Shifting the Focus from Emissions to Competitive Strategy:

Towards a New Conceptual Framework of Climate Policy and Innovation

Prepared by Margaret Taylor and Tobias Schmidt for the International Schumpeter Society Symposium

Draft: July 15, 2014

1. Introduction

Achieving climate stabilization will require cutting global greenhouse gas (GHG) emissions deeply and in a relatively short time frame, while still meeting the aspirations of a growing global population. Most climate models suggest that global GHG emissions – in particular, carbon dioxide (CO_2), which is emitted through the complete combustion of fossil fuels like coal, oil, or natural gas (listed in order of the amount of CO_2 emissions generally associated with the fuel) – need to be reduced on the order of 60% by 2050. Meanwhile, the global population is expected to increase 38% from 2010 levels in the same period, with India's population in 2050 expected to almost match the combined populations of the U.S. and China (Pew Research Center 2014). Rapid technological change in the direction of decarbonization is a crucial means to stabilize the climate, given this context.

International climate policy-making through the United Nations Framework Convention on Climate Change (UNFCCC) process, however, has traditionally (since at least the early 1990s) viewed the climate stabilization problem and its response not as a problem in inducing technological change. Instead, the dominant frame for climate policy has been based on resolving the "negative externality" of pollution associated with economically productive activities. To illustrate this market failure, which is the particular forte of environmental economics, consider a factory that manufactures goods for sale, but the production of those goods pollutes the environment and thereby imposes costs on third-parties who are outside the commercial transaction (e.g., society, the ecosystem, etc.). If public policy required the factory to pay the full social costs of its privately valuable activities, the factory would theoretically face a direct economic incentive to pollute less when producing its goods. This is based on the assumption that the factory would be forced to price its goods with the full social cost accounted for, possibly lowering its profits or prompting its consumers to respond by reducing demand and seeking alternatives. The main climate policy intervention implied by the negative externality concept is a form of carbon price, with many environmental economists advancing different arguments about whether that price should be imposed as a tax or derived from the clearing price of an emissions trading market.[1]

The means with which the factory pollutes less is generally "inside the black box" of technological change (Rosenberg 1982; Rosenberg 1994) for environmental economics, but the theory implies that the factory will respond to the social cost requirement by changing its production process in an economically optimal way, either by employing its own inventive capabilities or by adopting goods and/or services developed by suppliers. The theory also implies

[1] In the most basic form of an emissions trading program, policy-makers set a cap on the quantity of permissible emissions and distribute "allowances" 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.

that these actions will increase the costs of the goods manufactured by the firm, and therefore the price of the goods delivered to customers. For those who think about the end-user as a potentially valuable source of innovation, in the line of von Hippel (e.g., von Hippel 1976; Von Hippel 1986)., the increased price of the factory's goods gives consumers an incentive not only to reduce their demand for the firm's goods – potentially adopting instead goods that are substitutes on dimensions of price and/or quality – or to invent such goods themselves.

Although many economists believe that a policy requirement that a firm pay the full costs of its activities is the *only* public intervention justified in the climate policy arena,[2] some make room for additional interventions, as long as they can be justified by additional, but unique, shortcomings of the market (the idea of a "one-to-one" connection of market failure to policy intervention). Two market shortcomings, in particular, have generated attention, with both emerging, in a theoretical sense, from a closer attention than the negative externality market failure focus typically allows to the specific abatement technologies that could help achieve climate stabilization.

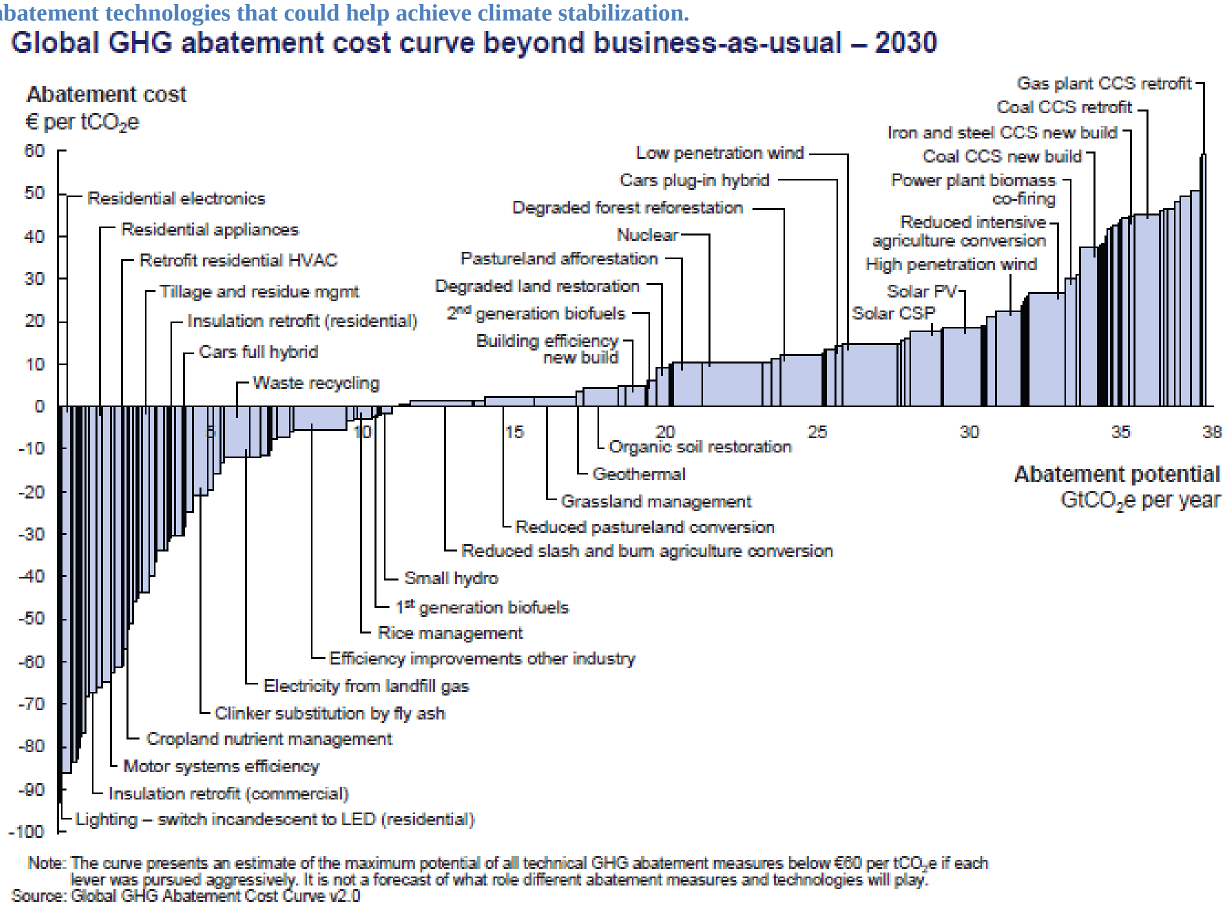

Figure 1**Error! Reference source not found.**, the "marginal abatement cost" curve (MAC curve), lays out many of the specific technologies that are currently understood to potentially play an important role in reducing CO_2 emissions. The MAC curve, which lays out the technologies by their cost and abatement potential, is sometimes discussed in three groups: (1) "negative cost" technologies that individually have low abatement potential, like energy efficient

[2] It is theoretically neutral with respect to the direction of technological change that it induces (although in practice, it tends to shore up a current least-cost selection environment) and it is supposed to affect the rate of technological change to a degree consistent with its level (although in practice, the number of options available to both polluters and consumers regarding technological change can dilute or enhance the effects of a carbon price on the rate of technological change).

appliances, which are not universally adopted despite the fact that they more than compensate the consumer who adopts them through energy savings; (2) "low-cost," medium abatement technologies that are considered both commercially ready and likely to be adopted if firms are required to pay full social costs; and (3) "high-cost," high abatement potential technologies like CCS that are not considered commercially ready. For the third group of technologies (i.e., those with currently high cost and high abatement potential; see, e.g., Jaffe, Newell et al. (2005)), many economists allow for an "innovation market failure" – i.e., the inability of firms to fully appropriate the returns of their research and development (R&D) expenditures – that could justify the intervention tool of public R&D expenditures. For the first group of technologies (i.e., those with negative abatement costs that save consumers money), less-than-universal adoption rates are sometimes considered evidence of a market imperfection (specifically, transaction costs; we refer to this broader phenomenon here in shorthand as the "energy-efficiency gap") that could justify the intervention tool of an information instrument (e.g., a government-sponsored label). For the middle group of technologies, which is typically considered close to commercialization, an appropriate social cost accounting intervention is deemed a sufficient incentive.

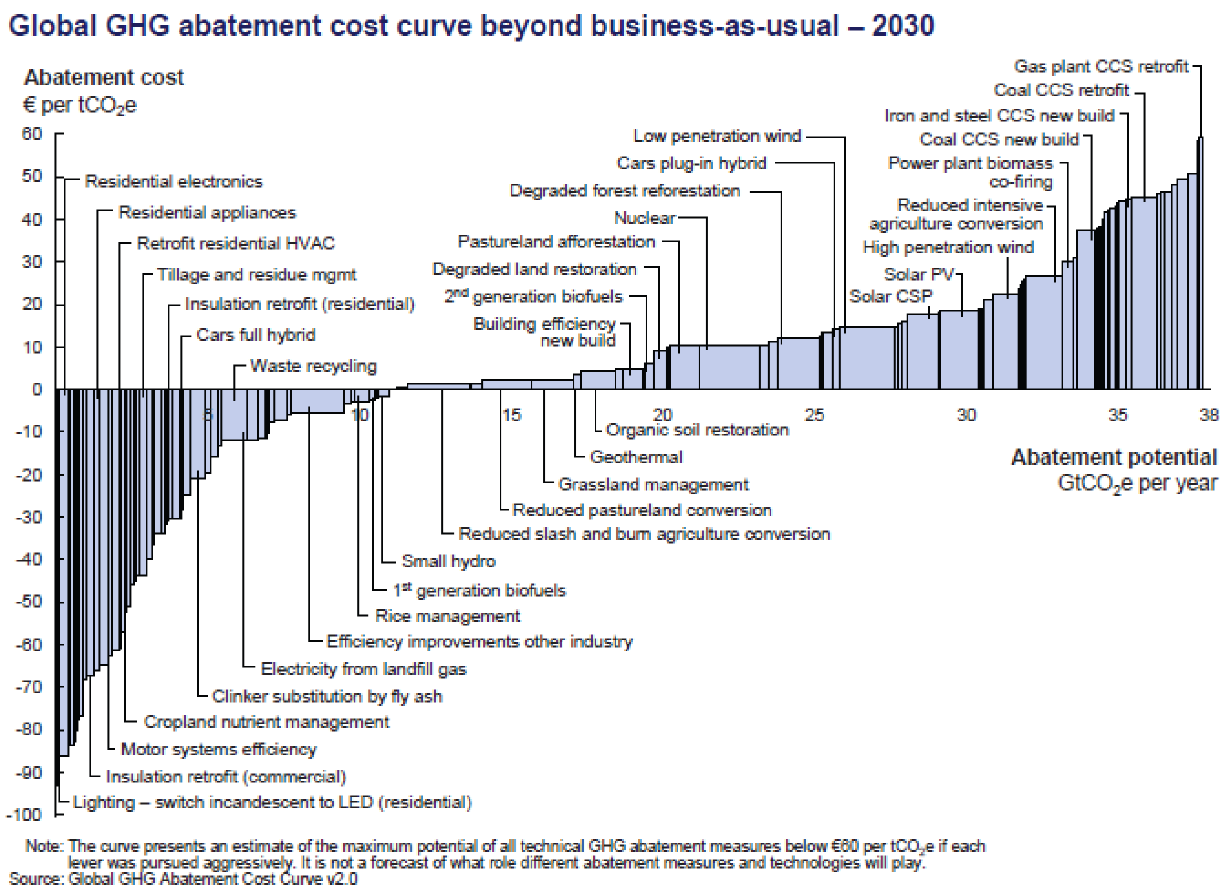

Figure 1: MAC Curve. Source: McKinsey&Company, 2009. Pathways to a low carbon economy - version 2 of the global greenhouse gas abatement curve.

Despite the fact that markets and their imperfections are used to justify all three of these policy instruments – full social cost accounting, public R&D expenditures, and information instruments – on different grounds, the negative externality, innovation market failure, and transaction costs associated with the energy efficiency gap all pay surprisingly little attention to the market conditions of the firms involved. We believe that this lack of attention to the competitive environment of relevant firms is a major blind spot in efforts to shape international climate policy, as it focuses the attention of policy design too much on the artifacts of current technology and emissions, and not enough on the incentives and actions of those who engage in the dynamic, and highly uncertain, innovation process. These actors do more than emit CO_2, engage in frictionless change of production processes and pass-through of costs to consumers, and sensibly decide to underinvest in R&D based on appropriability calculations: they also act strategically vis-à-vis their competitive environments. Some of these strategic behaviors have been the subject of past research outside the climate policy arena, while some are understudied. We believe that shifting the conceptual framework underlying climate policy to better incorporate insights involving competitive strategy will particularly aid in climate policy design in support of innovation. We also believe that it is currently an opportune time to shift this focus, as we approach a major decision point in 2015 regarding how the UNFCCC will operate beginning in 2020, when the current "extended Kyoto Protocol" phase of international climate policy-making concludes.

This paper is a first effort to shift this focus. We begin by focusing on the major source of the global CO_2 emissions that climate policy seeks to reduce, which is the electricity sector; in doing this, we are in keeping with the negative externality concept. But we go a step beyond this concept and consider electric utilities as firms embedded in a competitive environment, turning to Michael Porter's work and the work of Josef Schumpeter for inspiration, and develop a graphical language that assists in visualization of the likely effects of full cost accounting on innovation in this sector. In the following section, we consider where two specific technologies from the high-cost (third) group of MAC curve technologies fits into this picture, in order to assist in visualizing the likely effects of public R&D expenditures on these technologies. The paper concludes with reflections on next steps, which include sketching the market conditions for the manufacturers of negative abatement cost technologies in order to consider the value of information instruments in countering transaction costs in the uptake of these technologies (see, for example, (Houde 2012)).

2. Competitive Strategy and the Electricity Sector

Visualizing the competitive environment

We begin this section with a reminder of Porter (1980), which introduced the "five forces" of competitive strategy: (1) industry rivalry;[3] (2) the bargaining power of suppliers;[4] (3) the bargaining power of customers;[5] (4) the threat of new entrants;[6] and (5) the threat of substitutes.[7] These forces are illustrated in Figure 2, below. Note that Porter (1980) also recognized

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[3] The intensity of competitive rivalry is often the major determinant of the competitiveness of the industrial sector.
[4] Sometimes described as the market of inputs, this is the ability of the suppliers of raw materials, components, labor, and services (such as expertise) to the firm to pressure that firm. It is associated with the elasticity of the firm's demand for these supplies.
[5] Sometimes described as the market of outputs, this is the ability of customers to pressure the firm. It is often associated with the elasticity of demand for a firm's products.
[6] Profitable markets tend to attract new entrants. With their advent, the profitability of the sector declines towards zero in conditions of perfect competition.
[7] The existence of effective alternatives to valuable attributes of existing products (e.g., cost, quality) that can draw customers away from the currently bounded industrial sector.

government as a distinct competitive force that helps determine the structural conditions of many industries. Among other things, government actions can: form a barrier to entry and sometimes even exit in an industry; affect the positions of substitutes vis-à-vis existing firms; affect rivalry among existing competitors; and affect the relative positions of an industry's suppliers and buyers (government can even be a supplier or a buyer itself).

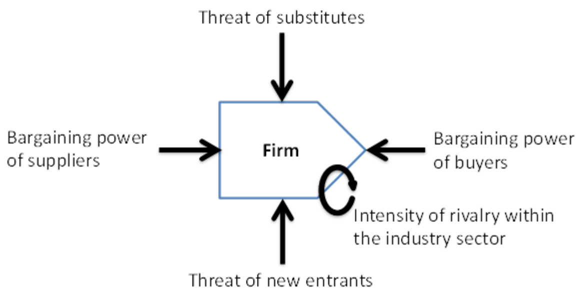

Figure 2: Porter's five forces

From these five forces, an interesting visualization can be created of the value chain of an industrial sector in its competitive strategy context. Simply by replicating Figure 2 enough times, both horizontally and vertically, it is possible to consider four of the five forces quite discretely, with vertical integration in an industry simple to map visually by clustering one or more supplier and/or customer chevrons into a single box (we will do this for the cases of wind power and photovoltaic power in section 3, below). By shading in the focal chevron of each step of the strategic value chain, it is further possible to emphasize the degree of market concentration of the firms in that step. Note that the degree of both vertical integration and market concentration in an industry has important implications for the innovativeness of the firms involved, following a chain of literature that originated with Schumpeter (1942).

In Figure 3, we illustrate, through four cartoon examples, how the market power of focal firms and the firms tied to them through the five forces can affect the incentives to innovate across a given technology's value chain. In this figure, the central chevron represents the focal firm in a specific value chain, with suppliers represented by the chevron to the left of that chevron, customers represented by the chevron to the right of that chevron, possible producers of substitute products in the chevron above that chevron, and possible new entrants into the industry in the chevron below the focal chevron. The shaded chevrons have market power in their respective industries. Whenever a dark chevron meets a bright chevron, the dark chevron has differentially stronger market power, potentially resulting in distorted prices, limited offerings of products to customers, etc.

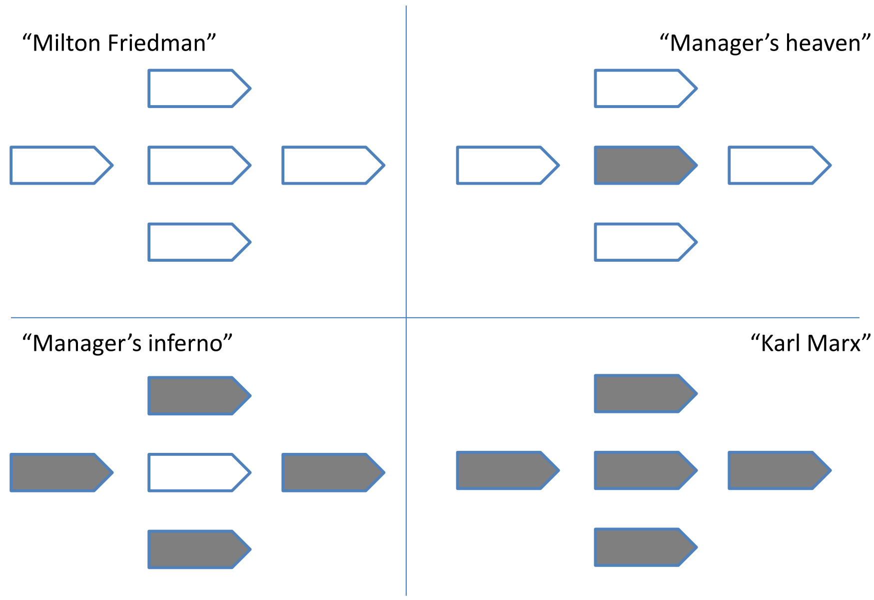

Figure 3: Illustrations of how competitive rivalry can play out across value chains

The “*Milton Friedman*” situation represents completely perfect market conditions, in which high rivalry exists in every chevron. In this extreme, both suppliers and customers have little bargaining power, while the threat of new entrants and substitute products is in equilibrium. In all the chevrons in this situation, firms have low profit margins and little potential to build up slack resources (Clarke and Davies 1982). Slack, however, is needed to engage in innovative processes (Cyert and March 2005), as innovation involves investing in projects whose outcome is uncertain and which might fail (Scherer and Harhoff 2000), so this could be considered a low-innovation situation.

The “*Karl Marx*” situation represents completely imperfect market conditions in which rivalry is non-existent. The most likely real-world scenario for this is one in which only state owned monopolies exist. In this situation, substitutes and new entrants are regulated by central planning authorities and customers and suppliers have no bargaining power because prices and quantities are fixed. In this scenario, innovation depends on government planning.

The “*Manager’s heaven*” situation represents completely differential market power between the focal firm and its suppliers, customers, potential substitutes and new entrants. In this situation, the focal firm has strong market power and the others each have weak market power. The bargaining power of the focal firm is consequently extremely high, while there is little threat of new entrants and/or substitutes. In this extreme, the focal firm is likely to focus on entrenching its position and rent seeking, with little incentive to innovate other than to establish planned obsolescence for the firm’s own products.

The “*Manger’s inferno*” situation represents completely differential market power between the focal firm and its suppliers, customers, potential substitutes and new entrants. In this situation, the focal firm has weak market power and the other firms each have strong market power. With the focal firm dominated by other firms in this way, there would be low incentives for the firm to take the risks of innovation and devote scarce resources to it.

This exercise illustrates how the background incentives for innovation can be worked through by policy-makers through a simple focus on the market power of emitting firms in their strategic context. In the next sub-section, we focus on the electricity sector, specifically.

The electricity sector

In the climate policy arena, the main type of firm that emits CO_2 is utility companies that generate electricity through the combustion of fossil fuels, with that electricity crucial to economic growth and quality of life, as well as the potential decarbonization of other sectors of the economy (note that global trends towards electrification are pressuring utility companies to invest in new capacity). The importance of reliable electricity to a nation's prosperity and security, and the distance limits to electricity transmission beyond a regional scale, has long contributed to making a nation's utility companies politically influential. The primacy of reliability as a defining attribute of electricity has also helped shape fairly conservative organizational cultures within utility companies, with these cultures not traditionally known for being highly innovative.

Figure 4, below, depicts our visualization of the power sector, with chevrons representing the major actors 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 supply chain. For more detail on the specific chevrons depicted in Figure 4, see

Appendix A.

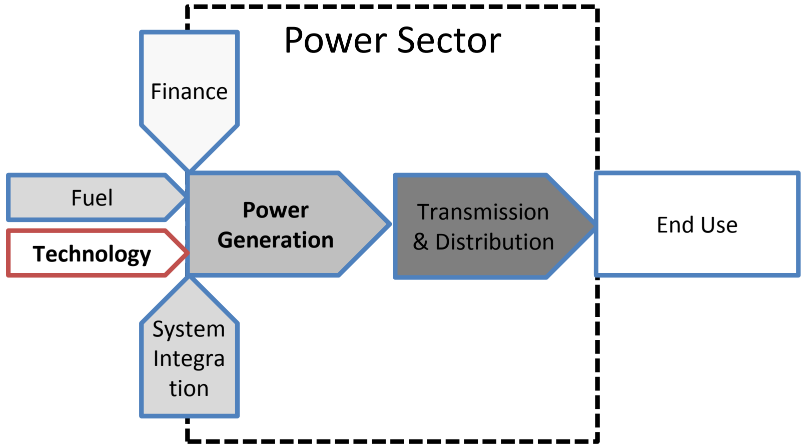

Figure 4: Conceptualizing the competitive environment in the electric power sector

In Figure 4, where one chevron touches another, a market transaction takes place, 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 low-carbon energy, such as renewables.

The different shades of grey in the figure represent the differential market power along the electricity sector supply chain, with darker shading representing stronger market power. The T&D chevron is darkest, as it represents a "natural monopoly." 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 is/was traditionally vertically integrated (i.e., one firm offering both power generation and T&D) and often publicly owned, although recent decades of privatization have changed this to a varying extent, depending on the nation and even the locality. Related to this situation of market power and its resulting innovation incentives, the technologies that are used by power generators and T&D operators 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" with respect to innovation (Pavitt 1984).

Note that in Figure 4, we deliberately do not shade the "technology" chevron because of the context-dependence of that chevron. In the next section of the paper, we will elaborate on two relevant technologies for decarbonization – wind power and photovoltaic power – using the visual language related to the five forces. At this preliminary stage of this paper, however, we have not yet shaded the relevant chevrons as our research on the market power of firms along the value chains of these technologies is not yet complete.

3. High Cost Technologies: Wind Power and PV Power

In this section, we consider the actors engaged in the value chains for wind power and solar photovoltaic (PV) power, two options for the "technology" chevron in the electricity sector illustration in Figure 4. Although these technologies are included as "high-cost" abatement technologies on the MAC curve, they are the most developed electricity sector generation technologies to use resource inputs that are near-zero emitting and widely distributed.[8] Today's wind and PV power generation 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.[9] In many nations, wind and PV power have received considerable public financial support to reach their current levels of cost, performance, and global diffusion. As mentioned above, economists who are willing to make space for more policy interventions beyond full social cost accounting see these technologies as candidates for correcting the "innovation market failure" through public R&D expenditures, rather than through some of the policy instruments that have supported their more recent development (e.g., renewable portfolio standards, feed-in-tariffs, etc.).

By mapping the value chains of these two technologies using the graphical language introduced above, with some modification, we can get a better sense of why the R&D policy instrument is likely to be inadequate in improving the costs and/or performance of these technologies, which is the unstated goal of correcting the innovation market failure in these technologies. The main modification we incorporate into our visualization here is that we introduce a way to think about vertical integration that required some re-thinking of our graphical approach to depicting market concentration. In this section, actors that are relevant to understanding the incentives to innovate in wind and PV power are represented by small colored boxes, with the colors identifying relevant types of actor. If a given actor typically 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. To be able to see this, we stopped shading the chevrons in the maps of the value chains for wind and PV power, and instead represented the level of competition associated with a given chevron by the number of boxes in that chevron. In this section, chevrons with more boxes have more competition and less market concentration.

Before proceeding with the visual mapping of the wind and PV value chains, however, it is helpful to provide some context on wind and PV power technology and trends.

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[8] 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.

[9] 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.

Trends in Wind and PV Power Technology

Figure 5 shows the broad trend in global wind turbine prices (Figure 5a) and PV module average selling prices (Figure 5b) 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.

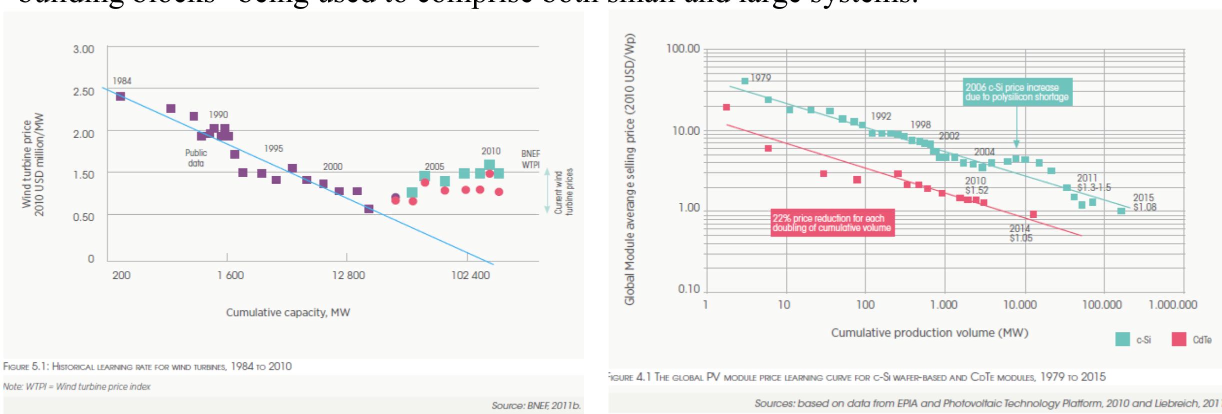

Figure 5: (a) The trend in global wind turbine prices graphed against the cumulative capacity of MW of electricity generated by wind turbines, with key dates highlighted. (b) The trend in global PV module average prices graphed against the cumulative production volume of modules, given according to MW and decomposed between crystal-silicon and cadmium telluride. Key dates are also highlighted in this figure. (IRENA 2013; IRENA 2013)

Wind power and PV power differ in many ways. As we will discuss, 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.[10] 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) scales in use (e.g., PV power is very modular, with even large plants rather small compared to conventional power generation technologies); and (e) 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 &

[10] 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.

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.

For more detail on wind and PV power technology, please see Appendix B and C.

Mapping the value chain of wind power

Here we briefly sketch some of the attributes of the major actors in wind power, as illustrated in Figure 6, below. For definitions of specific technologies, see Appendix B

(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, soel 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 balance-of-plant (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 electricity sector 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. [11] For wind farm

[11] 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.

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.

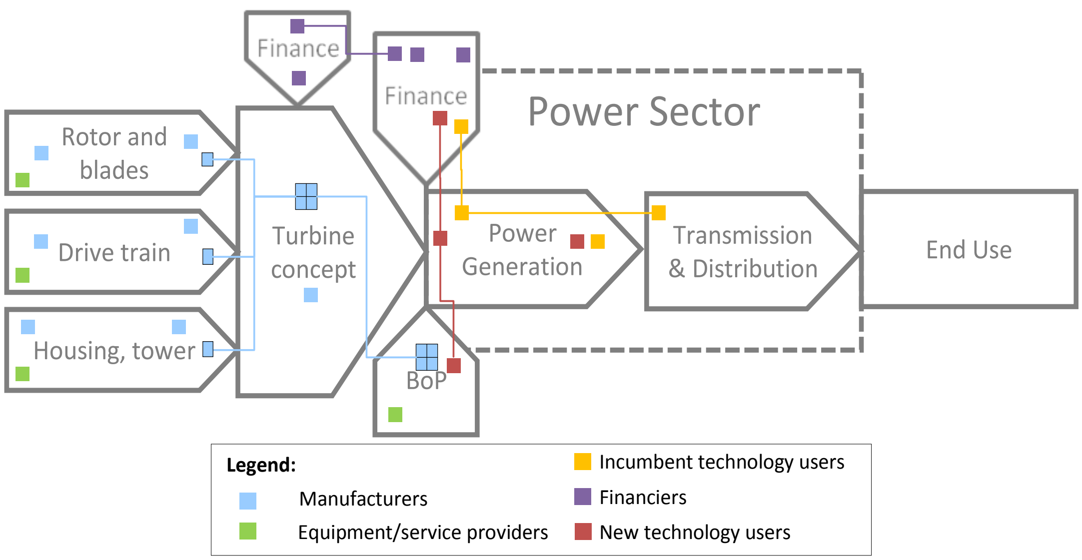

Figure 6: Actor level of the wind power value chain

Mapping the value chain of PV power

Here we briefly sketch some of the attributes of the major actors in PV power, as illustrated in Figure 7, below. For definitions of specific technologies, see Appendix C

(1) Manufacturers: The manufacturers of crystal-silicon PV are often highly vertically integrated.[12] 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). Balance

[12] 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.

of Plant (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 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.

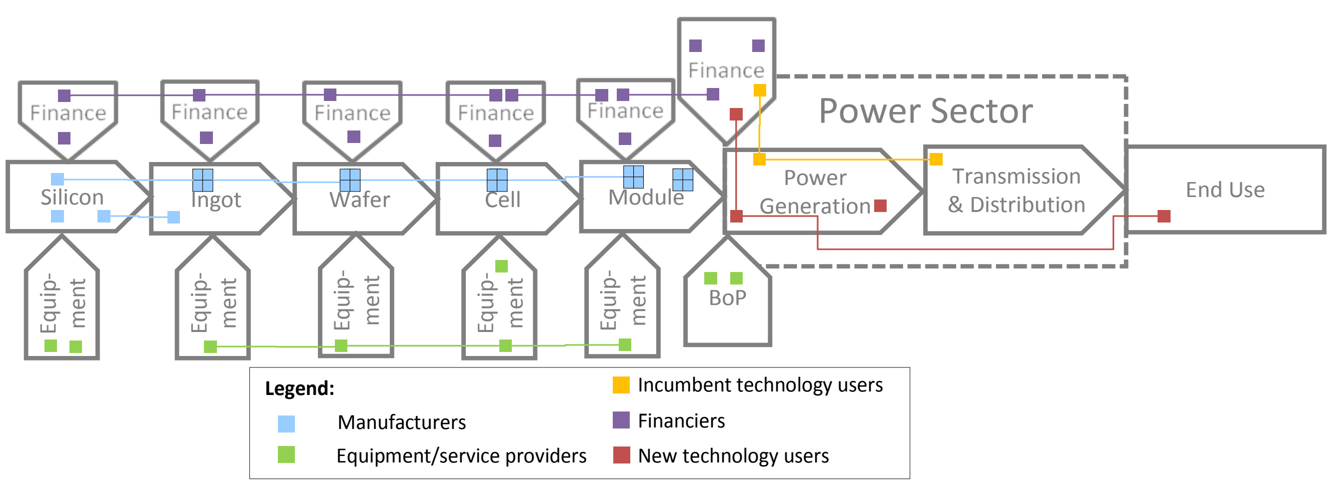

Figure 7: Actor level of the PV power supply chain

Considering the role of public R&D expenditures

We begin by noting that vertical integration is common in both the wind and PV power technology value chains. This is likely to play an important role in determining the likelihood of new entry in these value chains, based on specialization in specific components and/or manufacturing equipment. Vertical integration, of course, is also very important to innovation, as it affects not only the "make or buy" decision, but the overall absorptive capacity of the firm.

Figure 8 represents our attempt to depict the likely effects of public R&D expenditures on wind power and PV power in the current context of the electric power sector. One thing to note up-front is that the design of public R&D expenditure instrument matters to its effects, and is not a one-size-fits-all approach to counteracting the innovation market failure. In this figure, we considered a straight R&D subsidy as well as a related subsidy in the form of loan guarantees. For the loan guarantees, we depicted the instrument as having a primary effect on the turbine concept, and a lesser effect on the components and integrative architecture of the turbine concept. It is a bit unclear how the turbine concept is in need of a public boost to counteract a disincentive to innovate due to imperfect appropriability, as turbines are more typically considered process technologies, which are easier to maintain control over, particularly in conditions of vertical integration as we see exhibited today. In addition, the turbine concept has basically reached a dominant design (see Appendix B) with respect to generation, so loan guarantees might only be helpful in supporting some feature of a wind turbine system, such as its integration with storage and/or the grid.

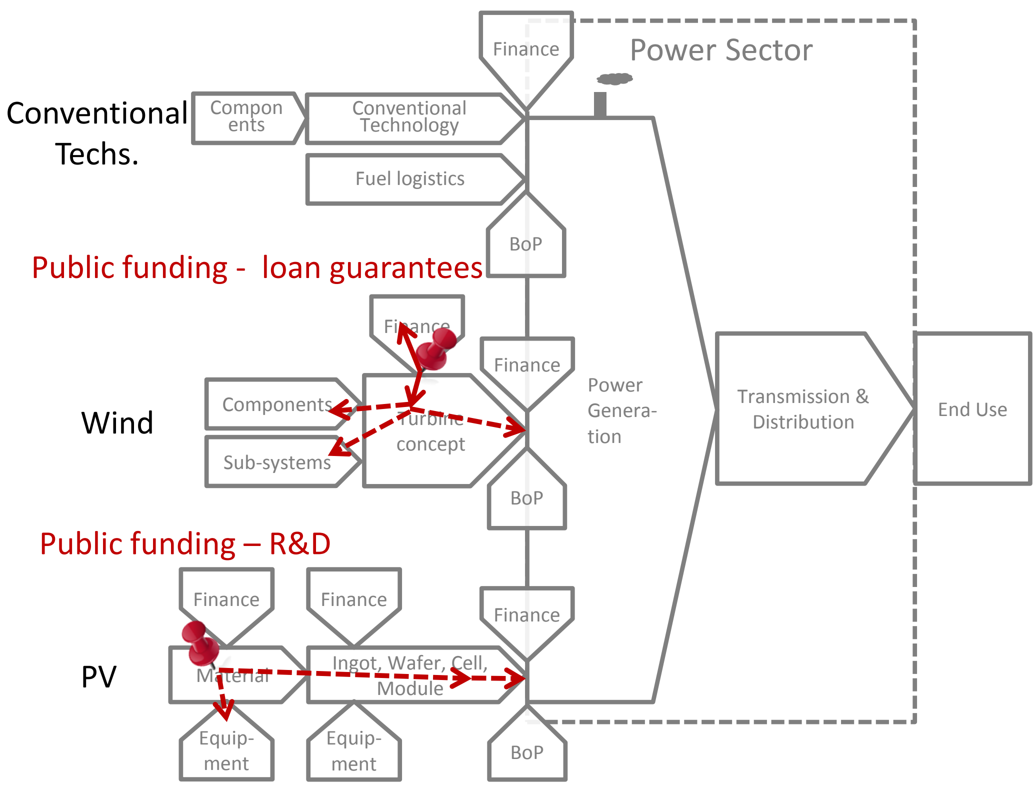

Figure 8: Graphic depiction of the likely effects of public R&D expenditures on wind and PV power technology as part of the electricity sector

For PV power, we depicted a more traditional public R&D subsidy, given the ongoing laboratory-scale research being conducted on alternative chemistries. But again, it is difficult to consider that this form of policy intervention is really responding to a condition of imperfect appropriability by firms, in part because of the dominance of China as a manufacturer of PV modules due to its lower costs.

4. Reflections

Environmental economics typically assumes perfect market conditions when calculating the MAC curve and deriving policy interventions. However, as argued above, such conditions are typically not present in high emitting sectors, their suppliers and/or their buyers. This has (at least) two important implications. First, the MAC curves (often calculated by consultants) might be quite inaccurate, as market power allows for strategic pricing. Carbon pricing regimes based on MAC curve assumptions might therefore be less efficient. Second, if emitting incumbent firms have high market power and their incentive to innovate is low (e.g., due to the lack of threats from new entrants or substitutes), the effect of policy on innovation and adoption of new technologies is limited.

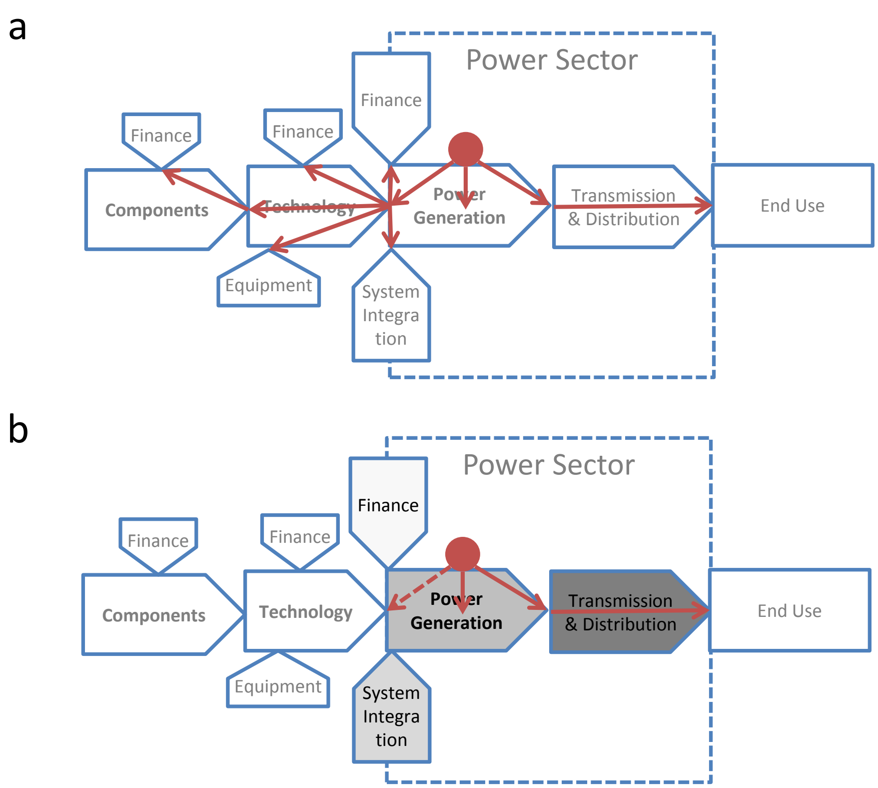

Figure 9: Effects of a carbon price under perfect (9a) and imperfect competition (9b)

Assuming perfect market conditions, a carbon price directly affecting all emitting firms – in our example of the power sector this would be the power generators (see Figure 4) – would be passed on to all firms (and households) along the value chain, up- and down-stream. The new cost factor would lead to relative changes in the electricity price, which could result in reduced demand or consumers switching to less carbon-intensive (and hence less affected) power generators. This again would provide an incentive for power generators to adopt new, less carbon intensive technologies and so forth. In sum, a carbon price would alter the equilibria along all markets found along the value chain. Thereby, actors along the entire value chain would be (at least indirectly) affected, resulting in changes of their innovation and adoption behavior. However, note that innovation effects would be rather marginal, due to the lack of slack – a precondition for innovation.

This latter notion is, however, not really relevant, as most carbon emissions-related value chains are far from perfect market conditions, anyway. Under non-perfect conditions, slack can be generated. Yet, whether this slack is invested in low-carbon innovation and adoption depends on policy. Importantly, policy effects will not be passed along the entire value chain. High market power (i.e., strong differences in firm concentration) can act as a reducing or even blocking element for the indirect effects of a policy instrument. For instance, if the market concentration of power generators is much higher than that of their customers (compare Figure 9b), they can simply pass through a carbon price to the customers instead of adopting new technologies (and thereby spurring innovation upstream in the value chain). More generally speaking, how the market power is distributed over the value chain strongly affects the effect of a policy which just targets one part of the value chain.

To counteract the blocking effects policy can introduce additional instruments, depending on the market concentration patterns, policy makers can decide where to intervene and how. But this is not an easy task: policy makers need to think about entire value chain and introduce policies whenever the effects do not reach other value chain steps. Consultants in the climate policy arena (who have, due to the Kyoto Protocol, thus far mostly focused on MAC curves and carbon-price related advice) should assist policy makers in this task.

If policy is designed accordingly, it can – by inducing technological change – even change market concentration: The German feed-in tariff (FiT) for PV power is one example. One important motivation for the main political advocates for the FiT was the breaking market power of power generators over consumers. In Germany, the market power of power generators was very high (up- and downstream). Historically, these were fully integrated firms, often owning and exploiting their own coal/lignite mines as well as operating transmission grids, and distribution networks. The Fit actually aimed at bypassing the power generators, by providing performance-based subsidies to house owners that installed PV modules on their roof top: the consumers of power would become their own power producers (also called prosumers). Hermann Scheer, a member of the Bundestag (the German parliament) for the social democrats and one of the most important proponents of the German Energiewende and the FiT postulated: "[To achieve a massive decarbonization of or society], We have no other choice than breaking the structural power of the existing energy system (…)" (Scheer 2005). A look at the recent decline in market shares and market capitalization of the large German utilities shows how the policy mix underlying the Energiewende (whose central instrument is the FiT) resulted in a drastic reduction of the market power of the (large) German utilities.

It is interesting to note is that the FiT is not alone in having this market concentration focus: many renewable energy-oriented policy instruments, including renewable portfolio standards, production tax credits, investment tax credits, feed-in-tariffs, and net metering, all have major historical and theoretical bases in counteracting the market failure of imperfect competition (see, for example, the investment tax credits and production tax credits that emerged from 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).

Our work on this project is not complete, but we hope that this paper will give you a sense of why we think it is important to shift the climate policy focus toward a framework that makes room for the market failure of imperfect competition, as well as those of negative externalities, imperfect appropriability conditions, and transaction costs. More importantly, why we think it is important that the one-to-one market imperfection to intervention concept is unhelpful, given the interaction, at the very least, between imperfect competition and counteracting negative externalities.

In the next steps of this project, we will be adding the focus on negative abatement cost technologies discussed in the introduction to the paper, as well as consolidating the visual language developed in sections 2 and 3 above. We welcome any comments that could help us improve our research.

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Appendix A: More Detail on the Depiction of the Electricity Sector in Figure 4

Here we define the chevrons in Figure 4 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.

Appendix B: More detail on Wind Power Technology and the value chain in Figure 6

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 5 through a combination of private and public forces that drove the technology in specific directions.[13] The primary direction of innovation has been toward increasing the amount of energy (kWh) that can be harvested through the technology. As Figure 10 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.

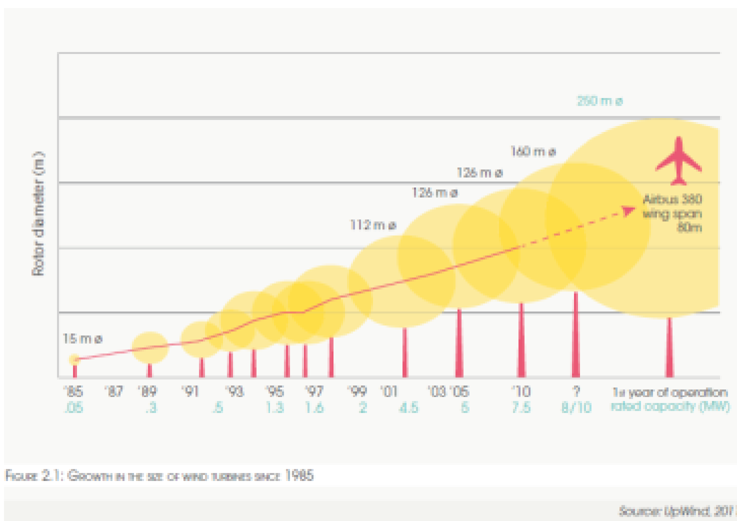

Figure 10: Growth of turbine size over time

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.[14] 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

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

[14] 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).

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 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.

More detail on Figure 6

Here we define the wind power chevrons in Figure 6 in more detail. Note that we do not define the rectangle of end use here, as it was defined above for the electricity sector.

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.

Appendix C: More detail on PV Technology and the PV Power value chain in Figure 7

Characteristics of PV 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 5, 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).[15]

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.

More detail on Figure 7

Here we define the PV power chevrons in Figure 7 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.

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

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.