the risk of not being able to get grid access and sell the produced electricity on the electricity market, is covered by feed-in priorities for renewables, which are part of the FiT legislation. The price risk, i.e., the risk of price volatility, is covered through fixed payments per kWh.

communities that invested in on-shore wind, thereby creating new technology users and opening the existing regime of power generators. Also local banks, so far mostly excluded from the power sector, became strongly involved in financing Wind farms. Finally, also large utility companies founded renewable energy business units (e.g., RWE Innogy), in order to profit from the support policies. "There is a different working environment in these subsidiaries, other people work there and the workforce is much younger, this is necessary as different know-how is required for renewable energies than was present in the utilities" (Rogge, Schneider et al. 2011, p. 520).[15]

Some differences between PTCs and FiTs

- Security provided to potential investors: While a FiT covers both market access risk and price risk, a PTC typically only covers the access risk part.
- Size of investment: FiTs can be designed in a way that they also make small scale investments attractive, whereas PTCs (due to their higher transaction costs) are rather limited to large scale investments.
- Investors attracted: Depending on the design, all types of investors (from large corporations to house owners) can be attracted by a FiT. A PTC is rather limited to actors with a high tax burden (typically corporations in other industries).

In terms of technology providers, the FiTs created globally operating firms with strong export orientation. Though relative global wind turbine market shares decline, Vestas is the largest technology provider since decades with a market share of 13% in 2011 (28% in 2007) (www.cleantechinvestor.com). Siemens Wind power (also based in Denmark) is the world's ninth largest producer (6% market share in 2011) but one of the leading companies in the off-shore business. Enercon is Germany's largest producer of wind turbines (with a global market share of around 8% in 2011 and 60% in Germany; www.dewi.de). While in Germany, Enercon is still the dominant player, market concentration has globally decreased over the last few years. Mainly Chinese manufacturers have gained larger market shares, mostly supplying to their home market and other emerging economies/developing countries (www.cleantechinvestor.com). Often manufacturers are actively providing equity to the projects (CPI, 2011) and are strongly involved in the erection of the wind farms. Nevertheless, in both countries a Wind innovation-ecosystem has developed featuring actors specialized in many wind-related activities.

PV

On the sector level, the FiT in Germany has led to a share of electricity generation of PV of 4.5% in 2012 (AGEB 2013), which corresponds to a AAGR of 67% over the last ten years (ObservER 2012). The total installed capacity reached 32.3GW at the end of 2012. These shares also create some issues at other parts of the power sector, namely system integration and wholesale market. Regarding system integration, the decentralized nature of PV requires further innovation of the grid system which was originally designed, to distribute centrally generated power and not to centralize distributedly generated power and re-distribute it. Also frequency issues arose in Germany, due to the fact that the inverters all stopped operating at a frequency above 50.2 Hz which became an issue with larger shares of PV capacity installed. New inverters are no longer subject to this issue (VDE

[15] These sub-units are often also located in "hipper" cities than the parents' companies headquarters (e.g., in case of RWE, where the renewable unit Innogy is located in Hamburg, while the RWE headquarters is based in the old industrial city of Essen) (Source: own interviews)

2011). Regarding wholesale markets: on very sunny days with little demand (e.g. public holidays), it occurred several time in 2012 that the wholesale prices reached negative values. The record was a negative price of -220EUR during Christmas of 2012, as shown in Figure 11. One factor was that the solar resource was much higher than typical for this time of the year. The other was that the demand prediction was very wrong, which also had to do with the weather extremes and reduced heating demand(temperatures reached about 20°C in Munich, i.e. 15 to 20°C over the normal values at this time of the year). It turned out, however, that it is less the technological capabilities that limit the prediction of demand, than the rules for predicting demand, which are completely outdated[16], stemming from the times before the German market liberalization (Energie & Management 2013).

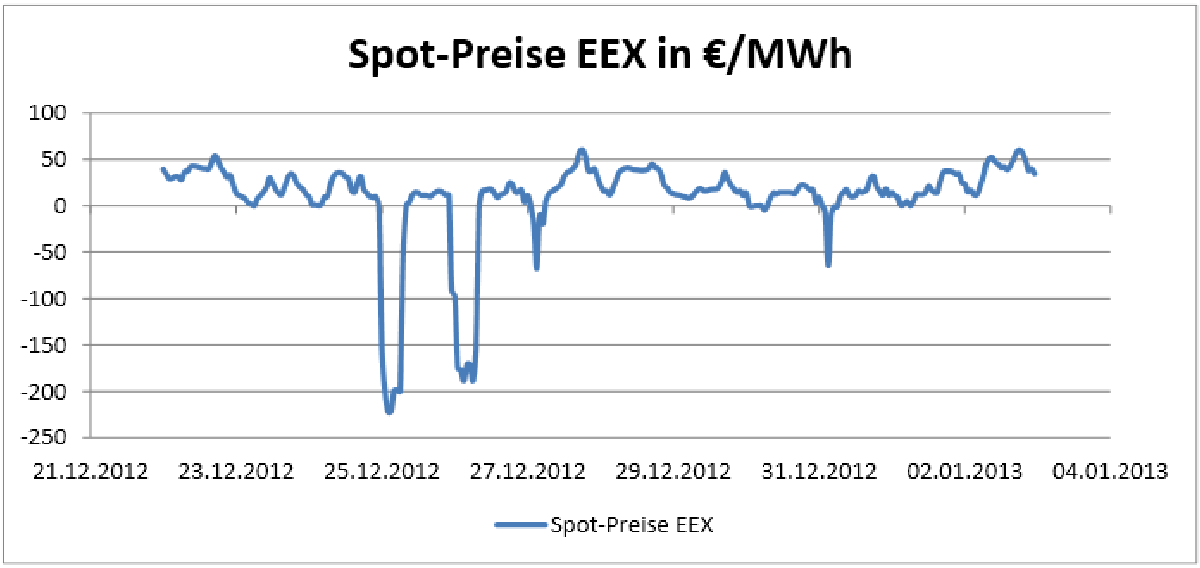


Figure 11: Spot price record in which record low is achieved. Source: www.eundt.at

On the technology level, the German feed-in tariff created a large industry of cell manufacturers and manufacturing equipment suppliers within Germany and (in case of suppliers also neighboring Switzerland). The German FiT for PV took off in 2000 (the 1991 FiT only affected wind, as it was not technology specific and therefore did not lead to investments into then much more expensive PV) but had been preceded by the so-called 1,000 and 100,000 roof programs, investment subsidy and loan instruments which had led to about 300MW of installation (www.bmu.de/N4248). Generally, FiTs have a positive effect on innovation (Johnstone, Haščič et al. 2010). However, in PV there are large spillover effects: Peters et al. (2011) show that domestic demand can incentivize innovative activities in other countries (incentive transfers). Another effect comes in form of knowledge transfers via export of capital goods (manufacturing equipment). Both spillover effects are important factors for the downturn of the German PV industry. Mainly Chinese manufacturers (backed by subsidies in form of low-cost debt) scaled-up production quickly resulting in the fact that about 80% of the newly installed PV cells in Europe in 2012 stem from Chinese manufacturers. The scaling of production, however, was so quick that it resulted in over-capacities and consequently in price drops and negative margins for the industry (Source: own interviews).
In terms of technology, Hoppmann et al. (2013) show that also for PV FiTs can lead to the lock-in of one dominant design and rather incremental than radical innovation.

[16] For instance the demand curves per household, which are aggregated to calculate the total residential demand stem from the 1980ies (Energie & Management, 2013).

In terms of actors, the German PV manufacturers do no longer play an important role in the world market (e.g., no German cell manufacturer can be found in the top 10 of world module producers). However, German firms are still global players in terms of module assembly (SolarWorld having the 7th largest global market share) and Silicon production (Wacker with the 4th largest global market share) (www.renewableenergyworld.com). The leading production equipment manufacturers still come from Europe (and the US). Centrotherm of Germany and Meyer Burger (a firm that was active in sawing first but then vertically integrated and now offers equipment for the entire value chain) of Switzerland are among the leaders in terms of global market share (NPD Solarbuzz 2013). In terms of end-users, the German FiT incentivized completely new players to enter the power sector. House owners, thus far mere end-users, became "prosumers" (producer and consumer) by installing roof-top mounted PV capacity. According to CPI (2012) they invested over 14bn EUR in equity by 2011. Additionally, new project developers and farmers invested in larger plants. Similar to the case of wind, local banks became active in financing PV capacity. Bürer and Wüstenhagen (2009) and Hoppmann et al. (2013) show that also venture capitalists trust FiTs, financing the build-up of the industry.

Another important actor group is the installers. Germany has by far the lowest soft-cost (BoP) worldwide (Seel, Barbose et al. 2013), which is driven by a range of factors, e.g., the FiT design (no cap, tariff degression), permitting rules, and induced local learning by installers. Also other businesses innovations were triggered, e.g. in form of companies offering insurance for PV modules and BoP. However, as the German FiT generally already provides for a positive business case, it also reduced the diversity of business models. While on the one hand, this resulted in highly standardized, efficient processes, it also reduced innovativeness and diversity in terms of business models , which is for instance much higher in the Netherlands, where policy support is less generous (Huijben and Verbong 2013).

EU ETS

The EU Emission Trading System (ETS) is the world's largest cap-and-trade system and started in 2005. While the main goal of the ETS is to reduce emissions, the EU also expected innovation effects. The first two phases of the EU ETS (2005-2007 and 2008-2012) were characterized by the free allocation of emission rights based on the principle of grandfathering (i.e., the emission rights were allocated based on the past emissions of a plant and reduced over time). The third phase, in which the emission rights (EUAs) for the power sector are auctioned, started in 2013 (Rogge, Schneider et al. 2011). Due to the economic crisis in Europe and the fact that emission rights of phase two were transferrable to phase three, there is an oversupply of EUAs resulting on low EUA prices (around 4 EUR in July 2013; www.eex.com). A proposal to increase the price by means of a reform of the mechanism is currently being debated in the EU parliament (The Guardian 2013).

On the sector level, Schmidt et al. (2012; 2012) show based on survey data in seven EU countries that the EU ETS has increased investments into emitting technologies (mainly coal). This mainly has to do with the design of the ETS, specifically the allocation of free emission allowances in the first two phases of the ETS (2005-12) (Rogge and Hoffmann 2010; Rogge, Schmidt et al. 2011)[17].

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[17] "First, our interviews reveal a temporary spike of interest in getting new fossil-fuel-fired plants in Germany operational by 2012. As main reason, interviewees mentioned that the free allocation of EUA for new plants greatly improves their profit- ability. Another reason mentioned is the German allocation rule of guaranteeing an unchanged level of free allocation (i.e. a compliance factor of 1) for 14 years. This 14-year rule was reported to work as a strong incentive for many investors – including investors other than the big incumbents – to get new plants operational by 2012, but was later abolished by the EU Commission" Rogge, K. S. and V. H. Hoffmann (2010). "The impact of the EU ETS on the sectoral innovation system for power generation technologies - Findings for Germany." Energy Policy **38**(12): 7639-7652..

Also fuel switch to gas did not take place as “the CO2 price would have to be 60–70 EUR/t CO2 to make gas profitable”(Rogge and Hoffmann 2010, p. 7647). Non-emitting technologies like Wind and PV were not affected in terms of diffusion, as the carbon price is simply too low to push Wind or PV beyond the profitability threshold (Schmidt, Schneider et al. 2012).

Also on the technology level, the effects of the EU ETS on both Wind and PV are very limited. Schmidt et al. (2012) find that it is rather the long-term targets, which underlie the EU ETS, that trigger innovation in renewable energy technologies than carbon price ETS itself. Rogge and Hoffmann (2010) find that the EU ETS slightly reinforces the innovation incentivized by other policies (e.g., FiTs and R&D support). However, several studies (Rogge and Hoffmann 2010; Calel and Dechezleprêtre 2011; Rogge, Schmidt et al. 2011; Rogge, Schneider et al. 2011; Schmidt, Schneider et al. 2012) show that the EU ETS has triggered innovation in the most threatened technology: coal-based power generation, e.g., in form of efficiency improvements. This together with the increased diffusion of coal plants due to the ETS, leads rather to an increase in efficiency and thus a “lock-in into fossil centralized power generation” (Schmidt, Schneider et al. 2012, p. 36)

On the actor level, the EU ETS has induced organizational innovation in form of routine changes, as e.g., CO2 prices and scenarios are incorporated in into investment appraisal (Rogge, Schneider et al. 2011). Further organizational changes happened in form of adjustments of corporate vision statements (mainly due to the long-term targets) and new organizational structures, e.g., in form of trading desks. New renewable energy business units of larger power utilities (see above) were however rather driven by the renewable energy support policies (FiTs etc.) than by the EU ETS (Rogge, Schneider et al. 2011).

5. Conclusion

This paper took the milestone of the atmosphere’s surpassing of 400 parts per million of carbon dioxide for the first time in millions of years as an opportunity to reflect on the state of what is known empirically about policy and research aimed at redirecting and accelerating technological change for wind and PV power. Our approach to doing this was to methodically think through the dependent variable of technological change, conceiving it as three levels that follow a supply chain logic and exist with a geographic dimension. These levels are the emitting sector (the power sector), the technologies of relevance to emissions reduction, and the actors that engage in the many processes of innovation, and are the sources of knowledge with its complex, non-linear flows. We employed a visualization approach in order to think through these levels, as well as the first- and second-order effects of policies on technological change. The results give us the ability to see patterns of effects across instruments, and helps us better understand why some policy instruments are likely to be better suited to certain challenges in wind and PV power than others.

For example, wind power technology particularly benefits from policies that help provide the sector with data and associated models regarding the operating experience of larger turbines in different geographies over sustained time periods.[18] Policies that encourage demonstration will continue to be very important in the future of this technology. In addition, providing knowledge transfer opportunities may be particularly important for the public sector to do in this industry, based on past successes with this type of approach (Taylor dissertation, Taylor LAPO), and the role that

[18] Although there is a role for public R&D as well as demonstration in designs that represent a more radical departure from the dominant design.

regulation has traditionally played in the power sector, which is less challenged by wind power than by PV power. Note that there are many opportunities for learning to occur in wind power technology, which is a complex, open system, with one of the most foreseeable trends in the technology the enhancing of this complexity and openness as pressures for better grid integration make coupling the technology with advanced storage more likely (McNerney, Farmer et al. 2011) (Tushman and Anderson 1986).

Meanwhile, crystal silicon PV power can benefit less from demonstration than from policy efforts that help reduce costs up the supply chain. To the extent that growing markets for PV power affect the pace of innovation in new equipment development and diffusion along the supply chain (Hünteler, Hoffmann et al. 2012) policies that create new markets can be very beneficial (as well as have spillover political economy effects as end-users begin to see themselves more as members of the power sector and change agents regarding climate mitigation).[19] However, given that a dominant design has not yet emerged in PV power, to our way of thinking, policy-makers should be careful about enabling too strict a preference for a single configuration. The existing modular nature of PV power, even as it scales up with increased generating capacity, will safeguard against this, to some extent, as long as any crystal-silicon specific BOP (e.g., linkage to the grid or between modules, etc.) that has the potential to block out other chemistries and configurations does not become standardized. Note again that there is a potential role for demonstration as PV power coupling with storage becomes more of an issue, and PV therefore becomes less of a commodity product and more of a complex, open system.

Although the approach we used in this report to structure empirical knowledge (and mainstream innovation-relevant theory) of relevance to the effects of policies on innovation in wind and PV power can still use refinement, we believe that it holds considerable promise and is applicable beyond the context of renewable energy. Even within Table 3 itself, we can see how applicable the Figure 10 visualization is to understanding the tradeoffs between the major clean energy strategies of fuel choice/modification, capturing unrealized within-actor efficiencies, pollutant control (i.e., carbon capture and storage), modification of the end-user's relationship with the power sector, and, of course, substitute generation in the form of renewable energy. We also believe that the questions this approach raises in the process of applying it can be very helpful in establishing a future empirical research agenda. For example, the decision whether to place a pin inside a chevron instead of at a connection point between chevrons is parallel to a choice either to conduct an empirical study of internal organization processes as they respond to a policy instrument, or to study market transactions as they relate to that instrument.

We have several thoughts for future work, based on this project. One is to use the patterns that emerged in Figure 10 to help establish a new categorization of policy instruments based on their effects on innovation, rather than their relevance to frames like environmental economics and public budgeting, which is the current practice. A categorization based on effects of innovation will draw more attention to the attributes of policy design, such as stringency (and how it is measured); compliance flexibility/technological neutrality (and related issues such as effect on dynamic efficiency, lock-in, etc.); timing (and its potential coordination with the business cycles of relevant actors); and de-risking investments in clean energy technologies for different financial and other actors. Other productive areas we believe that empirical research could inform include: (a)

[19] Such behavioral change has long been a goal of energy efficiency advocates.

considering what role there might be for new financial actors, such as small banks, etc., in a changing power sector; (b) helping policy-makers to better understand their economic development strategies related to clean technology as being related to their existing core competencies in adjacent industries like equipment supply, raw material processing, etc.[20]; and (c) investigating the predicted importance of end-users as a source of innovation in renewable energy, following on the work of von Hippel.

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[20] For example, the absence of a German semi-conductor industry explains, at least to some extent, the recent shake-out of German solar firms, although German expertise in equipment has maintained so-called “green jobs” within the country.

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