# Catching-up in green industries: The role of product architecture

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**Abstract**

As latecomers to the industrialization process, developing countries may face barriers to upgrading from the production of mass-produced goods to higher-value technologies. Scholars have suggested that 'windows of opportunity' can temporarily lower entry barriers and provide an opportunity for latecomers to catch up. In this paper, we use the literature on product architecture to build on the concept of windows of opportunity. We explore how changes in a technology's use environment can create opportunities for indigenous innovation and upgrading in specific sub-systems or components of complex technologies. Using a comparative qualitative case study focusing on three renewable energy technologies, we develop a typology of catching-up opportunities. Our findings suggest that policymakers should target technologies in their industrial strategies based on their potential for entry and upgrading based on an evaluation of the product architecture, and should seek opportunities to capitalize on a local niche that creates a need for innovation.

**Keywords:** catching-up; global value chain; product innovation; technology lifecycle; modularity; complex product system

## 1 Introduction

The United Nations' Sustainable Development Goal (SDG) 9 aims at inclusive and sustainable industrialization and innovation. For many developing countries, this involves achieving the twin goals of industrialization and decarbonization by localizing industries around low-carbon energy technologies. Establishing such 'green' industries will require firms in developing countries to build up their technological capabilities, actively engage in the innovation process, and participate in the shaping of technological trajectories (Fagerberg and Godinho, 2009; Fu et al., 2011; Malerba and Nelson, 2011).

However, as latecomers, developing country firms often face entry barriers to the innovation process. While entry early in a technology's lifecycle (i.e. the early stages of technological development) provides greater opportunities for product innovation, latecomers frequently lack the technological capabilities and resources to act as entrepreneurial innovators themselves. As a result, many latecomer countries tend to localize the production of technologies late in their lifecycle, drawing on comparative advantages such as low cost of inputs (e.g., labor or land). For such technologies, the potential for future product innovation and learning is typically low, providing little opportunity for building technological capabilities (Fu et al., 2011; Perez and Soete, 1988).

Recognizing the tendency for latecomers to remain stuck on mature technologies with low potential for growth and development, (Perez and Soete, 1988) proposed that latecomers should instead seek to exploit 'windows of opportunity' – or the opening of a new technological trajectory that temporarily lowers entry barriers and creates an opportunity for latecomers to catch up to or even 'leapfrog' incumbents. Expanding on this idea, (Lee and Malerba, 2017) outlined three possible windows of opportunity for latecomers: a technology window (i.e., a radical innovation or appearance of a new technology), a demand window (i.e., creation of a new or a change in demand), and an institutional window (i.e., a change in public policies).

Thus far, the literature applying this framework has provided insight on different patterns of catching-up, including leapfrogging and path-following catching-up (Lee and Lim, 2001; Wang and Kimble, 2011). However, Click or tap here to enter text.relatively few studies have focused on how windows of opportunity may arise *within* a specific module (i.e. sub-system or component, cf. Section 2) of a technology (and thus, a specific segment of a technology's value chain). Such opportunities can be particularly relevant for technologies with complex product architectures (Binz et al., 2017; Quitzow, 2015; Schmidt and Huenteler, 2016), particularly as entry opportunities may arise in a specific value chain segment. Furthermore, subsequent opportunities to upgrade via vertical integration to other innovation and industrial activities in the value chain can depend on the product architecture and associated types of value chain governance.

In this paper, we Click or tap here to enter text.address the following research question: How does changing a technology's use environment create opportunities for the entry and upgrading of latecomer firms within the value chains of complex technologies? We take a comparative approach using the cases of three low-carbon energy technologies to explore how windows of opportunity arising from changes in demand and the institutional environment can create conditions of lowered entry barriers for latecomers within certain value chain segments, and how such opportunities are influenced by the technology's product architecture.

Our results indicate that while changes in a technology's use environment may create windows of opportunity for catching up in specific modules and hence value chain segments, whether latecomers can exploit them depends on two factors related to the technology's product architecture. First, it depends on the degree of integrality of the module, i.e. the degree of interdependence of its design and performance on other modules. Second, it depends on how the interfaces of the module are defined, i.e. whether they are closed interfaces with firm-internal definition, or open interfaces with industry-wide definition. We further discuss how the specific combination of these two characteristics can lead to different implications for policymakers aiming to achieve SDG 9[1].

The rest of this paper is structured as follows. Section 2 gives a theoretical background on product architecture and its implications for entry opportunities for latecomers. Section 3 describes the technology case selection and the qualitative methods. In section 4, we present the results, including the general

[1] In particular, we focus on SDG 9.B ("support domestic technology development, research and innovation in developing countries, including by ensuring a conducive policy environment for, inter alia, industrial diversification and value addition to commodities").

innovation patterns of each case technology when introduced to a new use environment. Section 5 concludes with a discussion for policymakers seeking to promote industry localization and upgrading via vertical integration in industries characterized by highly globalized value chains.

## 2 Theoretical background

In this paper, we focus on global value chains, which encompass the activities undertaken by firms to bring a technology through different phases of production, delivery to customers and end use (Kaplinsky and Morris, 2000). We conceptualize technologies as systems composed of various *modules*[2] that are linked together via *interfaces*[3] to perform certain desired functions (Henderson and Clark, 1990; Murmann and Frenken, 2006; Tushman and Rosenkopf, 1992). A technology's *product architecture* defines the number of modules, maps modules to their functions, and defines the interfaces between the modules (Fixson, 2005; Ulrich, 1995).

The concepts of global value chains and product architectures provide three theoretical foundations for this paper. First, the patterns of industrial organization and the product architecture are closely linked (Gereffi et al., 2005; Murmann and Frenken, 2006). For example, different modules sharing a common interface are often produced by different firms that are linked to each other via the value chain (Malhotra et al., 2019; Stephan et al., 2017). Second, the product architecture influences innovation patterns throughout a technology's lifecycle, and the potential windows of opportunity that can arise in specific value chain segments (section 2.1). Third, analyzing whether innovations in response to windows of opportunity impact the design of specific modules or their interfaces enables us to determine the impact of such innovations on barriers to entry for latecomer firms in specific value chain segments (section 2.2).

[2] Modules are defined as technological sub-systems characterized by relative design independence across their boundaries, but high interdependence within their boundaries (Baldwin and Clark, 2004; Cabigiosu et al., 2013; Campagnolo and Camuffo, 2010).
[3] Interfaces are defined as a set of rules that establish the functional and design relationship between modules (Baldwin and Clark, 2000).

### 2.1 *Changes in use environment and resulting windows of opportunities within a technology's product architecture*

The literature on technology lifecycles describes the temporal patterns of innovation as a technology matures (Abernathy and Utterback, 1978; Davies, 1997; Fixson and Park, 2008; Huenteler et al., 2016a, 2016b). As illustrated in Figure 1, a technology's lifecycle begins with a search for a dominant product architecture, often based on experimentation and user feedback (Nahuis et al., 2012; von Hippel, 1994). Once a dominant design has been established, two changes occur. First, the locus of innovation shifts to the individual modules, beginning with product innovations in core modules (i.e. the modules with the greatest number of architectural links to other modules) and eventually propagating to more peripheral modules (Davies, 1997; Murmann and Frenken, 2006). Second, innovation tends to shift from product to process innovation, as user feedback becomes less important in the technology lifecycle (see Figure 1a) (Abernathy and Utterback, 1978; Huenteler et al., 2016b). Once this shift has occurred, there are fewer opportunities for catching-up, as the rate of product innovation drops, leading to a tendency for firms who enter the global value chain late in the technology lifecycle to remain limited to activities with low added value (Lee, 2013).

To avoid this, (Lee and Malerba, 2017) recommend that latecomers should exploit windows of opportunity resulting from disruptions in the technology lifecycle (see Figure !a). These disruptions can kick the locus of innovation back up the design hierarchy, creating opportunities for indigenous product innovation, local learning and capability-building (Frenken and Boschma, 2007; Perez and Soete, 1988; Windrum and Birchenhall, 1998). Lee and Malerba (2017) categorize these disruptions as technology windows, demand windows, and institutional windows. A technology window arises on the supply-side, often due to a radical innovation, disruptive innovation, or spillover from another sector (Christensen and Rosenbloom, 1995; Dosi, 1982; Levinthal, 1998). As technology windows are difficult to predict or control for latecomers, in this paper we focus on the two windows associated with a technology's *use environment* – namely demand and institutional windows – further elaborated in the paragraph below.

A demand window may arise due to significant changes in the use environment of a technology. Complex technologies can fulfil multiple dimensions of merit (e.g., cost, safety, convenience etc.) (Tushman and Rosenkopf, 1992). These dimensions of merit may vary across use environments, or over time within a use environment. For example, different weighting of *user preferences* can result in a different set of technology selection criteria across markets, leading to the need for product innovation to adapt the technology when moving to new markets (Anadon et al., 2016; Levinthal, 1998; Nahuis et al., 2012). Similarly, institutional windows may also create a disruption in the technology lifecycle, as regulations or standards imposed by *public policies* can also play a role in technology selection and evolution (Lee and Malerba, 2017; Tushman and Rosenkopf, 1992).

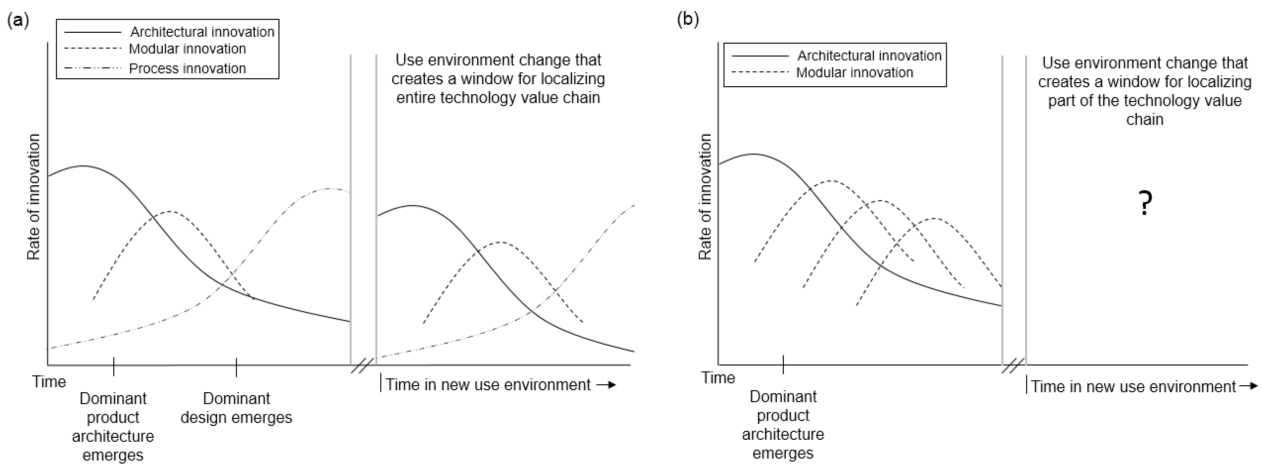


Figure 1: Catching-up in response to a window created by a change in use environment for (a) mass-produced products and (b) complex products (adapted from Abernathy and Utterback, 1978; Davies, 1997)

More recently, several studies have improved our understanding of how firms in latecomer countries can take advantage of such windows of opportunity for renewable energy technologies, and the strategies and trajectories that latecomer firms can pursue to catch up (Dai et al., 2021; Hain et al., 2021; Lema et al., 2021). As a result, there is increasing recognition that technology- and sector-specific characteristics such as technology cycle time (Rosiello and Maleki, 2021), technological complexity (Quitzow et al., 2017; Schmidt and Huenteler, 2016; Surana et al., 2020), and need for customization (Binz et al., 2017; Malhotra and Schmidt, 2020) can play an important role in shaping processes for technological learning and catch-up. With few exceptions, the majority of such studies have focused on catching-up processes among latecomer firms (mostly original equipment manufacturers or OEMs) and nations in the design and production of a dominant design, as seen in Figure 1a. However, relatively few studies have focused on the fact that for more complex technologies, windows of opportunity may arise in the design and/or production of only one module (for examples, see Dai et al., 2021; Gao and Rai, 2019; Haakonsson and Slepniov, 2018; Surana et al., 2020). Thus, latecomers could catch up in specific value chain segments, rather than taking over the entire value chain. In this paper, we adopt this perspective related to the global value chain and product architecture to explore how 'windows of opportunity' may lower entry barriers in specific value chain segments (see 1b).

### *2.2 Innovation within a technology's product architecture and its implications for latecomer firms*

In the previous section, we highlighted the importance of product innovation in creating entry opportunities for latecomer firms in specific value chain segments. However, whether or not a latecomer can successfully exploit these opportunities may be influenced by several additional factors related to the product architecture and value chain governance (Gereffi et al., 2005; Henderson and Clark, 1990).

First, the *type of product innovation* influences the barriers for entry for latecomer firms. For example, a change in use environment could spur a need for incremental product innovation (i.e. mere refinements of modules and their interface design concepts). Incremental innovations tend to reinforce the competencies and competitiveness of existing firms, creating (even) higher entry barriers for latecomers (Dosi, 1982; Tushman and Murmann, 1998). In contrast, product innovations that overturn core design concepts in the modules (modular innovation) or interfaces (architectural innovation) may create more viable entry points for new firms (Henderson and Clark, 1990).

Second, the *degree of integrality* (or conversely, modularity) of the product architecture also influences entry barriers for latecomer firms. The degree of integrality is closely related to the concept of *complexity* of information and knowledge transfer required between value chain steps. A modular technology is characterized by a one-to-one mapping of modules with functions and decoupled modules, whereas integral technologies typically entail one-to-many or many-to-one mapping of modules to functions and/or close coupling of modules with each other (Gatignon et al., 2002; Ulrich, 1995).[4] Increasing architectural integrality generally results in higher entry barriers for new firms (Surana et al., 2020), as the required design capabilities to manage innovation are higher when there is a complex coupling of modules to each other, or of modules to technology functions (i.e. when changing one module can affect the overall functioning of the technology in multiple ways) (Anadon et al., 2016; Henderson and Clark, 1990; Murmann and Frenken, 2006). Third, the interface definition between modules influences how their corresponding value chain segments are organized. Several scholars have proposed that product architecture mirrors production architecture, where integral products should be produced by highly vertically integrated organizations whereas modular products can be developed by autonomous organizations (Baldwin and Clark, 2000; Colfer and Baldwin, 2016; MacCormack et al., 2012), following the hypothesis that well-defined interfaces reduce the need for coordination between module producers (Helfat, 2015; Sanchez and Mahoney, 1996). Similarly, the literature on global value chains considers the extent to which knowledge can be *codified* as an important determinant of the type of value chain governance. The ability to codify product specifications and interface definitions can enable modularity in value chains. However, recent literature has highlighted that the resulting industry structure depends not only on how well-defined interfaces are, but also *how* they are defined, for example through open industry-wide standards, informal design rules or heuristics, or closed firm-internal logics (Cabigiosu et al., 2013; Gawer, 2014; Hofman et al., 2016). How interfaces are defined dictates the required architectural knowledge and capabilities that must be embedded in a successful module producer or module innovator, as well as the degree of interaction required between module producers and integrators. Industry-wide interfaces are the most open to external innovators, as they require little coordination with existing technology suppliers to enter the value chain (Gawer, 2014). Conversely, the coordination required for modules with closed interfaces can involve the sharing of knowledge of an

[4] It is important to note that modularity is a *continuous* characteristic ranging from completely modular to integral (Campagnolo and Camuffo, 2010). Also note that modularity can be defined at multiple levels of analysis. Modularity at the subsystem level does not necessarily entail modularity at the component-level (Murmann and Frenken, 2006).

incumbent firm's core competencies, creating incentives for that firm to vertically integrate, rather than collaborate with external entities (Davies, 1997).

The literature on innovation management has provided insights on how innovation patterns within a technology's product architecture influence industrial organization. However, much of its focus has centered on the supply chain strategy of incumbents (e.g., make-or-buy decisions) (Cabigiosu et al., 2013; Fixson, 2005), with little attention paid to how different innovation types influence learning and capability-building in latecomer contexts. On the other hand, there is a strand within the literature on global value chains that has an explicit focus on knowledge transfer and capability-building, with a focus on how characteristics of transactions between firms and their respective capabilities influence these processes. However, few studies in this literature engage with technology-specific characteristics, how they influence interactions between firms, and hence, how they influence opportunities for latecomer firms to enter and upgrade in global value chains. In this paper, we combine concepts of global value chains and product architecture from the perspective of a latecomer country seeking to capitalize on windows of opportunity and build-up innovation capabilities through technological learning.

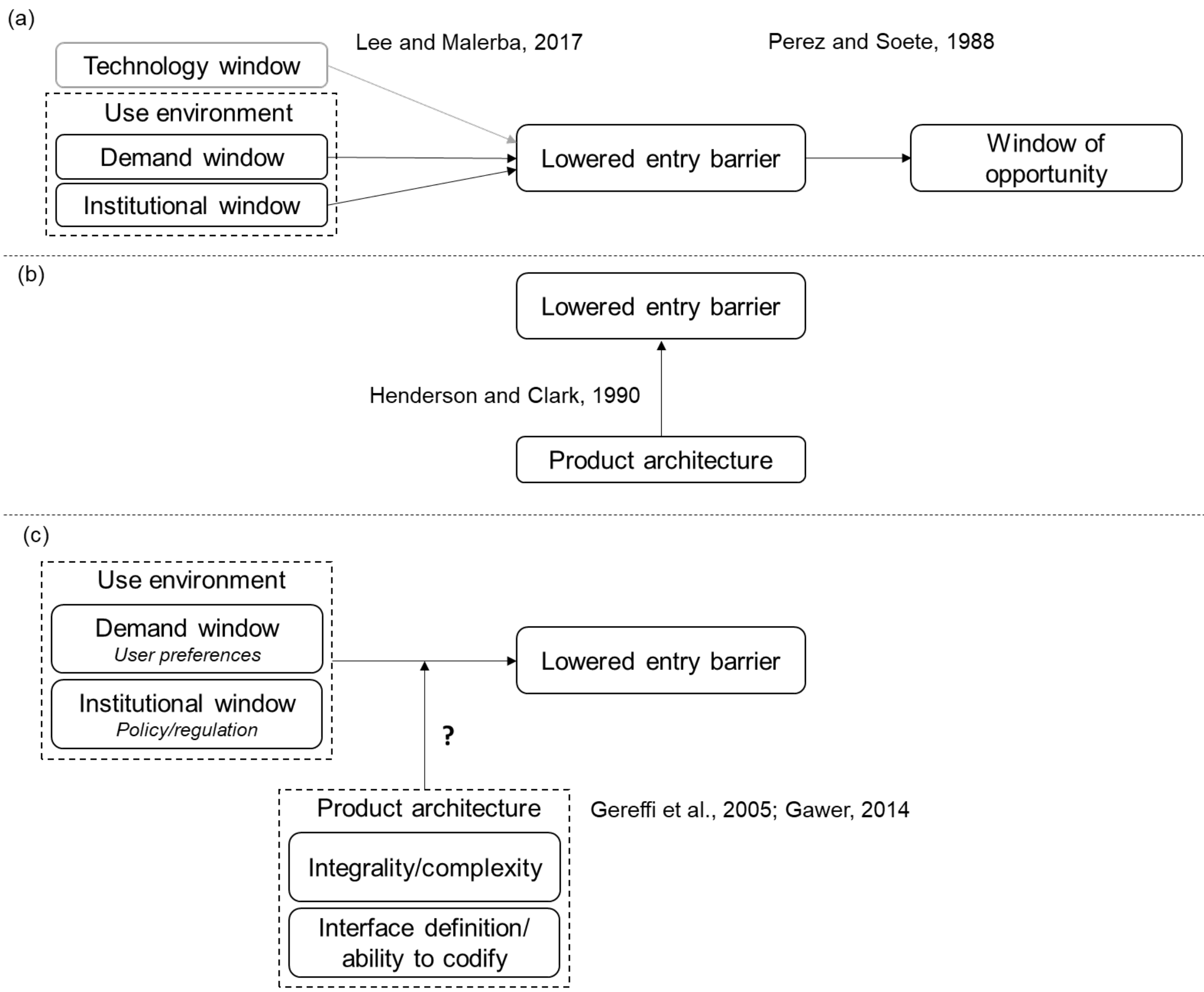


Figure 2: (a) Literature on catching-up of latecomers that investigates how technology, demand, or institutional windows can lower entry barriers for latecomer firms, providing a window of opportunity for catching-up to incumbents, (b) literature on the role of product architecture in catching-up processes, and (c) the theoretical framework of this paper that integrates the literature streams, focusing on the role of product architecture in moderating windows of opportunity in global value chains.

## 3 Materials and Methods

The following section outlines the research design, including the rationale for the technology case selection (3.1) and methods (3.2). Further, a brief description of each case technology, including its operating principle and industry structure, is provided in section 3.3 to aid in later understanding the results.

### *3.1 Case selection*

Using a comparative research approach with diverse cases (Seawright and Gerring, 2008), three low-carbon energy technologies, namely, solar photovoltaic (PV) systems, wind turbines, and biomass for power generation, herein referred to as biomass power[5], were chosen as the research cases for two theoretical reasons. Firstly, these technologies exhibit a range of overall complexity in their product architectures, as shown in Figure 3 (Binz et al., 2017; Schmidt and Huenteler, 2016). Solar PV is the simplest of the three technologies, exhibiting interfaces defined by industry-wide standards and high architectural modularity (Huenteler et al., 2016b). Wind turbines are considered to have a hierarchical product platform architecture, with several variable modules designed around a stable core module, allowing for customization of platforms to different contexts[6] (Baldwin and Woodard, 2009). Finally, biomass power is considered a complex product system (CoPS), as the modules and interfaces in a biomass power plant are often designed specifically for each application, making it both highly design-intensive as well as customizable (Binz et al., 2017). Due to this variation in complexity of the technologies, we expect that there will also be variation across modules in terms of their integrality and interface definition, and associated variation in terms of types of interaction between value chain segments. Secondly, all three technologies are deployed for power generation applications and are relatively mature technologies. This specificity has deterred radical speciation of the technologies, allowing us to assess the impact of use environment on a stable set of modules.

[5] Excludes traditional biomass energy (for heat), as well as biogas-based technology.
[6] While this platform structure offers some modularity, the electrical and mechanical modules within a wind turbine typically interact at multiple levels of this hierarchy as defined by platform-specific design rules (Andersen, 2004).

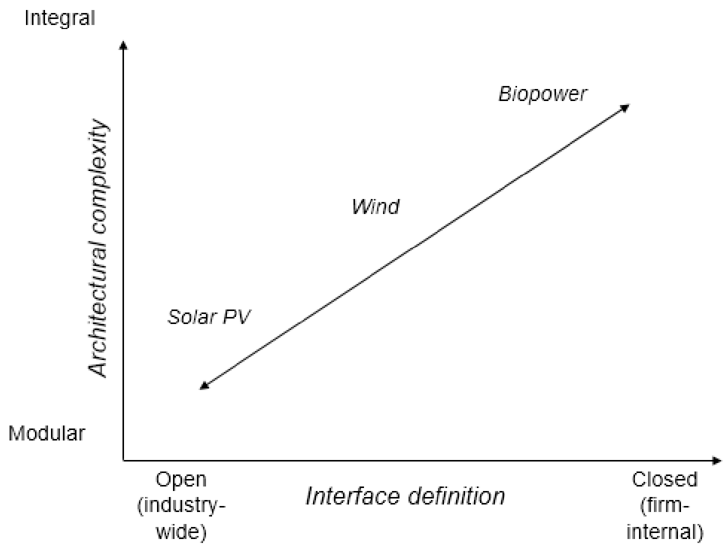


Figure 1: Conceptual schematic showing the variation of technology cases according to their architectural complexity at the technology-level and openness of interface definition

These technologies were also chosen for several practical reasons. Solar PV, wind, and biomass power are increasingly targeted in national technology deployment policies. These technologies originally diffused in European and North American markets, and have subsequently been deployed on a large scale in latecomer countries, providing an opportunity to explore the influence of these new use environments on these technologies (REN21, 2016). Additionally, several latecomer middle-income countries[7] have enacted policies with the aim of developing local industries around these technologies, despite limited understanding of their effectiveness (Lewis and Wiser, 2007; Matsuo and Schmidt, 2019; Schmidt and Huenteler, 2016; UNCTAD, 2014). Finally, all three technologies have the potential to create sustainable industrial growth and thereby decent jobs in developing countries (Cantore et al., 2017).

### *3.2 Methods*

In this paper, we use qualitative, comparative case study methods to expand existing perspectives on the technology-specificity of industry localization patterns, and build theory regarding entry opportunities for latecomers (Eisenhardt, 1989). Specifically, the methods proceeded in three steps. Firstly, we determined the product architecture of each technology. For wind and solar PV, in addition to reviewing technical

[7] Recent examples include Argentina, Brazil, India, Egypt, Morocco, and South Africa

literature, we largely built on the characterization of product architecture developed by Huenteler and colleagues (Huenteler et al., 2016a, 2016b). For biomass power, we reviewed 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 conducted in March 2017 with technical experts on biomass power systems.

Secondly, once we had established a comprehensive understanding of the product architecture of each technology, we conducted 25 semi-structured interviews with industry experts from the PV (8 interviews), wind (9 interviews) and biomass power (8 interviews) industries. For all of the technologies, we aimed to interview representatives from leading technology suppliers working across global markets, industry experts/consultants with both technical knowledge and knowledge of market dynamics, and representatives from engineering, procurement, and construction (EPC) companies[8]. These interviews were conducted by phone or Skype, with the exception of five in-person interviews. An overview of the sample can be found in Table 1.

[8] EPC companies are responsible for the engineering design; procurement of materials, equipment, and services; and construction of a project. For large infrastructure projects, they therefore are a key actor in project realization.

| | Organization role | Technology | Interviewee role |
|---|---|---|---|
| 1 | Technology supplier | Solar PV | Engineer |
| 2 | Technology supplier | Solar PV | President |
| 3 | Technology supplier | Solar PV | Former CEO |
| 4 | Technology supplier | Solar PV | Head of power solutions |
| 5 | EPC | Solar PV | Senior project manager |
| 6 | EPC | Solar PV | Senior analyst |
| 7 | EPC | Solar PV | Managing director |
| 8 | Consultant/industry expert | Solar PV | Senior analyst |
| 9 | Technology supplier (OEM) | Wind | Product manager |
| 10 | Technology supplier (OEM) | Wind | Former Chief Operating Officer |
| 11 | Technology supplier (OEM) | Wind | Former Chief Technology Officer |
| 12 | Technology supplier | Wind | Director |
| 13 | Technology supplier | Wind | Managing director |
| 14 | Technology supplier | Wind | Head of electrical systems |
| 15 | Technology supplier | Wind | Manager |
| 16 | Consultant/industry expert | Wind | Senior director |
| 17 | Consultant/industry expert | Wind | Independent expert |
| 18 | Technology supplier | Biomass power | Director |
| 19 | Technology supplier | Biomass power | General manager |
| 20 | Technology supplier | Biomass power | Strategy and business development manager |
| 21 | Technology supplier | Biomass power | Vice President of sales |
| 22 | EPC | Biomass power | Project manager |
| 23 | Consultant/industry expert | Biomass power | Owner |
| 24 | Consultant/industry expert | Biomass power | Researcher |
| 25 | Consultant/industry expert | Biomass power | Researcher |

Table 1: Sample for industry interviews

The aim of the interviews was to understand the general industry trends and market structures for each case technology (see section 3.3 below), the type of innovation required in order to adapt each technology to different use environments, and the implications of these innovations on the structure of the technology's value chain. Two members of the research team independently coded interview transcripts according to the type of innovation required in a new use environment, the locus of innovation within the product architecture, 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.

Thirdly, 43 semi-structured interviews were conducted with representatives from firms in middle-income countries – many that have enacted green industrial policies – and are latecomers to the solar PV, wind, and biomass power industries (see Table 2 below for overview). The aim of the interviews was to understand the windows of opportunities arising from changes in demand and institutional environment, entry barriers, and capability-building process within global value chains. Interviewees encompassed a broader set of stakeholders: in addition to technology suppliers, EPC companies, and industry experts/consultants, we interviewed project developers, heads of industry associations, policymakers focused on innovation policy, and financiers. These interviews were conducted largely in-person (with the exception of 11 phone or Skype interviews) over the period from June 2017 to May 2018, and were conducted either in English or Spanish and coded in their original language.

| | **Organization role** | **Technology** | **Interviewee role** | **Country** |
|---|---|---|---|---|
| 1 | Technology supplier | Solar PV | Managing director | South Africa |
| 2 | Technology supplier | Solar PV | Managing director | South Africa |
| 3 | Technology supplier | Solar PV | Development manager | Mexico |
| 4 | Technology supplier | Solar PV | Senior director | Argentina/Mexico |
| 5 | Technology supplier | Solar PV | Managing director | South Africa |
| 6 | Industry association | Solar PV | President | Mexico |
| 7 | Industry association | Solar PV | Executive director | Mexico |
| 8 | Developer | Solar PV | CEO | South Africa |
| 9 | Developer | Solar PV | Development director | Mexico |
| 10 | Developer | Solar PV | Partner | Mexico |
| 11 | Developer | Solar PV | Director of operations | Barbados |
| 12 | Developer | Solar PV | Country manager | Jamaica |
| 13 | EPC | Solar PV | Business development manager | South Africa |
| 14 | Consultant/industry expert | Solar PV | Renewable energy leader | South Africa |
| 15 | Consultant/industry expert | Solar PV | Senior energy analyst | South Africa |
| 16 | Financier | Solar PV | Principal | South Africa |
| 17 | Financier | Solar PV | Manager renewable energy | South Africa |
| 18 | Technology supplier (OEM) | Wind | Manager | South Africa |
| 19 | Technology supplier (OEM) | Wind | Manager | South Africa |
| 20 | Technology supplier (OEM) | Wind | Technical specialist | Mexico |
| 21 | Technology supplier (OEM) | Wind | Director | Egypt |
| 22 | Technology supplier | Wind | Managing director | South Africa |
| 23 | Technology supplier | Wind | Business manager | South Africa |
| 24 | Technology supplier | Wind | General manager | South Africa |
| 25 | Technology supplier | Wind | Manager | Mexico |
| 26 | Industry association | Wind | President | South Africa |
| 27 | Industry association | Wind | Executive director | Mexico |
| 27 | Developer | Wind | Manager | South Africa |
| 28 | Developer | Wind | Executive | South Africa |
| 29 | Developer | Wind | Managing director | Mexico |
| 30 | Developer | Wind | Development manager | Mexico |
| 31 | Developer | Wind | CEO | Mexico |
| 32 | Consultant/industry expert | Wind | Analyst/researcher | South Africa |
| 33 | Financier | Wind | Energy specialist | Latin America |
| 34 | Technology supplier | Biomass power | Head of business development | India |
| 35 | Industry association | Biomass power | Director | South Africa |
| 36 | Industry association | Biomass power | Director | Mexico |
| 37 | Developer | Biomass power | Manager | South Africa |
| 38 | Developer | Biomass power | Director | South Africa |
| 39 | Developer | Biomass power | Director | Mexico |
| 40 | Developer | Biomass power | CEO | South Africa |
| 41 | Consultant/industry expert | Biomass power | Director | Mexico |
| 42 | Policymaker | Biomass power | Science & Technology | South Africa |
| 43 | Policymaker | Biomass power | Director green industries | South Africa |

Table 2: Overview of interview sample in latecomer countries

### *3.3 Description of case technologies and their market structure*

#### 3.3.1 Solar PV

Solar PV systems convert solar radiation into electricity using the photovoltaic effect. Solar PV systems are composed of three modules: (i) the solar PV panels, (ii) the mounting system, and (iii) the grid connection system (Boxwell, 2012). The solar PV panels, each comprised of strings of encapsulated solar cells made of various semiconducting materials, convert sunlight into DC electricity. The mounting system holds the solar PV panels against natural forces (e.g., gravity, wind) while the grid connection system, including the inverter, energy management system, conductors, and other electrical components, converts the DC power generated by the solar PV panels to usable AC power. Each of these modules has interfaces typically defined by industry standards and a single function, giving solar PV a 'plug-and-play' characteristic.

The modularity and open interfaces of solar PV have resulted in two key industry trends. Firstly, as the innovation trajectory of solar PV is driven by independent innovations in modules, the industry is trending towards vertical disintegration into specialized module suppliers. As this specialization tends to reinforce competencies of these suppliers, increasingly the PV market is characterized by just a few leading firms providing the core modules[9]. Secondly, several core modules, including solar PV panels, are relatively mature, mass-produced products. As a result, competitiveness in their supply, which is based on price competition, is driven largely by process innovation, learning-by-producing, and exploiting economies of scale in manufacturing (Quitzow, 2015; Schmidt and Huenteler, 2016).

#### 3.3.2 Wind

A wind turbine converts the kinetic energy of the wind into 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 four modules: (i) the rotor, (ii) the power train, (iii) the mounting and encapsulation system, and (iv) the grid connection system (Huenteler et al., 2016b). This design captures the kinetic energy

[9] In particular, Chinese firms dominate the manufacturing of solar cells and panels, with the vast majority of their manufacturing facilities located in China (Nemet, 2019; Zhang and Gallagher, 2016).

of the wind using three blades rotating about a horizontal axis (rotor)[10]. 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). The drive train is housed in a nacelle, which is mounted on a tower and structurally supported by a foundation. Finally, electricity produced by the turbine is either stored or fed into the electric grid.

Wind turbines are designed in firm-specific platforms, with each platform designed for a certain wind class (which is defined by the average wind speed, turbulence, and extreme gust wind speeds at a particular site). Module interfaces are then governed by design rules specific to that platform. As the wind turbine industry has matured, wind classes have become increasingly better characterized. As a result, many turbine OEMs have developed a portfolio of standard turbine platforms able to meet most wind regimes worldwide. This standardization of wind classes, combined with the complex interdependence of modules and platform-specific design rules, has resulted in both a highly vertically integrated and consolidated industry[11].

### 3.3.3 Biomass power

Biomass power plants convert biomass feedstocks into electrical energy. While this definition encompasses several processes and conversion pathways, in this paper we focus on the combustion of solid biomass to generate steam, which is used in a steam cycle to produce electricity. We focus on this process as it has been the dominant biomass power technology deployed (van Loo and Koppejan, 2008). Biomass power plants typically consist of an architecture that includes five modules: (i) the fuel handling system, (ii) the fuel combustion system, (iii) the power generation system, (iv) the pollution control system, and (v) the grid

[10] 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).

[11] In 2017, only four OEMs (Siemens, Vestas, Goldwind and GE) accounted for 54% of turbine sales (Efstathiou, 2018).

connection system. Biomass feedstocks[12] are transported from the point of fuel delivery or storage to the combustion system, or boiler, via the fuel handling 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 boiler technology. The heat released from combustion is used to produce high pressure and high temperature steam for use in a steam cycle. Technologies for power generation in a steam cycle are quite mature, and are deployed in other thermal power plants such as coal-fired power plants. In this process, steam energy is converted into mechanical energy in a steam turbine, and this mechanical energy is subsequently converted to electrical energy using an electrical generator. Finally, the combustion of biomass produces pollutants and ash, which need to be treated or handled appropriately by the pollution control system.

As a CoPS, each biomass power plant must be specifically designed for each project based on feedstock characteristics, beginning with the design of the combustion system. As these designs typically emerge through learning-by-using the boiler with a particular feedstock, many boiler manufacturers are often highly specialized in the feedstocks available in their home markets. As a result, globally, the biomass power industry is less concentrated and less vertically-integrated compared to wind power. Within feedstocks, however, certain activities such as the boiler or fuel handling is often concentrated within a few leading firms. For example, boiler designs for combustion of feedstocks common in industrialized economies in Europe and North America are relatively mature and standardized. While some companies provide technologies and/or services related to multiple modules of biomass power plants, more often technology suppliers are horizontally integrated, and offer multiple technology options for the same module (e.g., multiple boiler designs for combusting one type of feedstock). Additionally, lead suppliers of biomass power plant modules are frequently diversified in other business activities related to the feedstock (e.g., pulp and paper industries), rather than specialized in solely biomass power.

[12] In this paper, we focus on biomass feedstocks not suitable for human consumption, including agricultural residues, industrial waste, and forestry residues. Energy crops, or biomass grown explicitly for energy purposes, are not considered.

# 4 Results

The following section presents the results of the interviews. For each technology, we first describe the windows of opportunity that arise due to a change in the technology's use environment, with the discussion structured around three drivers of product innovation inductively derived from the analysis of the interviews: the need to ensure functionality, meet different user preferences (demand window), and conform to or meet certain policy/regulatory constraints (institutional window). In a second step, we deep dive into one particular module of each technology that was identified by interviewees as particularly relevant for latecomers. In these deep dives, we elaborate on the learning and capability-building process as determined by the product architecture from a latecomer's perspective. At the end of Section 4 we synthesize our findings in Figure 7.

## *4.1 Solar PV*

### 4.1.1 Innovation opportunities in response to a change in use environment

Results of the first set of interviews showed that solar PV systems can maintain functionality in a range of applications and contexts with either no or only incremental innovation needed. While solar irradiation patterns can vary across contexts, these changes have no impact on the operating principle of the solar panel, which converts solar irradiance to a homogenous energy output (DC electricity). This characteristic not only allows for the application of solar panels in any irradiation condition, but also enables standard interfaces with peripheral modules (such as the inverter) by limiting the impact of changing irradiation conditions. In some cases, incremental adjustments are made to PV systems in order to maintain functionality in difficult environmental conditions, such as upgrading cooling systems for inverters, reinforcing mounting systems under extreme loading conditions (e.g., potential hurricane threats), or different galvanization methods to improve mounting structure resilience in corrosive environments (Gao and Rai, 2019). However, because interfaces are defined by stable open standards, changing the design of individual modules has little to no impact on the design of other modules or the PV system as a whole. As a result, all of these design adaptations or improvements can occur in parallel, and are then often globally applicable. Finally, as PV systems are composed of arrays of panels, they can be scaled from kW-scale rooftop applications to MW-scale plants, with relatively minor architectural adaptations required. Consequently, the product innovations spurred due to maintaining PV functionality are usually managed by incumbent PV firms, rather than allowing entry of latecomers.

Beyond these incremental innovations, our interviews show that institutional windows of opportunity have appeared in many latecomer middle-income countries, resulting in innovation in solar PV mounting systems. Specifically, in markets with both excellent solar resources and highly competitive renewable energy programs (e.g., competitive auctions[13]), even minor improvements in system efficiency are highly valuable. One key innovation that offers such efficiency gains is the introduction of solar tracking, rather than fixed tilt mounting systems (modular innovation). For example, one tracking system supplier explained that the highly competitive auctions conducted in Mexico in 2016 and 2017 created a new market for solar tracking systems. This is because the increase in efficiency resulting from the use of tracking systems were attractive for EPC companies and project developers looking to provide production guarantees for extremely aggressive offers, as it gave them an additional buffer to meet their contracted obligations.

Of the product innovations outlined above, all are incremental innovations or adjustments to a modular component (serving one function) with open interfaces, with the exception of solar tracking systems (see Figure 4). While solar tracking systems also have open interfaces, and are therefore compatible with a wide range of panel or inverter suppliers, they are more integral than the other components, as they serve the dual functions of supporting solar panels and optimizing solar production.

[13] Following the successful implementation of competitive auctions in South Africa, these policies, which award contracts to renewable energy projects with the lowest price offer, are growing increasingly popular in emerging economies.

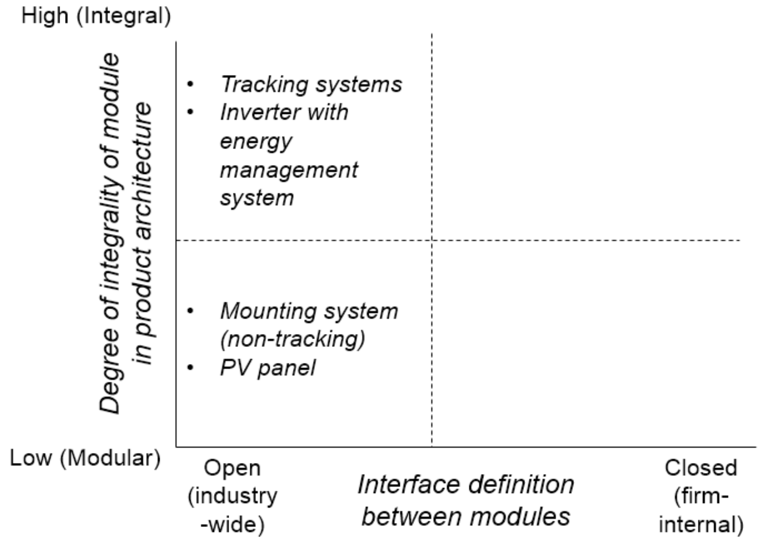


Figure 2: Categorization of several PV modules according to their degree of integrality within the product architecture and inter-module interface definition

#### 4.1.2 Exploring opportunities for latecomer catch-up: Solar tracking systems

Solar tracking systems have been particularly interesting from a latecomer perspective. As explained, such systems are viable in contexts with highly competitive solar PV markets and high solar irradiation, meaning they have evolved primarily in and for latecomer contexts – rather than in forerunner contexts such as Japan and Germany with less attractive solar resources. While many industry-leading firms are based in the US (e.g. Nextracker, Array Technologies, GameChange Solar) and Spain (e.g. PV Hardware, Soltec, Nclave, STI Norland), their manufacturing facilities are located close to major markets in Latin America (particularly Mexico, Brazil and Chile), the US, the Middle East and South Asia (particularly India). In addition, opportunities to enter the industry and to compete with international players in the local market have arisen for firms from latecomer contexts such as Brazil (e.g. Politeconaço Industrial Ltd), South Africa (e.g. PiA Solar) and India (e.g. Mahindra Susten, Vikram Solar, Scorpius Trackers).

Unlike traditional mounting systems that just perform a structural function, interviewees explained that tracking systems introduce both mechanical complexities due to their moving parts and optimization/software complexities due to their role in increasing electricity production. As a result of these complexities, learning-by-using is crucial, as explained by one interviewee, "we have 12 GW deployed, and that's our living lab. All the mistakes have been there. We had our first iteration of the product [...] and then there were a lot of issues that were worked out, and then our second iteration of the trackers is probably about a GW." Importantly, while this learning-by-using often happens in localized markets (Gao and Rai, 2019), the knowledge gained through this use phase is typically applicable across a wide range of markets globally. In other words, tracking companies have used specific latecomer markets as a testbed for product development, but then are able to export their products to markets worldwide (i.e. tracker companies compete on a global level). This ability to export is also facilitated by the open interfaces of these systems, allowing them to be integrated with a range of other PV panel and inverter manufacturers.

Furthermore, due to both the open interfaces and the high module knowledge required for designing a tracking system, tracking companies are often specialized, rather than part of existing PV panel manufacturing firms. As explained by one interviewee: "the way I see the trend going is more for the opposite of [vertical integration], which is more specialization [...] prices are so low, you really need the best of the best." This trend has three implications for latecomers. Firstly, this disintegration creates entry points for latecomers, as the capabilities needed for tracker design typically lie outside of the core competencies of incumbents – both in terms of existing fixed tilt mounting suppliers and panel manufacturers that may have developed in-house mounting designs. In the past, this has allowed tracking companies to catch up to mounting system suppliers with much longer track records. Secondly, this specialization typically requires high module design capabilities for new entrants. With the tracking industry maturing, entry barriers may increase as innovation in these technologies shifts to competence reinforcing, incremental improvements in tracking design. Finally, because PV systems' interfaces are industry-wide, generally little interaction is needed between tracker suppliers and other segments in the global value chain. Consequently, learning-by-interacting along the global value chain is limited, which also provides few opportunities for upgrading via vertical integration.

### *4.2 Wind power*

#### 4.2.1 Innovation opportunities in response to a change in use environment

Unlike solar PV, wind turbines are sensitive to changes in wind energy inputs, requiring the selection of an appropriate turbine platform in order to ensure functionality in a new use environment. As the wind industry has matured, turbine OEMs have developed portfolios of turbine platforms to suit different wind classes, each with their firm-internal platform-specific design rules (see Figure 5). While extreme wind conditions have spurred architectural innovation and the development of new turbine platforms or designs in the past[14], generally only innovations in specific modules are needed to ensure turbine functionality. For example, certain climate conditions have necessitated innovation in turbine blades – ranging from modular innovation for hot-air circulation de-icing systems to incremental innovations in blade coatings (e.g., anti-erosion coatings in desert environments such as those in Egypt). For these incremental innovations, the learning normally falls to one of the existing international OEMs, further reinforcing their design capabilities. One representative based in a local subsidiary of a leading OEM explained: "we are the entry door to the technology groups [...] sometimes a customer will say, 'hey, I need a cold weather solution or a hot weather solution,' so we go back to the engineering teams back in [the OEM home country], and then we start finding the solution."

One interesting modular innovation that has arisen in many latecomer contexts due to both user preferences and regulatory constraints (demand and institutional windows of opportunity) are concrete towers. Concrete towers that are assembled on-site enable turbine OEMs to build taller turbines that can capture more uniform and higher wind resources, as steel towers of similar heights often face bottlenecks in transport[15]. For example, a new market for concrete towers was created through South Africa's Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) for two reasons. Firstly, interviewees explained that the high costs of capital in South Africa (and often in middle-income countries in general)

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[14] These extreme conditions are rarely found in onshore applications, but are more common for offshore wind which is thus far irrelevant in middle-income contexts and therefore not covered in this paper.
[15] Transport restrictions such as viaduct heights or maximum turn radii can limit the size of turbine towers in certain markets.

favor wind farms with fewer but larger turbines, leading to a significant reduction in capital expenditure with only a slight penalty on plant capacity factor. Secondly, the ability to manufacture concrete towers locally makes them an attractive option for fulfilling local content requirements[16], which are also growing increasingly prevalent in many emerging markets (OECD, 2015). Importantly, concrete towers are commonly supplied to OEMs by external suppliers, indicating a potential entry point for latecomer firms, which is explored further in the following section.

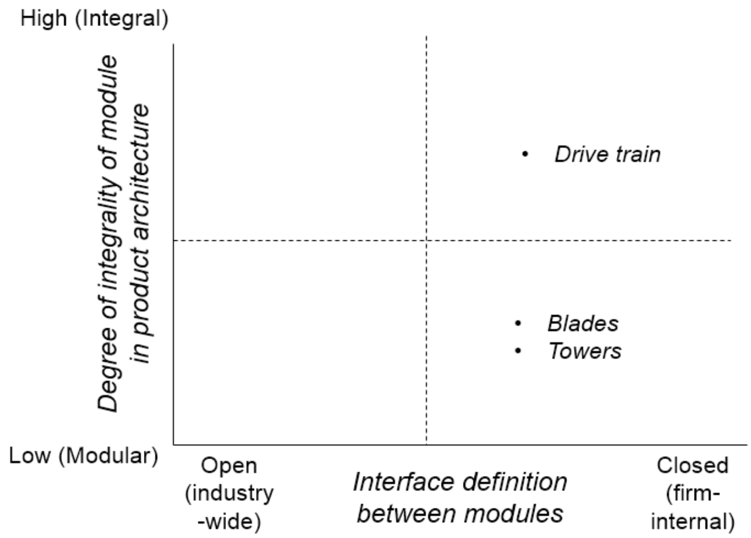


Figure 3: Categorization of several wind turbine modules according to their degree of integrality within the product architecture and inter-module interface definition

### 4.2.2 Exploring opportunities for latecomer catch-up: Concrete towers

The presence of local content requirements, high cost of capital, and/or constraints related to transport infrastructure has led to the emergence of opportunities for firms to produce concrete towers for wind turbines in several latecomer contexts. Some prominent examples are Brazil (Hochstetler and Kostka, 2015; Kuntze and Moerenhout, 2012), South Africa (e.g. GRI Towers South Africa, DCD Wind Towers) (Matsuo and Schmidt, 2019; Rennkamp and Boyd, 2015) and India (e.g. Wind World India), where firms have often developed significant module-specific design capabilities for innovation and manufacturing of wind turbine towers. This is exemplified by one local tower designer in South Africa: “it’s a concrete machine [...] you’re

[16] Local content requirements for wind power in South Africa increased from 25% in auction rounds 1 & 2 of the REIPPP to 40% in rounds 3 & 4.

talking about things that are totally outside of the envelope of a regular building. So we had to invest in software, we had to learn a lot of engineering, we had meetings with specialists from all over the world [...] until we were able to learn it." Additionally, a new tower design typically forces the establishment of a new set of design rules, and (incremental) innovation in the turbine platform architecture.

This has implications for both the capability build-up in the latecomer firm and the incumbent OEM. For the latecomer, development of the tower design requires iterative cycles of development and testing, as well as close collaboration with the OEM. One tower designer explained this process, which begins with data related to the typical loads acting on the tower as follows: "…and you take that, do a first design and then start iterating, because the loading changes – you have more mass [...] so you do an iteration, it returns to you and probably you do between 2 and 5 iterations." This process can lead to the build-up of significant tower design capabilities through learning-by-using and learning-by-interacting with the OEM, allowing the latecomer to develop a concrete tower design that could be globally competitive. However, the build-up of local capabilities is restricted to the tower design only (i.e. module design capabilities), and likely even only one OEM-specific turbine platform. At the same time, the turbine OEM gains architectural capabilities, further reinforcing its position as the key integrator of the technology. The modularity of the tower, combined with the only incremental architectural innovations required, effectively acts as a barrier to vertical integration, even in the presence of non-open interfaces.

## *4.3 Biomass power plants*

### 4.3.1 Innovation opportunities in response to a change in use environment

Like wind, biomass power requires adaptation to its energy input to ensure functionality. For biomass power, 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 turbines, which require the use of different turbine platforms to suit different wind regimes, changing the feedstock of a biomass power plant results in a 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." Different combustion system designs each operate with distinct principles. The most mature design, fixed grate boilers, evolved predominantly for the combustion of wood and wood residues in industrialized economies. However, when moving to other contexts with different feedstocks, such as agricultural residues (e.g., rice husk), combustion in a grate-fired boiler led to operational problems[17]. Consequently, many boiler OEMs are developing different boiler designs for these feedstocks[18]. These designs 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 biomass power to specific feedstocks typically requires complementary modular innovations. Once the combustion system design 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. Beyond the customized design of boiler technology, ensuring functionality of a biomass power plant is largely a design optimization problem involving incremental adjustments to both the combustion system design and complementary modules.

Steam turbines, on the other hand, are highly complex, and typically have standardized interfaces to minimize the need to customize them for each application. Hence, biomass power engineers will select the appropriate turbine from a catalogue of designs. 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." Due to this customizability, biomass power plants have closed interfaces, with the exception of the steam turbine and pollution control system, as shown in Figure 6.

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[17] The higher ash content and lower ash melting temperature of these agricultural feedstocks often resulted in sintering of ash on the grate.

[18] E.g., circulating fluidized bed or atmospheric fluidized bed designs

As the proper combustion system design is central to plant functionality, typical user preferences (e.g., cost) can often be difficult to accommodate, as one boiler manufacturer explained: "if we're talking about difficult raw materials and fuels, then there's no option [...] either you need to have financing for [the appropriate] boiler or you cannot construct at all." Policy and regulatory frameworks also often impact the design of the core module and subsequent complementary modules, creating institutional windows of opportunity. For example, interviewees explained that environmental regulations can restrict the selection of boiler type, as pollutant formation is predominantly a function of the combustion process. While certain incremental innovations can be made to the pollution control system to improve environmental performance, meeting strict environmental standards often requires an overhaul of the combustion technology since end-of-pipe solutions can prove to be technically impractical or uneconomical.

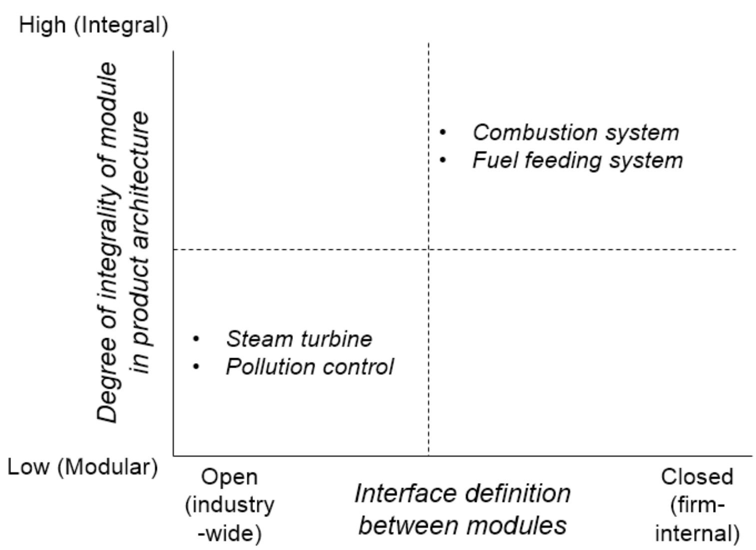



Figure 4: Categorization of several biomass power modules according to their degree of integrality within the product architecture and inter-module interface definition

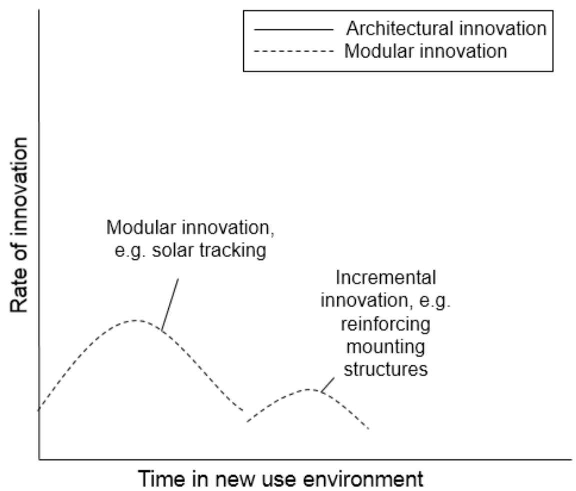
### 4.3.2 Exploring opportunities for latecomer catch-up: Combustion systems

Early biomass power combustion system designs were developed in European and North American markets, predominantly specializing in woody feedstocks which are easily combustible. As a result, the need to adapt combustion systems for more difficult to burn feedstocks more prevalent in latecomer countries (including agricultural residues such as rice husks or straw) represents a demand-side window of opportunity. In the development of this combustion technology, learning-by-using is crucial to developing the appropriate technology, making home markets an important aspect of competitiveness and capability-building. Thus, opportunities for boiler manufacturers have largely arisen in latecomer contexts with large domestic markets and non-woody local biomass feedstocks. For example, firms in India (e.g. Thermax Ltd, Thermodyne Boilers, Prime Thermals), Malaysia (Hansen and Ockwell, 2014) and China (Hansen and Hansen, 2021; Lin and He, 2016) have built up significant design capabilities through deployment in their respective domestic markets.

The centrality of understanding feedstock characteristics – including basic combustion parameters (bulk density, moisture content etc.) as well as how to handle the feedstock – is often a core competency in combustion system design, as knowledge about potential design configurations of the fuel feeding system is needed in order to optimize combustion processes. As a result, often the design of the fuel feeding system and the combustion system occur in parallel, frequently leading to vertical integration of the two activities. Interestingly, this vertical integration process has happened in both directions, where combustion system designers develop fuel feeding capabilities, as well as cases where companies specialized in feedstock processing/handling develop combustion design capabilities – typically by hiring individuals or acquiring firms with these design capabilities. Finally, given the architectural knowledge needed to develop combustion system designs, and the need to design the other biomass power plant modules around the combustion system, suppliers of these core modules often build architectural capabilities, allowing them to become turnkey suppliers or EPC contractors for the entire system.

| Conceptual schematic of technology lifecycle | Illustrative examples |
|---|---|

**Solar PV**



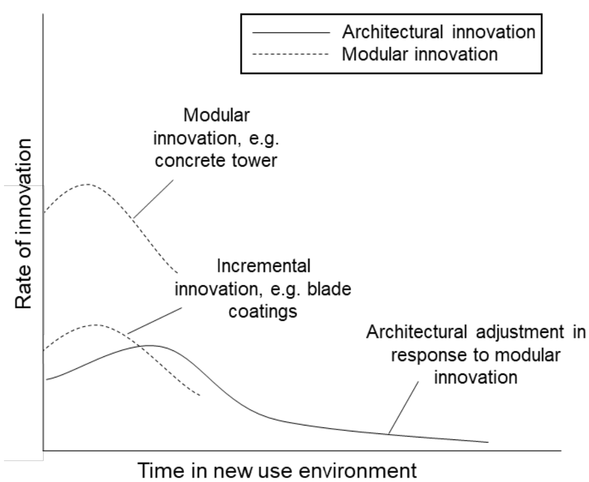

*Modular innovations:*

- Fixed-tilt to single-axis tracking due to *user preferences*

*Incremental innovations:*

- Reinforcing mounting structures to ensure *functionality* in high wind loads or corrosive environments
- Improvements in cell technology due to *user preferences* or *policy*

**Wind**




*Modular innovations:*

- Direct-drive wind turbine spurred by *user preferences* for low maintenance
- Concrete towers driven by local content *policies* and *user preferences* as higher towers can optimize cost/capacity factor

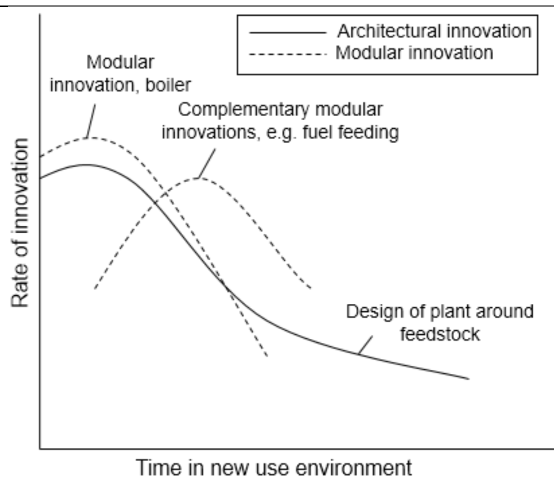
*Incremental innovations:*

- Special coatings on blades to ensure *functionality* in corrosive environments
- Software improvements to optimize wind farm performance in response to *user preferences* for greater short-term financial returns over turbine life

*Architectural innovations:*

- Adjustments in design rules between interfaces in response to a modular innovation

**Biomass power**




*Modular innovations:*

- Innovation in the combustion system to ensure *functionality* with a particular feedstock
- Innovation in the fuel feeding system to ensure *functionality* with a particular feedstock

*Incremental innovations:*

- Air staging within combustion systems, which reduces NOx formation, to meet environmental *regulations*

*Architectural innovations:*

- Changing interaction of fuel feeding and combustion system to *ensure functionality* or meet heat and electricity load requirements demanded by *user preferences*

Figure 5: The impact of use environment in spurring product innovation each case technology's lifecycle

# 5 Discussion

In this section we discuss the implications of our results for policymakers in latecomer countries regarding strategies for industrial catch-up. In our case selection, we had outlined three technologies ranging from modular and open-interface to a CoPS. Within each of these technologies, individual subsystems also exhibit a range of modularity and interface definition, with different implications for the entry and upgrading opportunities for latecomers, as summarized in Figure 8.

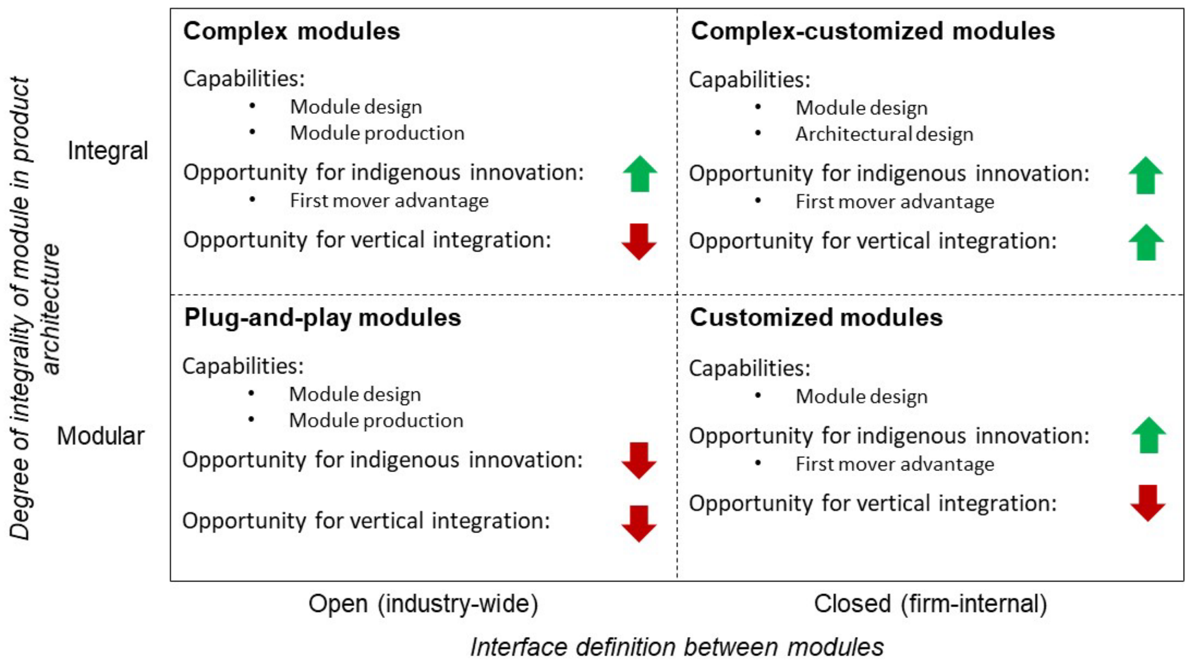



Figure 6: A typology of catching-up opportunities for various modules based on their degree of integrality within the product architecture and its interface definition

Design and manufacture of plug-and-play modules (such as PV panels or steam turbines) offer the fewest opportunities for latecomers. While entry barriers for these value chain segments are low in theory, competition in these open-interface modular products tends to occur on a global level, with specialized manufacturers that have built up significant capabilities. Therefore, the required capabilities needed to catch up to these manufacturers is high, typically exceeding the capabilities existing in many latecomer countries. Furthermore, as many of these products tend to be mass-produced technologies characterized by process innovation, opportunities for indigenous innovation in existing dominant designs are also low. While catching-up in these products has been analyzed in other studies (see e.g., Lee (2013)), given both the entry and upgrading challenges for these plug-and-play technologies, policymakers in latecomer countries should also consider targeting the localization of value chain segments in the other three quadrants.

For complex modules (integral open interfaces such as PV tracking systems, inverters or battery packs for electric vehicles), windows of opportunity have been created in the past as a result of changing demand (for example, increasing price pressure on project developers in competitive markets with good solar resource). However, in such cases, catching-up often requires exploitation of a first mover advantage. Due to their open interfaces, competition in these products often ultimately occurs between global actors - similar to modular value chains described by Gereffi et al. (2005). Competitiveness in these products therefore typically requires the early recognition of a window of opportunity, and dedicated support for local deployment to allow latecomer firms to build technological capabilities in module design. Such local deployment is needed to enable latecomers to become competitive in export markets, thereby providing the production scale typically needed to maintain competitiveness in global markets (i.e. once process innovation also becomes important).

For customized modules (modular closed interfaces such as wind towers, blades or electrolytes for lithium-ion batteries), windows of opportunity may arise from the creation of a local niche (e.g. different climatic conditions, local content requirements) that triggers a demand for a modular innovation. In order to exploit this niche, latecomers must build up module design capabilities, particularly through learning-by-using, making dedicated demand-pull policies important. Furthermore, closed interfaces typically require greater interaction of module suppliers with system integrators – similar to captive value chains described by Gereffi et al. (2005) in early stages of catch-up, with graduation to relational value chains as latecomers develop module design capabilities and begin co-innovating with OEMs. Policy could help foster this interaction by supporting industrial zones or testing facilities that bring together multiple value chain actors. However, closed interfaces also can lead to market fragmentation, which can limit catching-up opportunities due to insufficient market volumes to incentivize investments in the local innovation system. Reaching this critical size can be problematic if a use environment is too heterogeneous, leading to over-speciation of technologies and fragmentation of the local market. Within our case technologies, we observed this issue particularly for wind turbine blades, which need to be designed specifically for each turbine platform. Consequently, deployment policies aiming to localize these value chain segments should consider not only the total size of the market for the technology, but also the diversity of the use environment and market structure (i.e. the number of OEMs active in the local market). Supporting localization of such components may require additional industry policy mechanisms to ensure adequate market volume, such as export credit assistance or regional aggregation of demand to help component suppliers tap markets with similar use environments. While a latecomer may be able to become a competitive regional supplier of a specialized component, it is unlikely to break into other parts of the global value chain, as the modularity of the component limits the build-up of architectural capabilities that are a likely prerequisite to vertical integration.

Finally, complex-customized modules (integral closed interfaces such as biomass power plant combustion systems and turbines for geothermal power plants) provide the highest opportunity for latecomers. This is because both the probability of emergence of windows of opportunity in new market niches, as well as the potential for vertical integration (or ‘hierarchy’ in the framework of Gereffi et al., 2005) along the value chain in CoPS is high. However, doing so requires the accumulation of both high module and architectural design capabilities through learning-by-using. For CoPS, these capabilities are typically built through inter-project learning, making a rather homogenous domestic demand important for building sufficient local capabilities. For example, in the case of biomass – which can be used in a range of energy conversion processes – creating these conditions may require a targeted demand-pull approach. For instance, Brazil, a country rich in bagasse resources, specifically oriented their policy to target liquid biofuel production, rather than allowing the market to become fragmented across different applications. Finally, given both the importance and high value of architectural knowledge for these technologies, policy could also seek to support integration of local players into EPC roles, for example through joint ventures. In the case of biomass, already, many local players may have specialized knowledge about indigenous feedstocks, giving them an advantage in breaking into the role of an integrator – a high-value activity that is also ‘exportable’ to countries with similar biomass feedstocks.

The typology shown in Figure 8 adds to the existing literature on how technology-inherent characteristics influence learning processes and industrial catch-up among latecomers. Recent studies indicate that technological complexity and the need for customization influence the level of capabilities required for innovation (Schmidt and Huenteler, 2016), the rate of technological progress (Malhotra and Schmidt, 2020; Wilson et al., 2020), the level of interaction required between value chain segments (Malhotra et al., 2019), and the spatial dynamics of innovation systems (Binz and Truffer, 2017). Other studies have combined these frameworks with insights from the literature on latecomer development to investigate the dynamics of technological catch-up, either focusing on entire technologies and industries (Binz et al., 2017; Hansen and Hansen, 2021; Quitzow et al., 2017) or considering specific value chain segments as their unit of analysis (Dai et al., 2021; Gao and Rai, 2019; Surana et al., 2020; Zhang and Gallagher, 2016). Our typology contributes to this stream of literature by explicitly linking technology-inherent characteristics (specifically, the integrality and interface definition of the technology's modules) with types of interaction described in the literature on global value chains, thus better integrating the two streams of literature. In particular, our findings complement those of studies like Quitzow et al. (2017) and Surana et al. (2020) by highlighting that complexity is not the only technological characteristic that mediates the entrance and upgrading of firms in global value chains – the interface definition of modules can also be important in determining the nature of interaction and opportunities for upgrading of latecomer firms.

The typology can also help middle-income countries in complementing broader efforts to strengthen the country's technological capabilities and national innovation system with measures to develop more targeted energy and industrial strategies. Specifically, our results show that policymakers may want to target or exclude specific technologies within their industrial policies. For example, given the difficulty in gaining and maintaining competitiveness in open-interface technologies, implementing a protectionist policy for these technologies in a country with limited internal market size is likely only to hurt industry growth and deployment outcomes. In South Africa, for example, relatively high local content requirements for solar PV were achieved using 'transfer pricing,' in which solar modules were imported cheaply and the price was marked up to achieve the local content threshold, making projects more expensive without creating any additional local value. For such technologies, policymakers should consider including them in their energy policy portfolio, while actively excluding them from their green industrial policy strategy.

Ideally, policymakers need to be conscious of technologies' product architectures, changes in their demand and institutional environments, and their influence on indigenous innovation, capability-building and types of interaction in global value chains. We observe that demand and institutional windows of opportunity for renewable energy technologies are interlinked, since demand-pull policies play an important role in creating markets for new technologies in the energy sector, and policy design plays an important role in determining which service characteristics are favored in a particular market. Thus, while conducting ex-ante studies to design deployment and green industrial policies that anticipate or actively create windows of opportunity for specific components and technologies, may place additional strains on policymakers, it may be necessary to increase such policies' effectiveness. As a corollary, national, bilateral, and multilateral initiatives to achieve SDG 9 should also focus on building policymakers' capabilities for understanding and evaluating technologies.

Finally, because learning-by-using mechanisms are important to foster indigenous product innovation, financial support for the deployment of these technologies may be needed, as commercial finance is typically too risk-averse to support new technologies (Mazzucato and Semieniuk, 2016) – particularly if they originate in a latecomer context.

## 6 Conclusions and future research

Our results show the importance of both the 'windows of opportunity' created by a new use environment in specific segments of global value chains, as well as the role of the product architecture in moderating these opportunities. While these windows are difficult to predict, a key observation is that the rise in demands from emerging and developing countries often creates a large demand window, as many technologies that evolved in the incumbent contexts are not optimized or even completely unsuited for meeting conditions in the latecomer contexts. Consequently, policymakers should be wary of importing entire value chains – from project development, to EPC, to technologies – as this could lead to a failure to recognize local windows of opportunity when they do arise. Instead, policymakers could try to incentivize greater participation from local actors more familiar with local characteristics of the use environment. Rather than imitating the technology pathway taken by incumbents, there is a potential to explore how demand shifts in latecomer markets can create opportunities for a subset of technologies more suited to these specific markets (e.g., in the case of biomass feedstocks). This would likely require greater interaction among latecomer contexts with similar use environments, and a shift away from the current assumption of technology transfer from incumbents to latecomer countries.

This study provides insights into how technology characteristics moderate windows of opportunity for the entry and upgrading of latecomers in global value chains. Conceptually, it helps in bridging the gap between the literature on global value chains and the literature on innovation management by explicitly considering how the product architecture influences the type of interaction between value chain segments and hence moderate latecomers' opportunities for upgrading and vertical integration. Future research could build on these insights and further substantiate these findings. Quantitative analyses, for example using patent data or data on the localization of different technology production facilities, could provide further evidence of the role of changing use environments in driving technological innovation and speciation. Additionally, this study was based on broad set of interviews with firms in middle-income countries, which were used to formulate general patterns. Thus, our findings are only generalizable to other middle-income country contexts. Future work could investigate the applicability and extension of our findings to lower-income countries. Finally, we have investigated factors in the use environment that lead to the creation of windows of opportunity in specific segments of global value chains of different technologies. In reality, the creation and exploitation of such windows of opportunity is also dependent on the prevailing political economy in the country. Thus, future research could focus on the role of politics and political economy on the successful catch-up of latecomer firms and countries.

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**Appendix A**

**Table A1: Interview guide used for semi-structured interviews.**

During the interview, the generic terms that are included in this interview guide in square brackets were replaced by appropriate specific instances of technologies and modules. Please note that the interview questions were also adapted based on whether the interviewee was from an incumbent or a latecomer firm.

| Category | Exemplary Questions |
|---|---|
| Changes in use environment and windows of opportunity | We are interested in the “use environment” of a <technology>. And this is because we have the understanding that the design logic of a <technology> is shaped by feedback between user-defined service characteristics – basically design attributes like being low-cost, reliable etc. – and the technical functions and constraints of the <technology> design. Does this logic make sense to you? |
| | When we first started research into <technology>, we assumed the service characteristics were constant and weighted equally. In reality, how do these service characteristics change in a new use environment? |
| | Thinking about these changes you just mentioned, which of them pose a challenge or risk when developing <technology> in a new use environment? Why? |
| | How do these changes in service characteristics influence the design of the <technology>? |
| | How do you learn which design changes need to be made to the technology or any one of its modules in order to adapt it to a new environment? (e.g., by ex-ante calculations, testing on-site, consultations) |
| | How do these design changes affect other aspects of the technology’s design or use? (e.g., how are these innovations integrated into the technology design?) |
| | Is a strong home market important for technology development and innovation? Do you see any differences in the design or operation of a <technology> from a OEMs from different countries?<br>If yes, how did these differences come about?<br>If no, thinking back to earlier stages of the industry, were there any key differences in the design of <technology> that were developed specifically for a market? |
| | Do these new markets present an opportunity for an OEM to expand its core competencies and tap into other new markets (e.g., gaining a foothold in an emerging opportunity)? Why or why not? If so, how would these competencies be developed? |

| | |
|---|---|
| Types of interaction in global value chain | How are these innovations integrated into the OEM's supply chain? (e.g. vertical integration, outsourcing, horizontal integration) |
| | In the absence of any local content requirements, are there any components that would naturally be sourced from local suppliers? Why does it make sense to source these locally? |
| | What kind of coordination or interactions are required in order to ensure compatibility of these components with the overall design? |
| | Let's now consider that there are local content requirements, and that the components you just mentioned do not fulfil the local content quota. Which technology components would you believe are most conducive to being sourced locally? |
| | What kind of local capabilities, in terms of knowledge or technical skills, would be required in order to produce these components locally? |
| | If these competencies weren't already existing, would an OEM choose build up these local capacities? Why or why not? If yes, How would the OEM build up these capabilities? |
| | Again, what kind of coordination or interactions are required in order to ensure quality and compatibility of these components with the overall design? |
| | What factors influence the decision to open local manufacturing hub versus decision to purchase from local suppliers? |
| | Would an OEM want to outsource a core component – would there be a risk of compromising competitiveness or product differentiation? |
| | Where is the industry seeing investments in local manufacturing hubs? What kind of technology components and why are these attractive? |