3rd International Conference

on Public Policy (ICPP3)

June 28-30, 2017 – Singapore

Panel T16P22 Sustainable Development and Policy

P22 Industrial Development as Pathway for Achieving SDG 9: Retention and Deployment of 'Policy Space' in the Industrial Aspirant Countries (IACs) of Global South

Title of the paper

Greening industrialization: Understanding how a technology's product architecture and use environment affect local low-carbon industry development

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Date of presentation

June 29, 2017

Abstract

In many Industrial Aspirant Countries, policymakers aim to create a local industry around low-carbon technologies. In this paper, we draw from literatures on catching-up and technology lifecycles to explore how localization potential varies across technologies and countries. Using the cases of wind and biopower energy techologies, we show how the adaptation of these technologies to a new use environment can spur modular innovations at different levels in each technology’s product architecture. We propose that these modular innovations, because they require less cumulative knowledge than other types of innovation, can create opportunities for latecomer firms.

Key words: local learning, industry policy, product architecture, catching-up, technology lifecycle, wind, biopower

1 Introduction

With the falling costs of low-carbon energy technologies and the growing global momentum for their deployment, policymakers increasingly view clean energy policy not solely as a means of meeting national emissions reduction targets under the Paris Agreement, but also as an economic opportunity. In many countries – from those seeking to create jobs, to fossil fuel exporters looking to diversify their economy, to those anticipating a shift to a clean technology-driven economy – industry policy is being packaged into energy policy (Rodrik 2014). This coupling is evident in the widespread use of local content requirements (LCRs), or provisions mandating locally-sourced good or services, in clean energy deployment policies. While LCRs were most commonly enacted in OECD countries (e.g., Spain, France) and major emerging economies (e.g., Brazil, China and India), they are increasingly applied in other developing and emerging economies, despite limited understanding of their effectiveness (OECD 2015). As these green industrial policies could be key both for laying the foundation for more sustainable growth and for creating political agency for a low-carbon transformation (Meckling et al. 2015), there is a need to better understand how to design them effectively. In particular, current policies that target industry localization often mandate LCRs on a suite of low-carbon technologies, without considering how localization potential may vary not only across geographies, but also across *technologies*.

The literature on catching-up of 'latecomer' firms such as those in emerging economies identifies domestic technological capabilities as necessary for successful industry localization (Bell & Figueiredo 2012). Technological capabilities refers to the resources – whether technical, organizational, or managerial – to not only utilize technologies, but also adapt, improve, or produce technologies (Morrison et al. 2008; Schmidt & Huenteler 2016). Typically, a distinction is made between *manufacturing capabilities*, or the ability to execute technology production processes, and *design capabilities*, or the ability to move from technology imitation to technology change and product development (Lall 1992; Schmidt & Huenteler 2016). In order to develop a competitive domestic industry around a certain technology, these capabilities need to be accumulated and augmented through a dedicated and purposeful process of learning (Bell & Figueiredo 2012).

The relevant capabilities and learning mechanisms are, however, different across technologies. Most of the literature on catching-up has focused on how industry development for technologies at different stages of maturity necessitate different technological capabilities and resources (e.g., Surana & Anadon 2015; Hansen & Ockwell 2014; Karltorp 2015). Only recently has research linked technological capabilities for catching-up to other technology characteristics such as their complexity. By investigating these technology characteristics, Schmidt & Huenteler (2016) built a typology of low-carbon technologies according to their design- and manufacturing- intensity, and the types of capabilities and learning mechanisms required for their localization. In particular, they proposed that localizing an industry around design-intensive, or complex, low-carbon technologies requires building up innovation capabilities through experimentation in tweaking technologies to meet user needs and use environments. Fostering this learning mechanism, known as learning-by-using[1], necessitates user-producer interactions and iterative cycles of product innovation (Rosenberg 1982; Nahuis et al. 2012). As a result, the authors hypothesized that persistent low-carbon technology deployment policies, which create domestic markets for experimentation, are necessary for building competitive industries around these complex technologies (Schmidt & Huenteler 2016).

While this typology offers an important starting point for understanding which technologies and shares of their value chain can realistically be localized, we argue that it can be further developed in two ways. Firstly, the required technological capabilities and local learning

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[1] We understand learning-by-using to involve the feedback from experience in utilization of a technology into the development and improvement of subsequent technology models (Rosenberg 1982).

potential will also depend on the *type of innovation* (further explained in section 2.1) needed to adapt the technology to its use environment. Secondly, the authors group complex technologies into a single category; however, technologies will lie along a *spectrum* of technological complexity (Binz et al. 2017). The degree of complexity in a technology's *product architecture* – which defines both the subsystems and components of a technology as well as how they interact – entails different entry barriers and capabilities for latecomer firms seeking to localize component manufacturing.

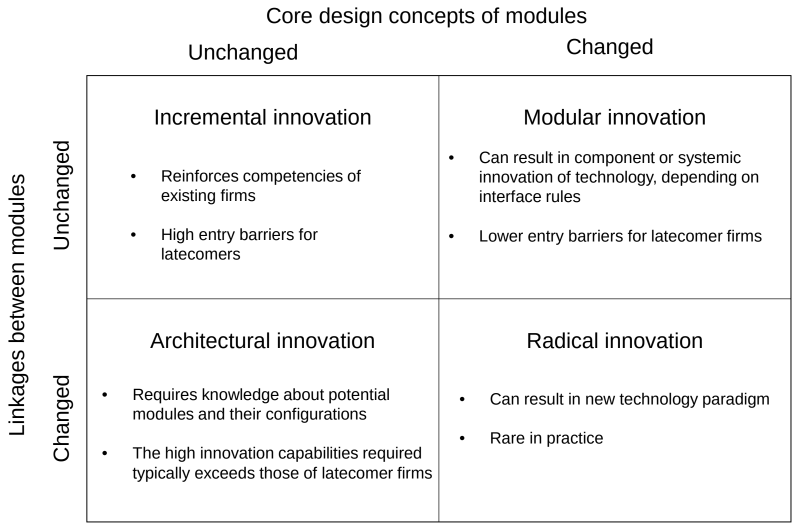
In this paper, we explore how a technology's use environment and product architecture influences opportunities for local learning and industry activity. After a theoretical overview of complex technologies and their innovation patterns and the role of use environment as a creator of opportunities for technological innovation (section 2), we present the research cases and methodology in section 3. Results and preliminary propositions are presented in section 4. Finally, we conclude with an outlook of future research and next steps for the study.

2 Theory

2.1 Types of innovation and technological capabilities

In this paper, we conceptualize technologies as systems composed of various subsystems and components that are linked together to perform certain desired functions (Tushman & Rosenkopf 1992). In taking this systems perspective of technology, it is useful to organize a technology according to its *modules* and its *product architecture* (Henderson & Clark 1990). Modules are physically distinct parts of a technology system that can be designed and produced independently (Baldwin & Clark 2004). These modules can be individual components, entire subsystems, or assemblies within subsystems. The product architecture defines how these modules are integrated (i.e. their interfaces).

Using this distinction between modules[2] and product architecture, Henderson & Clark (1990) classified four types of innovation according to whether it impacted the design of specific modules or their interaction (see Figure 1). On one end of the spectrum lies *radical innovation*, or innovation which changes both the core design of modules as well as their linkages. This type of innovation is akin to the "waves of creative destruction" envisioned by Schumpeter (1934). However, in practice, radical innovation is quite rare. The other extreme is *incremental innovation*, or the incremental refinement of an existing design, resulting in technological trajectories (Dosi 1982). Incremental innovation tends to enhance the competencies of existing firms (i.e. knowledge is cumulative), making the successful entry of latecomer firms difficult (Tushman & Rosenkopf 1992).



Linkages between modules	Core design concepts of modules: Unchanged	Core design concepts of modules: Changed
Unchanged	Incremental innovation • Reinforces competencies of existing firms • High entry barriers for latecomers	Modular innovation • Can result in component or systemic innovation of technology, depending on interface rules • Lower entry barriers for latecomer firms
Changed	Architectural innovation • Requires knowledge about potential modules and their configurations • The high innovation capabilities required typically exceeds those of latecomer firms	Radical innovation • Can result in new technology paradigm • Rare in practice

Figure 1: Four types of innovation, adapted from Henderson & Clark (1990)

In contrast to competency-reinforcing incremental innovations, *architectural* and *modular* innovations arise when firms acquire competencies outside the existing engineering or scientific paradigm underlying a product. Depending on whether a new or incumbent firm develops these competencies, architectural and modular innovations can either strengthen a firm's position, or

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[2] Henderson & Clark (1990) use the terms *subsystems* and *components* as the building blocks of a complex technology system. However, in this paper, we adopt Baldwin & Clark's (2004) term, *module*.

lead to its obsolescence (Tushman & Anderson 1986; Gatignon et al. 2002). *Architectural innovation* occurs when the integration and relationships between components changes without changing the core design of individual modules (Henderson & Clark 1990). While architectural innovation can, to some extent, build on a firm's previous knowledge, managing the innovation process is difficult. By definition, architectural innovation requires knowledge about possible module configurations, which in turn necessitates knowledge about individual modules themselves – both existing modules and potential alternatives[3]. Consequently, high innovation capabilities are needed to manage this process. Experimentation with new product architectures is also costly and risky, as demand for the resulting product is not guaranteed (Davies 1997). Therefore, the technological capabilities and resources required for successful architectural innovation often exceeds those available in latecomer firms in emerging economies.

Architectural innovation of *complex technologies* is particularly challenging. While we do not attempt a formal definition of technological complexity, we generally regard complex technologies as those featuring a large number of modules that interact at multiple subsystem levels and a high degree of customization (Davies 1997; Simon 1962). Given the uncertainty and large number of degrees of freedom associated with the design of complex technologies, continued experimentation with product architecture often hinders the ability of a firm to exploit economies of scale or other positive feedbacks (Arthur 1989). The lifecycle of a complex technology is therefore characterized by an early stage of experimentation with different product architectures; however, this so-called "era of ferment" is eventually ended with the emergence of a dominant product architecture (Davies 1997). After this emergence, the locus of innovation shifts towards product innovations at the subsystem and module level (Clark 1985; Murmann & Frenken 2006).

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[3] Note that architectural innovation does not require that *no* changes are made to modules, just that the *core design* of modules is unchanged.

Product innovation at these lower hierarchy levels can also be a *modular innovation* if it entails a change in the core design of a module (Henderson & Clark 1990). A modular innovation can be standalone, or can require complementary modular innovations, or can even spur another architectural innovation. The extent of the "disruptiveness" of such a modular innovation on the technology as a whole depends on how well the interfaces between it and the remaining system are defined. When these interfaces are well defined, for example by formal industry standards or more informal design rules, the design of different modules can occur in parallel by independent entities (Baldwin & Clark 2004). As long as a firm follows these interface rules, its modular innovation will be compatible with the overall technology system. Thus, entry barriers for latecomer firms are lowered, as firms require innovation and production capabilities for a single module – rather than the entire technology system. In this case, a modular innovation at lower levels of the hierarchy often results in an incremental innovation at the system level. In this paper, we refer to this type of modular innovation as a *component modular innovation* (Davies 1997).

In the absence of these well-defined interfaces, a change in the core design of a module can result in a *systemic modular innovation* (Davies 1997). This type of modular innovation is triggered when modules are interdependent and changing the design of one module necessitates a change in one or more other modules. Successful systemic modular innovation requires coordination and interaction, particularly if modules are produced by separate entities (Davies 1997). This requirement entails three implications for industry structure and latecomer firms. Firstly, due to greater tacitness of knowledge involved, latecomer firms typically need greater innovation capabilities (Polanyi 1958). Secondly, the coordination required for systemic innovation can involve the sharing of knowledge of a firm's core competency (Davies 1997). Consequently, an existing firm may be reluctant to transfer such knowledge to other firms – particularly if the manufacturing capabilities required to produce the interdependent module are low. Finally, due to both of these factors, technologies requiring systemic innovation are more conductive to being produced by vertically integrated entities (Murmann & Frenken 2006).

2.2 Use environment as a creator of opportunities for technological innovation

In the previous section, we reviewed types of innovation, without yet specifying why such innovations may be necessary. As stated previously, complex technologies allow a high degree of customization. Thus, complex technologies are essentially unfinished as they enter a new use environment (Rosenberg 1982; Nahuis et al. 2012). Successful innovation therefore results from an iterative process of adapting technologies to the needs of different users (Murmann & Frenken 2006; Lundvall 1988). Due to the prominent role of feedback from a use environment in shaping technological change, application of a complex technology in a new domain may create opportunities for local learning and industry activity (Levinthal 1998; Windrum & Birchenhall 1998; von Hippel 1994).

When a complex technology is introduced in a new use environment, several factors may influence its form. Firstly, certain adaptations may be needed to ensure a technology reaches a minimum threshold of *functionality* (Levinthal 1998) (i.e. it can fulfil its operational purpose). Secondly, complex technologies, due to their high customizability, can fulfil multiple dimensions of merit (e.g., cost, safety, convenience etc.) (Tushman & Rosenkopf 1992). These dimensions of merit may vary across use environments, for example due to a different weighting of *user preferences,* resulting in a different set of technology selection criteria across markets (Levinthal 1998). In addition to different user preferences, context-specific socio-political factors that further constrain dimensions of merit can also play a role in technology selection (Tushman & Rosenkopf 1992). These factors include regulations or standards imposed by public policies. While these factors may create an opportunity for technological innovation, whether this opportunity will be tapped depends on the *resources* available in the new domain (Levinthal 1998). In the context of industry localization, these resource factors include the availability of local technological capabilities and the volume of the market. Volume is important both to justify investments in innovation or local capability-building as well as to foster sufficient opportunities for learning-by-using (Mowery & Rosenberg 1982).

In sum, a new use environment may create impetus for technological innovation in a complex technology (see (a) in Figure 2)). The type of innovation and resulting opportunity for local innovative activity will, however, depend on the specific characteristics of the technology (i.e. its product architecture) (b). Whether a local industry can emerge from this opportunity (c) will be moderated by the resources available to the new domain (d). This preliminary research framework is shown in Figure 2. In this paper, we focus on the relationship between use environment, technology characteristics and opportunities for technological innovation. While we do touch upon resource aspects and implications for localization, these aspects will be studied more in-depth in future research (see section 5).

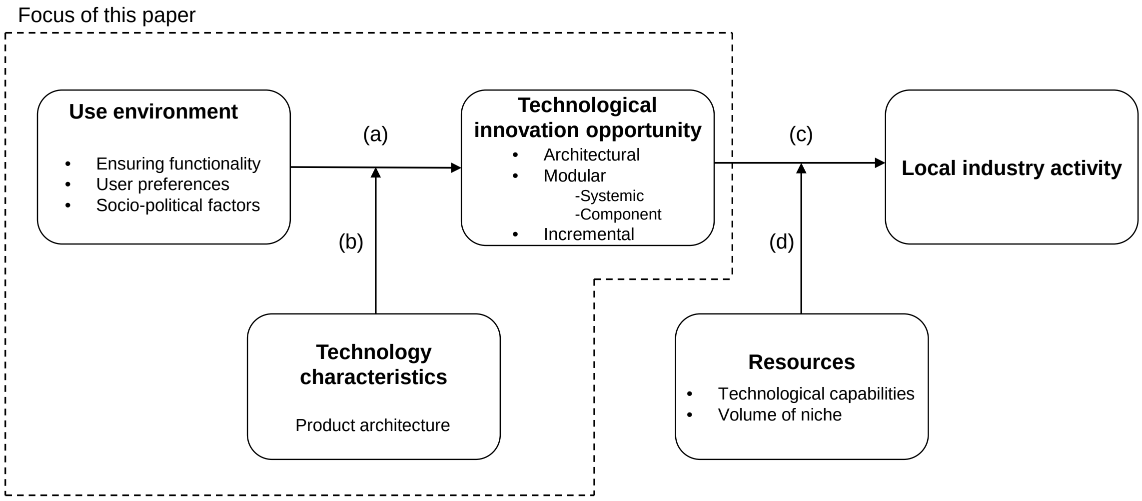

Figure 2: Preliminary research framework

3 Research cases and methods

3.1 Research cases

Wind and biomass for power generation, herein referred to as biopower, were chosen as the research cases for four theoretical reasons. Firstly, both technologies can be considered complex technologies with a product architecture arranged in a nested hierarchy and module interactions at multiple levels of this hierarchy. Due to this structure, certain modules will be more core, requiring complementary changes in other subsystems, while others will be more peripheral. Whether a core or peripheral systems requires adaptation to new use environments will impact both the nature of the opportunity created as well as the technological capabilities required to exploit this opportunity (Tushman & Murmann 1998). Secondly, both technologies are deployed specifically for power generation applications. This specificity limits the typical dimensions of merit and has deterred radical speciation of the technologies. As a result, both wind and biopower have established a dominant product architecture, which allows us to examine the impact of use environment on a stable set of modules. Thirdly, as power generation technologies, socio-political dimensions of merit may exert a greater influence on technological change, given the high degree of regulation in the power sector (Gillingham & Sweeney 2012). Finally, these technologies have already diffused sufficiently in different use environments. While their general product architectures have remained stable across use environments, we can observe a degree of speciation for each technology (Lema et al. 2016; Junginger et al. 2006).

These technologies were also chosen for several practical reasons. Wind and biopower are often targeted in national low-carbon energy technology deployment policies (e.g., feed-in-tariffs). While these technologies originally diffused in European and North American markets – and more recently India, China and Brazil – only in recent years have these technologies been deployed in middle and lower- income countries (REN21 2016). Consequently, the influence of these new use environments on the technologies is not yet well studied. Additionally, several countries have enacted national deployment policies targeting the localization of a wind and/or biopower industry (Lewis & Wiser 2007; UNCTAD 2014).

To define the boundary of our analysis, we delineate wind and biopower technologies according to their operating principle (Murmann & Frenken 2006). A brief description of each technology and its operation principle is provided section 3.1.1 and 3.1.2 to aid in later understanding the results.

3.1.1 Wind

A wind turbine converts the kinetic energy of the wind to electrical energy. In this paper, we focus on one particular operational principle, described below, as it dominates most modern turbines today. The modern wind turbine consists of a product architecture comprising a rotor, power train, mounting and encapsulation, and grid connection (Huenteler, Ossenbrink, et al. 2016). This design captures the kinetic energy of the wind using three blades rotating about a horizontal axis (rotor). Most turbines are upwind machines (i.e. the rotor faces the wind); to fully utilize the energy from the wind, the rotor must be yawed so it continuously faces the wind, and pitched to provide an optimum angle for the blades to rotate (Hau 2015). This rotational energy is converted to electrical energy via the power train, which includes both a mechanical power train that transfers the rotational energy from the rotor to the generator, and an electrical power train that ultimately produces AC power (Hemami 2012). These drive train components are housed in a nacelle, which is mounted on a tower. Towers can range from about 40 meters to over 100 meters in height and are structurally supported by a foundation. Finally, electricity produced by the turbine is either stored or fed into the electric grid.

The design of wind turbines is complex due to the large number of components and the complexity of their interaction, and requires high levels of tacit knowledge built up through learning-by-using processes (Garud & Karnøe 2003; Andersen 2004). As a result, the wind industry is highly vertically integrated and concentrated, with only five original equipment manufacturers (OEMs) accounting for nearly 50% of new installations in 2015 (BTM 2015). While the major OEMs originated in Europe, Chinese and Indian OEMs also currently represent a significant share of the global market, however mostly through domestic deployment.

3.1.2 Biopower

Biopower involves the conversion of biomass feedstocks into electrical energy. While this definition encompasses several processes and conversion pathways, in this paper we focus on the thermal-chemical conversion of solid biomass (i.e. combustion) to generate steam, which is used in a steam cycle to produce electricity. We focus on this process as it exhibits higher complexity of interaction between components than bio-chemical processes (i.e. anaerobic digestion to produce biogas) and is the dominant biopower technology (van Loo & Koppejan 2008). These thermal-chemical plants typically consist of an architecture that includes a fuel handling system, fuel combustion, a power generation system, pollution control and grid connection. Biomass feedstocks, which includes waste streams such as residues from the forestry, pulp and paper, and agricultural industries, are transported from the point of fuel delivery or storage to the combustion system, or boiler, via a fuel feeding system. The feedstock is combusted in the boiler, releasing energy in the form of heat (Nussbaumer 2003). The combustion process itself involves a series of complex physical and chemical processes that are sensitive to fuel properties and the choice of combustion technology. The heat released from combustion is transferred to a working fluid to produce high pressure and high temperature steam for use in a (closed) steam cycle. Power generation in a steam cycle is quite mature, and is deployed in other thermal power plants such as coal fired power plants. The most common pathway for energy conversion in a steam cycle is via a Rankine cycle (IRENA 2012), which expands steam in a steam turbine, converting steam energy into mechanical (shaft) power. This shaft power is subsequently converted to electrical power using an electrical drive train, and is utilized for self-consumption or fed into the electric grid. Finally, the combustion of biomass produces pollutants and ash, which need to be treated or handled appropriately.

Unlike the wind industry, biopower is less vertically integrated and less concentrated. While some companies provide technology and/or services at multiple levels of the hierarchy, more commonly technology suppliers are horizontally integrated, and offer multiple technology options for the same level of the value chain. Additionally, lead suppliers of biopower components are usually diversified in other business activities (e.g., pulp and paper industries, other power generation technologies), rather than specialized in solely biopower.

3.2 Methods

In this paper, we use qualitative, case study methods to expand existing perspectives on the technology-specificity of industry localization patterns (Eisenhardt 1989). Although some research studies have concluded that the build-up of technology-specific capabilities is important for industry localization (Schmidt & Huenteler 2016; Binz et al. 2017), little research has investigated the role of use environment in creating potential opportunities for local learning. Furthermore, these studies were conducted at the technology system level; in practice, emerging economies will likely localize the production of technology modules – rather than the entire value chain. Deeper case study analyses of specific technologies can therefore provide greater insight regarding which parts of the value chain may realistically be localized.

Specifically, the methods proceeded in three steps. Firstly, we determined the product architecture of each technology. For wind, we largely built on the work by Huenteler, Schmidt, et al. (2016) and Huenteler, Ossenbrink, et al. (2016), which developed a product architecture for wind turbines. For biopower, we reviewed technical literature, including technical handbooks, industry magazines and publications, and academic literature, to develop a preliminary draft of the product architecture. This draft was then refined and verified through two in-person semi-structured interviews with technical experts on biomass combustion systems.

Secondly, once we had established a comprehensive understanding of the product architecture each technology, we conducted 17 semi-structured interviews with representatives from 15 companies working in the wind or biomass industry. Of these, 9 were conducted with representatives from the wind industry, and 8 were conducted with representatives from the biopower industry. For both technologies, we aimed to interview representatives from leading OEMs working across global markets as well as industry experts/consultants with both technical knowledge and knowledge of market dynamics. Additionally, for biopower, we interviewed representatives from engineering, procurement and construction (EPC) companies, as these companies often have an understanding of component and subsystem interactions in the biopower plant design as well as considerations for equipment procurement. An overview of the sample as of May 10, 2017 can be found in Table 1. As of this date, interviews were still on-going.

Table 1: Sample for industry interviews

Type of organization	Wind	Biopower	Total
Lead OEM / Technology supplier	7	4	11
Consultant / Industry expert	2	2	4
EPC	-	2	2
TOTAL	9	8	17

The aim of the interviews was to understand the type of innovation required in order to adapt wind or biopower technologies to different use environments, and the implications of these innovations on an OEM’s supply chain. Before each interview, we conducted desk research on the interviewee and their organization, and tailored interview questions to each interviewee. With the exception of one interview, all interviews were conducted in teams of at least two researchers, however the lead interviewer remained constant throughout the study.

Thirdly, two members of the research team each independently coded interview transcriptions according to the type of innovation required in a new use environment, the locus of technological change, the influencing factor of the use environment, and the type of capabilities required for this innovation. We used the software MAXQDA to assist with the coding and analysis.

4 Results

The results of the interviews confirmed that both wind and biopower are not standardized technologies; each requires adaptation to new markets. In section 4.1 we present how these changes may create opportunities for localization for each technology, as well the modes and conditions under which localization occurred. We synthesize these results in section 4.2 and present preliminary hypotheses.

4.1 Wind

4.1.1 Opportunities for technological innovation in response to change in use environment

As energy conversion technologies, wind turbines are sensitive to changes in their *energy input.* In the case of wind, energy input refers to the wind class, which defines the average wind speed, turbulence, and gusty wind speeds at a potential site. Wind turbines typically are designed in platforms, with each platform rated for certain loads and wind classes or regimes. The development of a new platform often entails an *architectural innovation*: although the core principles behind each module typically remain unchanged, new complexities in the interactions of modules arise. For example, longer-bladed turbines designed to capture wind in low wind speed sites faced new failure problems at their connection to the hub, introduced vibrations and mechanical loads on other turbine components, and resulted in greater tip deflection which risked blade interference with the tower. As all of these interactions cannot be predicted during the initial design of the platform, new turbine platforms are typically rolled out in actual wind sites, and undergo iterative *incremental innovations*. This process either encourages vertical integration, or requires close interaction of module designers and turbine OEMs, as one interviewee from a turbine OEM said of its interaction with component suppliers: “We work closely with them, where we share with them our experience or data and then they use that or incorporate that when they're doing the design. So in some sense it is them designing, showing it to us, we make tweaks, and things like that, and then we go back. It's a lot of to and fro, in that sense.” As the wind turbine industry has matured, wind classes have grown increasingly standardized. As a result, many turbine OEMs have developed a portfolio of turbine platforms able to meet most wind regimes worldwide.

In addition to energy input, other physical factors in the use environment can affect a turbine’s *functionality,* leading to further innovation at the module level. For example, turbines operating in cold climates outside of the standard rated temperature range often require de-icing systems that circulate hot-air through the blades to melt accumulated ice and to improve turbine uptimes in freezing conditions (systemic modular innovation). Similarly, turbines deployed in deserts need special blade coatings or sealants for the nacelle to protect against corrosive desert conditions and sandstorms (incremental innovation).

Beyond the physical use environment, turbine innovations may arise to meet specific *user preferences,* or relative prioritization of merit dimensions such as cost, reliability, or safety. For example, direct drive wind turbines, which eliminate the need for a gearbox – typically the component requiring the most maintenance and repairs over the turbine lifetime – are deployed when users prioritize higher turbine availability and reliability over the capital costs of turbine. In onshore applications, direct drive turbines are attractive to users who “like the assurance of not having a gearbox...they would be people who have excess capital who bought the argument...that by using a gearless technology you [have] something that is lower risk.” (Interviewee from turbine OEM). Direct drive turbines using permanent magnets, a lighter and less bulky design compared to multi-pole direct drive designs, are also attractive in offshore applications in which the logistics of accessing the wind warm create higher maintenance and transport costs. As direct drive turbines are a *systemic modular innovation* due to the interaction of the mechanical and electrical drivetrains, this technology is often offered by turbine OEMs with either existing core competencies in electric machinery (e.g., Siemens or GE) or by OEMs that have acquired these competencies through acquisitions (e.g., Goldwind’s acquisition of Vensys).

With increasing consolidation of the wind industry, “[incremental] innovation is more a competitive driver. In order to compete for market space with four or five players, everyone's trying to become the best at the lowest cost - anything to bring down cost of energy. So either you produce more with the same components, or you lower the cost of your component service, things like that,” (Interviewee from turbine OEM). Incremental innovations in software have improved the efficiency of wind farms while advancements in blade structure and materials have resulted in lighter, longer and more durable blades, and firms are also improving organizational and production processes to reduce time to market. Importantly, due to the well-defined interfaces between modules once a turbine platform has been established, incremental innovations to modules can occur in parallel and can even be sold to customers as upgrades to existing designs.

Regulatory or policy interventions can also interfere with wind’s innovation patterns. In addition to regulations that influence technology selection in predictable ways – such as height restrictions – intricacies of policy design can also affect technological innovation in unwanted ways. For example, policymakers in certain developing countries in which investment risk is relatively high intended to 'de-risk' wind investments by stipulating that developers must utilize proven turbines with a site certificate in order to be eligible to receive public support. This requirement, although it simplified due diligence procedures for local financial institutions that provide loans to wind developers, constrained opportunities for context-specific innovation. Additionally, LCRs themselves have resulted in technology speciation in some contexts. In particular, concrete towers – rather than the typical steel towers – are often deployed in markets with LCRs as concrete is easily manufactured locally and can account for a significant portion of the turbine value. These concrete towers also enable turbine OEMs to build taller turbines that can capture more uniform and higher wind resources, as these towers can be manufactured on-site and thus do not face bottlenecks in transport[4].

4.1.2 Localization of component manufacturing

In addition to localizing tower manufacturing, turbine OEMs operating in markets with LCRs typically localize blade production, as it is also a bulky component with high transport costs and limitations. However, unlike towers, which can more easily be subcontracted through firms with existing *manufacturing capabilities* in concrete or steel structures, localizing blade manufacturing often requires that a lead turbine OEM or blade manufacturer invest in both a specialized manufacturing facility as well as training to develop local *manufacturing capabilities*. As a result of this investment requirement, the *volume* – or potential market size – is crucial. If a country's wind market is too small or too heterogeneous in the type of blade it requires, justifying such an investment is difficult, whereas in countries with large volumes,

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[4] Transport restrictions such as viaduct heights or maximum turn radii can limit the size of turbines in certain markets due to the inability to transport bulky components such as towers or blades.

localization of blade production may occur even in the absence of any LCRs. Beyond the tower and blades, localizing the production of other modules is rare. More complex modules such as gearboxes or transformers not only require volume, but also significantly more technological capabilities. Consequently, localization of such modules is likely only if a country has a suitable existing industry base.

In some cases, localization of module manufacturing facilities in a challenging use environment encouraged modular innovation, such as specific blade innovations for harsh climates. However, these innovations required high levels of local *design capabilities* and interaction between manufacturing facilities, turbine users, and R&D departments.

4.2 Biopower

4.2.1 Opportunities for technological innovation in response to change in use environment

Like wind, biopower requires adaptation to its *energy input*. For biopower, energy input refers to the biomass feedstock, which varies in type (e.g., wood versus straw), quality (e.g., moisture, ash or chlorine content), and availability. However, unlike wind, which required architectural innovation to suit different wind regimes, changing the feedstock of a biopower plant results in *modular innovation* of the fuel combustion system – a core module of the power plant. As one interviewee explained, “Once you have decided on what type of fuels and what is the [quantity] of fuels...then you take a call on which boiler technology to be utilized, at which temperature and pressure cycles should the combustion take place, and then you design the rest of the power plant around the same parameters.” The boiler technologies themselves each operate with distinct principles. The most mature boiler technology, fixed grate boilers, evolved predominantly for the combustion of wood and wood residues – the feedstock most available in Europe and North America. However, combusting agricultural residues (e.g., rice husk), which are more common in emerging and developing countries, in a grate-fired boiler led to operational problems, as the higher ash content and lower ash melting temperature of these feedstocks often resulted in sintering of ash on the grate. Consequently many boiler OEMs are developing circulating fluidized bed (CFB) combustion technologies for biopower that allow for lower combustion temperatures. These fluidized bed boilers offer greater fuel flexibility in the combustion process, however, because they require more uniform and smaller granules of fuel, the fuel handling system must also be significantly adapted. Thus, adapting biopower to specific feedstocks typically is a *systemic innovation*, as changing the boiler necessitates changes to other modules in the power plant. This type of modular innovation either results in competence destruction – for example for firms specialized in fixed-bed combustors – or competence acquisition. In some instances, firms specialized in fuel handling were able to expand their competency to biomass combustion by acquiring firms competent in boiler design and manufacturing.

Beyond the choice of boiler technology, ensuring *functionality* of a biopower plant is largely a design optimization problem involving incremental adjustments to both the boiler design and complementary modules. As one interviewee from a technical consultancy explained: “It will be like a puzzle, using many systems which are available and the main part...the combustor and the boiler, would be designed specifically.” Once the boiler technology type is chosen to suit the feedstock type, variations in other fuel parameters such as moisture content can be managed by changing design parameters of the boiler such as heat transfer area, or by tweaking the design of the fuel feeding system by changing the speed and mechanism of feeding fuel into the boiler. Depending on the boiler operation and feedstock, different operational impacts arising from ash formation and deposition may occur, both in the combustion system itself as well as downstream in ash handling systems. Thus, specific ash behavior must be accommodated either through specific boiler features that minimize ash accumulation, or through adjustments to ash handling mechanisms. Finally, the choice of boiler technology and feedstock will also impact the temperature and pressure of the steam used for power generation. As steam turbines themselves are complex technologies produced by a few leading firms worldwide, the interfaces of steam turbines are standardized. Hence, biopower engineers will *select* the appropriate turbine from a catalog of technologies; customization therefore must occur upstream of the power plant. The complexity of this optimization process necessitate high *design capabilities* in both the boiler engineer as well as the biopower plant integrator (typically an EPC contractor).

Given the importance of the boiler design in both ensuring plant functionality and in constraining the specifications of other biopower modules, biopower exhibits less flexibility in terms of meeting different prioritizations of merit dimensions. Although fluidized bed technologies are more expensive than fixed grate technologies, they are often the only suitable technology for “difficult raw materials and fuels, so then there’s no option. You cannot do it in grate type boilers...either you need to have financing for [a fluidized bed] boiler or otherwise you cannot construct the boiler at all,” (interviewee from a biopower technology supplier).

Regulatory or policy-related factors also play a less prominent role in technology development in biopower than in wind. Environmental standards, again, are met largely by optimizing the combustion process, with additional pollution control modules deployed to further reduce emissions as needed. While strict environmental standards can spur innovation in these pollution control modules, such innovations are typically incremental and reinforce the competencies of firms already specialized in these process technologies.

4.2.2 Localization of component manufacturing

The interviews and technical literature also have not shown that LCRs result in technology speciation. Instead, localization for biopower has been predominantly opportunistic. While high levels of local content have been achieved, this was done mainly through subcontracting to existing local firms – for example firms with *design capabilities* in material handling to supply the fuel feeding system or firms with *manufacturing capabilities* in process equipment to supply components such as pumps and valves. In markets where such capabilities are not existing, a developer may be deterred from entering a market with high LCRs. Localizing boiler manufacturing is particularly difficult, both because the necessary *design capabilities* are often prohibitively high and because the boiler quality will almost singlehandedly determine the operational characteristics of the plant. According to one technology supplier, "There is a lot of training also involved because basically all [boilers] are...tailor made, so it is not something that you just give the drawings and then they start to do it. You really have to do some training. You have to follow up. You have to have this quality assurance and so on." Additionally, many lead boiler suppliers may be unwilling to completely localize boiler production, as this is a core competency they choose to protect.

4.3 Technology lifecycles and implications for local learning

The results of the interviews, although preliminary, showed that both wind and biopower required adaptation to new use environment in order to maintain functionality, satisfy user preferences, and meet policy or regulatory requirements. However, due to each technology's unique product architecture, these adaptations produced different implications in terms of type of innovation and potential opportunities for localization (see Table 2 for a brief summary).

Table 2: Overview of innovation types and opportunities for latecomer firms

Type of innovation	Definition	Examples from case studies	Potential opportunity for latecomer firms
Architectural	Change in the integration and relationships between modules Requires new information exchange between module producers	New turbine platform for a specific wind regime	In mature or consolidated industries such as wind, strengthens position of existing firms as they acquire further architectural knowledge

Modular Systemic	Change in the core design of module that necessitates change in one or more other modules Entails a change or acquisition in engineering or scientific principle underlying design	Direct-drive wind drivetrains Fluidized bed combustion boilers	Can create opportunities for firms specialized in complementary modules in the value chain (i.e. through vertical integration)
Modular Component	Change in the core design of a module with well-defined interface rules Entails a change or acquisition in engineering or scientific principle underlying design	De-icing for wind turbine blades Steam engine in the power cycle	Can create opportunities for new firms, particularly for specialization in a technology niche
Incremental	Refinement of an existing design Draws from existing engineering or scientific principles	Improvement of blade structure (e.g., stiffness) Air-staging in stoker boilers	Reinforces position of existing firms

These innovations patterns can be understood in a more structured way by looking at each technology's lifecycle (see Figure 3). The development of a new turbine platform closely follows the theoretical lifecycle of a complex technology: following the emergence of a new product architecture, the locus of innovation shifts to innovation at the module levels (see Figure 3). In the current, rather consolidated wind industry structure, such an architectural innovation often means existing turbine OEMs (i.e. firms at the turbine assembly level) acquire these new architectural competencies. As existing lead turbine OEMs have already developed platforms for the standard wind classes, this type of architectural innovation is no longer necessary with each new use environment. Instead, introduction to a new use environment is more likely to spur modular innovation. At the module level, product innovations can also result in competence acquisition, for example in the case of a blade manufacturer developing competency in de-icing technology; competence destruction, as is the case of direct drive turbines for gearbox manufacturers; or competence reinforcement when innovations to modules are incremental.

Although it still follows the general lifecycle of a complex technology, the innovation patterns of biopower when it is deployed in a new use environment are slightly different from wind. Biopower is characterized by a stable product architecture, however, the combustion system must be specifically designed for each new project. As the combustion system is a core module, its design dictates the specifications of almost every other module. An innovation to this core module then can induce waves of complementary modular innovations. As a result, technology improvements and adaptations cannot occur independently; constant feedback is needed between the boiler designer and other module suppliers, until a comprehensive biopower plant design is achieved. Importantly, this design cycle typically restarts with each new biopower project, including those located within the same country.

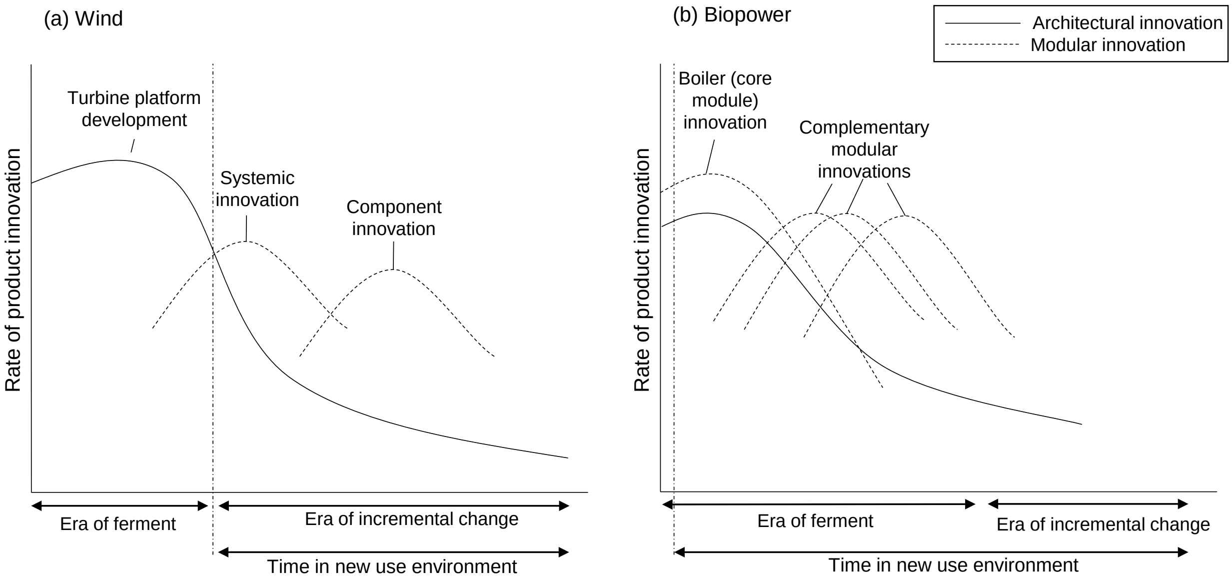

Figure 3: Technology lifecycles for (a) wind and (b) biopower

As modular innovations lower entry barriers for new firms, they can create realistic opportunities for latecomer firms in emerging economies. We therefore propose the first working propositions:

P1: Opportunities for local learning are more likely to arise when a new use environment spurs systemic modular innovation in a core module,

as changing a core module is likely to spur further innovations lower in the technology's product architecture (Murmann & Frenken 2006). Further, when modular innovations are systemic, module producers must interact and share knowledge about their module designs in order to ensure the compatibility of the overall design. As a result, a module supplier may more easily vertically integrate and become a supplier of a complementary module. We therefore suggest the second proposition:

P2: The more standardized interfaces are between modules, the less likely it is that local firms will break into other parts of the value chain.

The interviews also indicated that local manufacturing capabilities are a necessary condition for localization of component manufacturing to occur. If these capabilities are not already existing, they often must be built up through investments in production equipment and/or training. Given this need, we suggest that:

P3: The more new the production process for a module is to a country, the more important volume is for localization.

The propositions presented in this section are quite tentative, as data collection and analysis is still on-going.

5 Future research

This paper presents initial findings on the role of product architecture and use environment in creating opportunities for innovation and local learning. Thus far, data collection and analysis has focused on establishing the product architecture of each technology case, and understanding how variation in each technology's use environment can spur different types of innovation. We will continue to conduct and analyze interviews in order to refine our propositions.

However, in order to understand how countries can exploit these opportunities, we plan to also conduct an analysis at the country-level. Specifically, we plan to conduct interviews with stakeholders in Chile and South Africa to understand how local firms operating in wind and biopower industries were established. To date, the majority of studies that have investigated low-carbon industry localization have used Brazil, China or India as cases (Lewis 2011; Hochstetler 2015; Surana & Anadon 2015). However, these countries are unique due to their large markets, often making localization of manufacturing facilities attractive from a pure economic or strategic standpoint. Countries with smaller internal demands, such as Chile and South Africa, may therefore provide more applicable insights to other emerging or middle-income countries (Pueyo et al. 2011).

Chile and South Africa are both considered latecomers to clean energy markets, however in recent years they have experienced significant growth in renewable energy deployment. They were chosen as comparative cases to reflect variation in their renewable energy deployment policies, as well as the extent of variation of their use environments. In South Africa, the take-off of renewables is largely attributed to its renewable energy procurement program (Baker 2015). This program targets the deployment of utility-scale wind, solar and biopower projects through a competitive bidding process. Importantly, all bids must contain a specified share of local content that has increased with each bidding round. Biomass feedstocks in South Africa are diverse, however its wind conditions are rather similar across sites. Chile, on the other hand, has taken a technology-neutral approach to renewable energy deployment and does not specifically target industry localization. While forestry residues dominate its biopower applications, due to its geography it has a wide variation in its wind sites. While both countries have local firms active in the biomass and wind industries – including in equipment manufacturing, engineering, project development and O&M – South Africa’s wind industry is more diverse than Chile’s and vice versa for Chile’s biomass industry.

The main goal at the end of the study is to provide implications for policymakers in emerging economies in designing energy and industry policies to foster low-carbon industry localization.

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